WBGU

German Advisory Council on Global Change

Flagship Report

Water in a heated world

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Copy deadline: 19.07.2024

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This report should be cited as: WBGU – German Advisory Council on Global Change (2024): Water in a heated World. Berlin: WBGU.

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Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.d-nb.de/en.

ISBN 978-3-946830-10-8

Translation: Bob Culverhouse, Berlin

The R&D project that generated this report was conducted on behalf of the German Federal Ministry of Education and Research and the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection under grant number 13N0708A5. Responsibility for the content of this publication rests with the author.

Designed by: WERNERWERKE GbR, Berlin
Cover photo: Rosmarie Wirz/Kollektion: Moment Open/via Getty Images
The illustrative elements in the summary and at the beginning of the chapters show sections of high-resolution maps of water body structures in various regions of the world. Source: Pekel et al. (2016) and https://global-surface-water.appspot.com

Produced by: WBGU
Typesetting: WBGU

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Acknowledgements

The WBGU would like to thank all external experts for their input and valuable assistance.

As a technical introduction to the topic, the WBGU received valuable input at expert hearings on 9 and 10 May 2023 with Prof Dr Akiça Bahri (former Minister of Agriculture, Tunisia), Prof Dr Christoph Donner (Berliner Wasserbetriebe) and Prof Dr Uli Paetzel (Deutsche Vereinigung für Wasserwirtschaft).

On 17 November 2023, Dr Johannes Cullmann (UN Water) gave the WBGU highly interesting insights into multilateral water policy.

During the expert hearing on 2 May 2024, the WBGU had the opportunity to exchange views with Prof Dr Dietrich Borchardt (Helmholtz Centre for Environmental Research – UFZ), Dr Ines Dombrowsky (German Institute of Development and Sustainability – IDOS), Prof Dr Dieter Gerten (Potsdam Institute for Climate Impact Research – PIK), Prof Dr Hans-Peter Grossart (Leibniz Institute of Freshwater Ecology and Inland Fisheries), Dr Verena Höckele (Projektträger Karlsruhe/Wassertechnologie, Karlsruher Institut für Technologie – KIT), Prof Dr Torsten Schmidt (Instrumental Analytical Chemistry, University of Duisburg-Essen) and Prof Dr Kerstin Stahl (Institute of Hydrology, University of Freiburg).

Furthermore, the WBGU wishes to thank all those who provided valuable support through discussions, comments, contributions, advice, research and peer reviews of individual parts of this report: Dr Axel Berger (German Institute of Development and Sustainability – IDOS), Prof Dr Clara Brandi (German Institute of Development and Sustainability – IDOS), Supernumerary Prof Dr Carsten Butsch (Department of Geography, University of Bonn), Prof Dr Beate Escher (Helmholtz Centre for Environmental Research, Leipzig), Prof Dr Matthias Finkbeiner (Institute of Environmental Technology, Technical University of Berlin), Dr Christoph Lüthi (Swiss Federal Institute of Aquatic Science and Technology – Eawag), Dr Farhad Mukhtarov (International Institute of Social Sciences – ISS, Erasmus University Rotterdam), Alexandra Skinner (Zukunft – Umwelt – Gesellschaft (ZUG) gGmbH) and Dr Olaf Wirth (Institute for Enviromental Strategies).

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Acronyms and Abbreviations

AI	Artificial Intelligence
AMR	Antimicrobial resistance
ANK	Aktionsprogramm Natürlicher Klimaschutz *Action Program Natural Climate Protection*
ASEAN	Association of Southeast Asian Nations
AU	African Union
BMBF	Bundesministerium für Bildung und Forschung *German Federal Ministry of Education and Research*
BMEL	Bundesministerium für Ernährung und Landwirtschaft *German Federal Ministry of Food and Agriculture*
BMUV	Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz *German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection*
BMWSB	Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen *German Federal Ministry for Housing, Urban Development and Building*
BMZ	Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung *German Federal Ministry for Economic Cooperation and Development*
BUND	Bund für Umwelt und Naturschutz Deutschland *German Federation for the Environment and Nature Conservation*
BOD	Biochemical Oxygen Demand
CAP	Common Agricultural Policy
CBD	Convention on Biological Diversity
CCS	Carbon Capture and Storage
CJEU	Court of Justice of the European Union
CLP	Classification, Labelling and Packaging
CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Conference of the Parties
CWIS	Citywide Inclusive Sanitation
DALYs	Disability-adjusted life years
DFG	Deutsche Forschungsgemeinschaft *German Research Foundation*
DIN	Deutsches Institut für Normung *German Institute for Standardisation*
DüV	Düngeverordnung *Fertiliser Ordinance*
ECB	European Central Bank
EIB	European Investment Bank
ESAP	European Single Access Points
ESRS	European Sustainability Reporting Standards

EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FC	Fecal Coliform
FSM	Fecal sludge management
G7	Group of Seven (Canada, France, Germany, Italy, Japan, United Kingdom, United States of America)
G20	Group of Twenty (industrialized countries of the G7, emerging economies of the O-5, EU)
GBF	Kunming-Montreal Global Biodiversity Framework
GDP	Gross domestic product
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit *German International Cooperation Society*
GG	Grundgesetz *The Basic Law for the Federal Republic of Germany*
GHG	Greenhouse gases
GWL	Global Warming Level
GWP	Global Water Partnership
HICs	High-Income Countries
HKH	Hindu Kush-Karakoram-Himalaya
HQ_{100}	Hundred-year flood
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resources Management
KfW	Kreditanstalt für Wiederaufbau *Credit Institute for Reconstruction*
KMU	Kleinere und Mittlere Unternehmen *Small and medium-sized enterprises*
LDCs	Least Developed Countries
Li_2CO_3	Lithium carbonate
LiOH	Lithium hydroxide
LMICs	Low- and middle-income countries
MENA	Middle East and North Africa
MRC	Mekong River Commission
NAMs	New Approach Methodologies
NAPs	National Adaptation Plans
NbS	Nature-based Solutions
NDCs	Nationally Determined Contributions
NGO	Non-Governmental Organization
NOx	Nitrogen oxides
ODA	Official Development Assistance
OECD	Organisation for Economic Co-operation and Development
PAH	Polycyclic Aromatic Hydrocarbons
PBT	Persistent, bioaccumulative, toxic
PFAS	Per- and polyfluoroalkyl substances
PM	Particulate matter
PMT	Persistent, mobile, toxic
PPPs	Public-Private-Partnerships
PV	Photovoltaic
RCP	Representative Concentration Pathway
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SDGs	Sustainable Development Goals
SSP	Shared Socioeconomic Pathway
TDS	Total Dissolved Solids
TWS	Total Water Storage

UBA	Umweltbundesamt *German Environment Agency*
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNCTAD	United Nations Conference on Trade and Development
UNDP	United Nations Development Programme
UNECE	United Nations Economic Commission for Europe
UNEA	United Nations Environment Assembly
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNGA	General Assembly of the United Nations
UN Habitat	United Nations Human Settlements Programme
UN-ESCWA	Economic and Social Commission for Western Asia
UNICEF	United Nations Children's Fund
WEF	World Economic Forum
WEFE	Water-Energy-Food-Ecosystem
WHO	World Health Organization
WTO	World Trade Organization
WWF	World Wide Fund For Nature
WBGU	Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen *German Advisory Council on Global Change*

Summary

In a climatically and geopolitically heated world, the challenges surrounding water are becoming substantially more acute. Uncertainty is becoming the norm; the limits of controllability could be exceeded. What is needed is a climate-resilient water-management regime with a long-term view that combines thinking about blue and green water and is able to react flexibly to changes. It must incorporate existing, self-organized structures and needs to be accompanied and supported by science. An International Water Strategy with regional platforms should be developed.

Where there is water, there is life. Water is powerful yet fragile – an object of conflict and, at the same time, a unifying medium. Continuing, accelerated changes in the global water cycle are to be expected in the future. The effects of climate change, the overexploitation of water resources, the unequal distribution of water, the loss of ecosystem services, and threats posed by water-related health risks will continue to intensify. The assumption of stationarity – i.e. the idea that natural systems exhibit predictable variability within a defined time window on the basis of empirical observations – is no longer valid in the face of climate change. This will increasingly lead to threatening situations that are beyond the spectrum of human experience and could escalate into regional water emergencies. In extreme cases, situations arise in which the limits of controllability are exceeded, societal structures and ecosystems are substantially destabilized, and there is no longer any room for manoeuvre. These are threatening patterns with a planetary dimension.

A water-mapping initiative consisting of a scientific platform and a panel of experts should be launched internationally in order to recognize crisis developments at an early stage and avert regional water emergencies with a planetary dimension. Furthermore, there should be a systematic international exchange on effective adaptation and resilience strategies. These challenges face all countries, and an International Water Strategy should be sought to meet these challenges as a global community.

Climate-resilient, socially balanced water management worldwide, in which infrastructure and management approaches adapt to changes in local hydrological balances and increasing extreme events, is of key importance. This also includes the protection of water quality by consistently implementing the zero-pollution approach and the guiding principle of a circular water economy, incorporating ecosystems and the active management of green water in the form of soil moisture.

Moreover, sustainable water policy can only succeed if progress is also made in other policy areas. A stringent climate-change-mitigation policy, spatial planning for the conservation and restoration of ecosystems and the implementation of international biodiversity targets are essential to maintain room for manoeuvre. They must be closely linked to global social, economic and trade policies to make a peaceful "WaterFuture" possible. Private investment must be mobilized and public revenues stabilized in order to finance the adaptation to a changed water supply and increasingly frequent extreme events. Access to funding should also be improved for local actors.

Science is an important resource for enabling climate-resilient water management. It has an obligation to supplement empirical knowledge with projections of future changes and their uncertainties. At the same time, innovative approaches for dealing with large-scale and disruptive changes in water availability and increasingly frequent extreme events must be developed and scientifically monitored. Decision-making processes can be accelerated by providing real-time data and forecasts.

A sustainable WaterFuture requires goals and responsibility to be borne not only by the state but also by business and society. The state must create the conditions for this and lay down a political and regulatory framework that promotes self-organized structures and supports an education campaign for the responsible use of water. As a valuable resource, water should be priced consistently and in a socially balanced way in order to promote its efficient and sustainable use worldwide.

It is therefore of the utmost urgency to place the issue of water higher on the international agenda. The current strong momentum created by the UN Water Conferences in 2023, 2026 and 2028 should be used by governments to maintain a sufficient distance from the limits of controllability worldwide by taking comprehensive precautions. In the short term, effective strategies for resilient water management should be developed that will strengthen global cooperation in the medium term and lead to a water agreement supported by the international community in the long term.

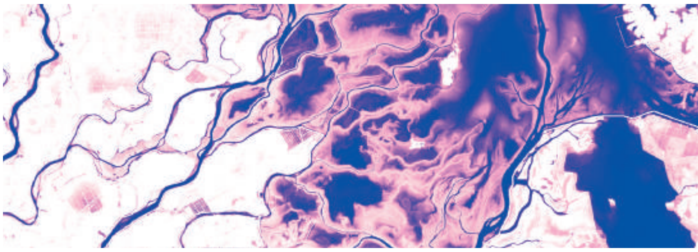
International water policy must adapt to the progressive and accelerated changes in the global water cycle. To this end, water should be considered a cross-cutting issue in many forums, but it also needs its own process and political attention. The WBGU recommends developing an International Water Strategy by 2030. The objectives and measures of the Strategy should also be incorporated into intergovernmental economic and trade relations to enable synergies between the protection of water resources and support for climate-neutral development and food security. In the long term, the strategy should be developed into a separate international agreement for water – comparable to the Rio Conventions.

Box 1 provides an overview of the WBGU's key messages.

Box 1

Core messages

- Keep the limits of controllability at a safe distance
- Anticipate and avert regional water emergencies with a planetary dimension
- Implement climate-resilient water management and maintain near-natural water quality
- Integrated climate policy, biodiversity policy and social policy are effective water policy
- Transformative water knowledge: forward-looking practice supported by science
- With society, not against it: the proactive state and self-organized society take up responsibility
- Take responsibility internationally – develop an International Water Strategy
- Use the national water strategy to foster the international discourse on water



How we use water today

On Earth, water passes through a continuous, global cycle, which constantly provides fresh water in the form of precipitation over land. This is then available as blue or green water: blue water includes all water resources in rivers, lakes, reservoirs and groundwater; green water refers to the water held in the subsurface as soil moisture; through plants it can productively promote the formation of biomass (Rockström et al., 2023). Ecosystems and their biodiversity are an important part of the global water cycle. Humans now greatly influence the natural water cycle – both regionally and globally – by abstracting, using and discharging water in many ways which have changed and continue to change evaporation, precipitation, groundwater recharge, runoff behaviour, water quality, etc. Furthermore, the massive impact of climate change and ecosystem degradation can already be felt today.

Globally, agriculture accounts for 72 % of all freshwater abstraction, industry for 15 % and municipalities and households for 13 % (AQUASTAT, 2024). However, the amount of water abstracted for agriculture as a percentage of total abstraction varies considerably by region and income level. In high-income countries it is on average only 41 % of the total withdrawals, whereas in low- and middle-income countries water abstracted for agriculture accounts for 80–90 % (Ritchie and Roser, 2017). The expansion of irrigated agriculture, the area of which more than doubled between 1961 and 2018 (UNESCO, 2024), and the water requirements of a growing urban population have led to the overuse of non-renewable groundwater (deep groundwater), and water tables have been falling further and further in many regions and cities around the world. The Middle East, North Africa, India, northern China and the Southwest of the USA are particularly affected. In most of these regions, water consumption for agricultural irrigation accounted for an average of over 90 % of total water consumption between 1960 and 2010. At least around half of this came from non-renewable groundwater (Wada and Bierkens, 2014).

About 2.2 billion people have no safe access to clean drinking water – low- and middle-income countries are particularly affected (UNESCO, 2024). The supply situation is especially difficult in rural areas, where four out of five people do not have safe access to clean drinking water. About 3.5 billion people have no access to an adequate, hygienic water supply. Official Development Assistence (ODA) to the water sector in 2022 was US$9.1 billion, more than 4 % below its 2018 peak (UN Water, 2024).

Between 2002 and 2021, 1.6 billion people were affected by flooding and about 100,000 lost their lives. In the same period, 1.4 billion people suffered from droughts, with about 21,000 deaths (UNESCO, 2024). Approximately half of the world's population currently suffers from severe water shortages for at least part of the year (IPCC, 2023).

In many regions of the world, efforts to ensure a safe water supply and disposal system have made significant progress, yet a substantial proportion of the world's population still does not have adequate access to these services: for at least three billion people, water quality is uncertain because of a lack of monitoring (UN, 2022). The threat caused by pathogenic microorganisms in drinking water still affects two billion people worldwide.

In addition to local effects, there can also be telecoupling effects via trade in goods whose production requires water. The water required for producing goods and the water contained in the goods can be tracked as virtual water flows across the globe. Approximately 65–90 % of global virtual water flows originate from trade with agricultural products, followed at a considerable distance by industry and the energy sector. Countries exporting agricultural goods in particular thus indirectly export their own water.

Water is wasted, overused and unfairly distributed in many places. Use patterns are shaped by political framework conditions and the existing water infrastructure which involve considerable path dependencies that make course corrections and substantial changes difficult.

Exacerbated water-related challenges in the future

Humanity, ecosystems and the planet are moving towards a future in which the quantities and quality of water available to humans and nature are subject to increasing change. The assumption of stationarity is no longer valid, particularly as a result of climate change.

Climate change and pollution

Climate change is intensifying the global water cycle: water is evaporating ever faster from the animal and plant world, as well as from soil and water surfaces, and the amount of water stored in the air is increasing – the air can store 7 % more water for every 1 °C of warming, making more and heavier precipitation events possible.

Progressive warming is driving global and regional changes in precipitation and evaporation, shifting the balance from frozen to liquid water, increasing the water content in the atmosphere and leading to an increase in extreme events such as floods and droughts. One billion people currently live near a coast and are directly affected by rising sea levels and correspondingly higher storm surges (IPCC, 2019). Precipitation is rising on a global average; every 1 °C added to global warming increases average precipitation worldwide by 1–3 %, whereby the extent and direction of the changes – and therefore their effects – vary greatly from one region to another. The amount of precipitation could increase by up to 13 % by the end of the century compared to the period 1995–2014. Since warming also leads to potentially higher evaporation, there are regional differences in the effects on the total amount of water available. Soil moisture and thus green water will decrease more and more in many regions. If global warming reaches 4 °C, this could mean a reduction in soil moisture of up to 40 % in Amazonia, southern Africa and western Europe, for example – while continuing to increase in other regions. In response to climate change, groundwater abstraction, e.g. for irrigation, can be expected to increase and could deplete the non-renewable groundwater resources worldwide. The combination of further rising temperatures, changing precipitation patterns, retreating glaciers and reduced snow cover means that average runoff volumes will increase as global warming progresses, albeit with regional differences. Increasing runoff volumes are predicted in particular for the northern high latitudes and regions in Central and East Africa, while decreases in the Mediterranean region and parts of Central and South America will lead to considerable shortages of blue water, especially in the summer months (Douville et al., 2021).

Water quality, too, will continue to decline in the future if the discharge of inadequately treated wastewater – currently about 80 % of the world's wastewater – and with it pathogens, persistent chemicals, nutrients and solid waste continues. As a result, groundwater, many freshwaters, coastal zones and seas are becoming dead zones uninhabitable for animals and plants due to a lack of oxygen and toxic blooms; the self-purifying power of water bodies is being lost. The complexity of pollution is increasing as a result of modern, newly developed substances, as well as mixtures of substances and possible interactions, e.g. with the microorganisms present (EEA, 2022). The long-term risks are yet unknown and are the subject of ongoing research. Micro- and nanoplastics, for example, can act as a vector for additional harmful contaminants with potentially serious consequences for the environment and health. In a future scenario without countermeasures, the amount of plastic – and therefore also microplastics and nanoplastics – released into the environment is expected to double globally to 44 million tonnes per year by 2060 (OECD, 2022). Climate change is further exacerbating the situation: during periods of drought, for example, the concentration of pollutants in surface waters can no longer be sufficiently diluted. Flooding and melting snow and ice mobilize pollutants, making them bioavailable. Rising water temperatures during heat waves influence the physical, chemical and biological processes in surface waters, which can affect the concentration and chemical properties of transported substances. Together with unabated climate change, this results in an extreme, barely controllable burden for global water resources.

The capacity for adaptation decreases continuously as climate change progresses – this affects people, technological and institutional systems as well as nature (IPCC, 2022). In order to largely maintain adaptability, there is no alternative to limiting climate change to 1.5 °C global warming in accordance with the precautionary principle and – if possible – even reversing it in the long term. This requires an end to anthropogenic CO_2 emissions and a sharp reduction in emissions of other greenhouse gases, as well as the removal of CO_2 from the atmosphere.

Socio-economic and geopolitical developments

In future, unless effective actions are taken, water use – and thus the risk of overuse – will continue to grow, depending on the region. UNESCO (2023) estimates that the global demand for water will increase by about 1 % per year and thus by 20–30 % by 2050. However, the margin of error for this assessment is more than 50 %. A large proportion of the expected increase in demand will happen in low- and middle-income countries, especially in emerging economies. Increases in demand by municipalities and households are strongest in regions where the water supply and disposal are being expanded. Increases in industrial water demand generally go hand in hand with advancing industrialization; demand can also fall again if there are improvements in the efficiency of water use. The demand for water in agriculture is driven primarily by irrigation. Projections on the development of water demand vary considerably, depending on the underlying assumptions on socio-economic, technical and climatic developments. The IPCC estimates that the demand for water for irrigation could double or even triple by the end of the century (Caretta et al., 2022). Projections show that rising irrigation requirements and increased evaporation as a result of climate change will contribute to accelerating the depletion of groundwater resources by the end of the century.

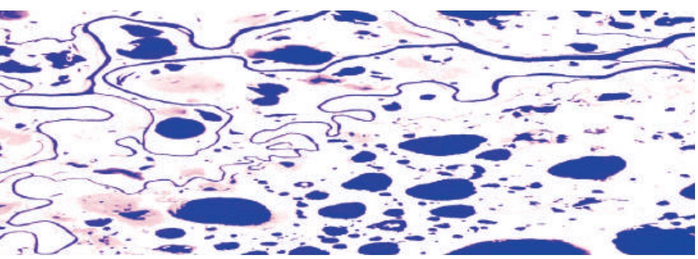
Global geopolitical and societal developments are likely to exacerbate the situation. A lack of water availability and extreme events such as droughts or floods can hinder growth, development and poverty alleviation. Multidimensional poverty and social inequalities, as well as autocratization and polarization processes, weaken societal cohesion, promote the fragmentation of governance systems and reduce societal resilience to water-related crises like droughts and floods. Water management is often a task that transcends political boundaries; like water-related multilateral negotiations it is therefore being made more difficult by current geopolitical tensions. Moreover, water crises are frequently caused not by a lack of availability but by unequal distribution. Climatically and ecologically induced resource availability and distribution deficits reinforce each other.

Damage to the health of species, ecosystems and humans

Increasing pollution, the growing climate crisis and their impact on hydrological processes and, not least, biodiversity will have direct and indirect consequences for human health and that of other organisms. This has an impact on the functioning and species composition of ecosystems. Water availability is fundamental to plant growth – and therefore to the functioning of ecosystems like forests or grasslands. Conversely, healthy ecosystems are essential for locally stable freshwater availability and quality. Water is therefore not only important for biodiversity; biodiversity is also important for water.

The interaction of climate factors can also change human living conditions so unfavourably that local livelihoods and food supplies are no longer guaranteed. Changes in water quality and quantity and the associated lack of safe water are only part of the threat situation. Water scarcity, pollution and flooding affect people both directly and indirectly. They can lead to the permanent loss of health and the loss of many human lives. Social structures and health facilities can also be lost. Irregular or insufficient water supplies impair not only the vitality of individual people and their performance in society but ultimately also the performance of society as a whole, with corresponding economic and socio-political consequences.

The emerging global exacerbation of challenges and their interaction can lead to emergencies that can hardly be controlled by humans. Examples of regional water emergencies that can also occur in the same or similar ways in other regions of the world are illustrated in Box 2.



Maintain a safe distance from the limits of controllability

Water emergencies can reach the limits of controllability, beyond which societal structures and ecosystems destabilize: humans and ecosystems in the affected region are deprived of their livelihoods (Box 2). In view of the predicted climatic, ecological, socio-economic and geopolitical developments, such boundary conditions and regional water emergencies can be expected to become increasingly common worldwide.

In order to maintain a safe distance from the limits of controllability, measures are required at the global, regional and local level (Fig. 2):

First, it is important to limit the exacerbation of challenges which, as global drivers, have a direct impact on the global water balance: this requires an ambitious climate policy, including compliance with the goals of the Paris Agreement, as this is the only way to limit the changes to the global and local hydrological balance caused by climate change. Equally important is the implementation of the Kunming-Montreal Global Biodiversity Framework in order to protect the fundamental role of nature in the global hydrological balance. The earlier action is taken, the more options there are.

Second, regional water emergencies must be avoided as far as possible. If the exacerbated water-related challenges cannot be controlled, the likelihood of regional water emergencies on a planetary scale will increase. Transformative adaptation measures and climate-resilient, socially balanced water management are needed as defence against such emergencies, since incremental adaptation measures will no longer be sufficient. This requires a willingness to radically change course, in particular by shaping structural change, for example in land-use, industrial, settlement and infrastructure policy – both nationally and in the context of international cooperation.

As it is not always possible to maintain a safe distance from the limits of controllability, regions at risk must prepare for a plan B at an early stage. If transformative measures no longer help, an orderly and timely withdrawal may be the only option left. Where the limits of controllability are crossed, the options for action are acutely reduced to reactive crisis and disaster management accompanying the retreat. Which risks are considered intolerable and which individual adaptation paths should be pursued is also the subject of societal negotiation processes.

Establish principles of action

The WBGU recommends climate-resilient, socially balanced water management based on the following principles:

- *Safeguard water as a common good for people and nature:* Water must be distributed and stored as a global, life-giving common good according to the needs of all people and nature. Nature-based, technical and institutional solutions for ensuring a resilient water supply with impeccable water quality must take into account and balance multifunctionality for humans and ecosystems.
- *Increase adaptability in the face of continuous change:* Systems for the provision and use of water should be kept resilient in the face of hitherto unknown fluctuations and ongoing changes that cannot be precisely predicted; they should be re-coordinated on a scientific basis. Administrations, operators and users must

Box 2

Regional water emergencies with a planetary dimension

Droughts and extreme precipitation will increase worldwide due to climate change. Melting glaciers will massively change the availability of water in many places. Added to this is the degradation and destruction of ecosystems that support valuable water storage, e.g. as green water. Water pollution will also increase significantly in some regions of the world. These exacerbated water-related challenges can mutually reinforce each other and, in the medium and long term, escalate into regional water emergencies with a planetary dimension. The extent and dynamics of these water emergencies can exceed hitherto manageable risks. Here, the WBGU describes five examples of regional water emergencies whose patterns can also be found in other regions of the world.

Water scarcity in cities

> 933 million
urban dwellers today are affected by water shortages

30–50 %
of the world's population will be affected by 2050

approx. **80 %**
growth in urban demand for water expected by 2050

In the last twenty years, over 80 large cities and metropolitan regions worldwide have been affected by severe water shortages (Rusca et al., 2023). The number of reports about cities threatening to run out of water is growing. In 2016, over 30 % of the urban population lived in areas where water was scarce. Lack of surface water, soil sealing, excessive groundwater use and the increase in the demand for water caused by (rapid) urbanization and rising per-capita demand are the main drivers of urban water shortages. Leaks in the water infrastructure and mismanagement are exacerbating the water shortage. The number of people living in cities facing water scarcity worldwide could increase from more than 933 million in 2016 to 1.6-2.3 billion people in 2050; that is between a third and almost half of the global urban population (He et al., 2021). The megacity of São Paulo (Brazil) experienced a severe water shortage in 2014-2016, while in 2019, Chennai (India), one of the world's wettest megacities, was affected by the worst water shortage in 30 years. Barcelona, Cape Town, Bogotá, Montevideo and Mexico City are further examples of cities where a water emergency has had to be declared in the recent past.

Increase in droughts and flash floods in the MENA region

6 %
of the world's population live in the MENA region

only **1 %**
of global freshwater resources is available there

24 %
decline in per-capita renewable freshwater availability between 2007 and 2018

By global comparison, the MENA region (Middle East and North Africa) will be one of the most severely affected by the negative effects of climate change (Hajat et al., 2023). Between 2007 and 2018, the availability of renewable fresh water per capita in the region fell by approximately 24 % (SIWI and UNICEF, 2023). Changing precipitation patterns, increasing aridity and droughts, heavy rainfall events and flash floods, and above all overuse, accompanied by major governance challenges in the equitable distribution of the few available freshwater resources are already leading to water shortages and unequal water availability for humans

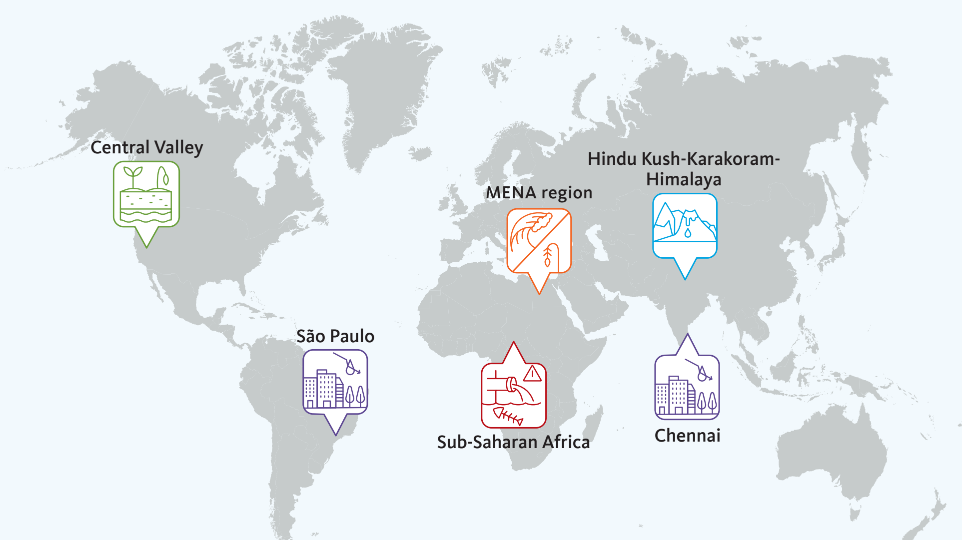


Figure 1
Geographical location of the regional water emergencies with a planetary dimension covered in the report.
Source: WBGU

and the environment in the region today. Projections indicate that a significantly more extreme climate can be expected in the MENA region in the future. Heat extremes, more aridity, longer-lasting droughts and more heavy rainfall events, combined with rising pressure of use, will further worsen water scarcity in the region in the future, with negative consequences for people and nature. This trend represents a global pattern: in 2022–2023, a drought emergency was declared in 22 countries worldwide (UNCCD, 2023).

Melting glaciers in the Hindu Kush-Karakoram-Himalayan mountain range: loss of large water reservoirs

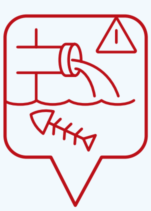
2 billion
people access their water from the region's river basins

200 million
people are already suffering from increased water stress

20 % to 65 %
glacier loss depending on climate scenario

After the poles, the glaciers of the Hindu Kush-Karakoram-Himalayan mountain range are the largest frozen freshwater reservoirs on Earth. The region's river basins supply almost two billion people with water, i.e. a quarter of the world's population. Even without further warming, a loss of more than 20 % of the ice mass and glaciated area in the mountain range is projected by 2100; this proportion increases to up to 65 % under different climate scenarios. Almost 200 million people in the region are already suffering from water stress (Nie et al., 2021) and the situation can be expected to worsen by the end of the century. A reduced supply of water – especially in river basins like the Indus which are largely fed by melting water – is combined here with an increasing demand for water. This development harbours considerable destabilization potential: for example, increased water stress for people and ecosystems can lead to societal and geopolitical conflicts, growing natural hazards can pose a threat to human life and infrastructure, and reduced runoff in the summer months can affect not only regional but also global food production. The region accounts for 61 % of the global rice harvest, 41 % of global potato production and 24 % of the global maize harvest (Hu and Tan, 2018). Melting glaciers also pose water-related dangers in other regions of the world; the southern Andes, western Canada, the western USA (especially Alaska) and the European Alps are particularly affected.

Water pollution in Sub-Saharan Africa



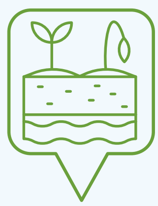
2.7 billion
people are today affected by water pollution

4.2 billion
is their expected number by 2100

38 %
of the world's population affected by organic water pollution will live in Sub-Saharan Africa in 2100

Globally, the number of people affected by water pollution from organic compounds could increase from 2.7 billion to up to 4.2 billion by the end of the century. Similar patterns are predicted for contamination by pathogenic microorganisms, salts and nutrients (Jones et al., 2023). This particularly affects Sub-Saharan Africa: by the end of the century, 25 % of all people – but 38 % of people worldwide affected by water pollution from organic compounds – are expected to be living in Africa. Pathogenic microorganisms pose a direct threat to human health; organic carbon compounds promote microbial growth and oxygen depletion in surface waters, leading to fish kills. Nutrients like nitrogen and phosphorus cause eutrophication, algal blooms and the loss of habitats and biodiversity. In addition to Sub-Saharan Africa, global hotspots of water pollution are also emerging in central and north-western Mexico, northern India and eastern China.

Overexploitation of groundwater and climate change in the Central Valley (USA)



25 %
of fruit and nut production in the USA originates from the Central Valley

10 %
water losses are expected in the region by 2030

75 %
of the wells have suffered a 1.5 metre lowering of the groundwater level 2018–2023

The risk of local water shortages has grown significantly in the Central Valley in recent decades due to rising demand and climate change. Groundwater loss has exceeded the rate of recharge on a multi-year average. As a result, more than 75 % of the wells suffered a lowering of the groundwater table by more than 1.5 m in 2018–2023 (CNRA, 2023). Maintaining the drinking water supply is becoming increasingly challenging in view of high consumption and more frequent dry periods. No alleviation of the situation is in sight. However, as a groundwater-dependent and semi-arid region, the Central Valley is not the only place in the world where there are signs of localized depletion of renewable groundwater resources with far-reaching consequences for people and nature. The north-east of China (Hai He Basin and North China Plain Aquifer), the north of India (Ganges-Brahmaputra Aquifer), the north-east of South America (São Francisco Basin), the southwest and south of the USA (Central and South High Plains), Eastern Europe (Don and Dnieper Basins) and the Middle East (Arabian Peninsula, Iran) are also reaching the limits of their natural carrying capacity as a result of years of intensive crop cultivation and the consequences of global warming.

prepare themselves for a highly dynamic situation. To achieve this, structures, as well as planning and decision-making processes, must be designed to be adaptable and correctable by all actors.

- *Resilience and risk prevention instead of emergency response:* The precautionary principle must be consistently applied to safeguard a climate-resilient water infrastructure and water quality. Risk prevention and risk minimization instead of emergency response should be the basis of planning processes and decisions in the entire water sector and sectors influenced by it.
- *Managing blue and green water across sectors:* Blue and green water must be considered and managed jointly and in all sectors in regional and local solution approaches. Both have strategic, geopolitical relevance: in addition to river catchment areas, transboundary evaporation and precipitation patterns must also be taken into account. Coherence between policy levels and fields is a prerequisite for this.
- *Enable a science-based discourse on challenges and options for action:* The WBGU recommends initiating a science-based discourse on strategy development and options for action in the face of uncertainties, taking the concerns of citizens and stakeholders into

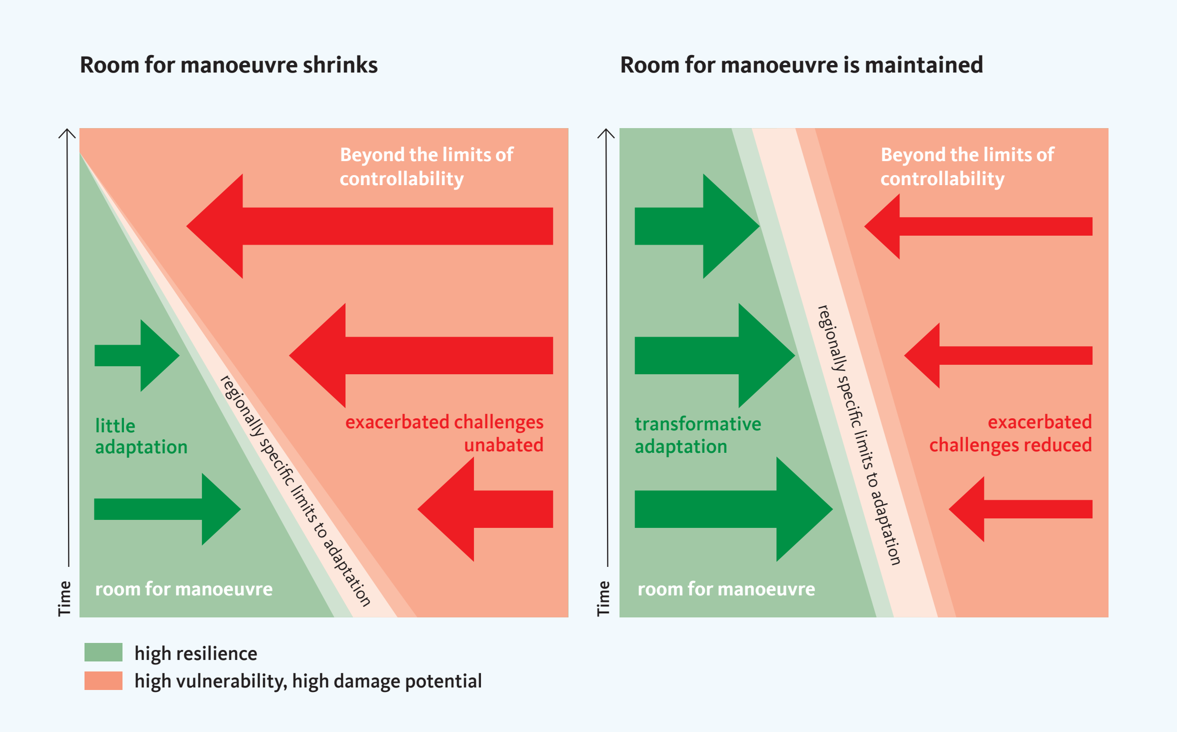
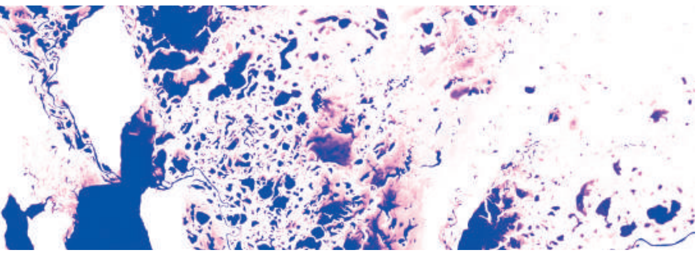


Figure 2
WBGU's concept on the limits of controllability. Unchecked aggravations of water supply, water distribution and extreme events, coupled with inadequate adaptation can lead to regional water emergencies and to the limits of controllability being exceeded. Beyond these limits, which can vary from one region to another, the risks are intolerably high (red area). Which risks are considered intolerable and which individual adaptation paths should be pursued is also the subject of societal negotiation processes.
Left: If only minor adaptation measures are taken, the room for manoeuvre shrinks (green area). Water-related challenges exacerbated by increasing climate change, ecosystem degradation and pollution, as well as socio-economic and geopolitical developments can unleash their full force. Vulnerability and damage potential increase, and the risk of exceeding the limits of controllability grows over time.
Right: Transformative precautions increase resilience and reduce the impact of exacerbated water-related challenges, while at the same time containing the exacerbated challenges themselves. Room for manoeuvre (green area) is also maintained in the longer term.
Source: WBGU

account. To this end, the severity and dynamics of exacerbated water-related challenges and resulting regional water emergencies with a planetary dimension must be identified, understood and options for action researched. Science should continuously inform policy-makers and take on an advisory role, e.g. by scientifically monitoring the instruments used. Political and societal participation, education and collaboration should be promoted.

- *Value water and appreciate the value of water:* Policy-makers, public institutions, companies and financial markets should embrace and integrate the value of water and the systemic nature of water risks into their decisions. Economic decisions must be compatible with the long-term goals of sustainable water management.
- *Accelerate implementation – encourage and promote self-organization:* The regulatory framework and all water-management instruments must enable accelerated implementation and involve informal, decentralized governance structures where appropriate. In particular, non-state, self-organized actors need to be involved and empowered.



Climate-resilient water management

In many places, overuse of water resources, unequal distribution, loss of ecosystem services, and water-related health risks are partly caused by misguided and ineffective water management. Management approaches aimed at overcoming shortcomings and deficiencies, such as the established Integrated Water Resources Management (IWRM) approach, do not yet meet the challenges of climate change. The essential features of a climate-resilient, socially balanced form of water management as outlined below, which are based on the principles of action described above, are intended to provide impetus for the further development of existing management approaches (IWRM, Water-Energy-Food-Ecosystem Nexus, adaptive water management) and for the more vigorous implementation of transformative adaptation in the water sector.

Making water management adaptable and resilient

The WBGU recommends establishing a new approach to water management that aims to live with – but also to minimize – uncertainty. Climate-resilient, socially balanced water management established across the board should proactively manage local, regional and global water cycles with foresight, and maintain the various functions of water for humans and ecosystems in the long term. Transdisciplinary and collaborative learning and decision-making processes across sectors and spatial scales are required to make action possible in the face of uncertainty. This is based on empirical data, real-time information and future projections under various climate scenarios on water supply and demand, whereby a rising demand for water in the course of the energy-system transformation must also be taken into account. This requires a digitalization campaign. Management methods must be constantly monitored on this basis and, if necessary, adjusted at short notice. To achieve this, planning and decision-making processes in water management must be adjustable, and infrastructure measures must be designed in a more decentralized and adaptive way.

Water management should moreover be geared towards preserving, strengthening and restoring a climate-resilient landscape water balance. As some of these measures only take effect after a time lag, it is necessary to combine them with short-term measures, but without creating undesirable path dependencies. In line with the integrated landscape approach proposed by the WBGU (2020), an integrated landscape and water-balance approach should be pursued that combines the protection of the climate and biodiversity, the land needed for food security, and the strengthening of natural buffers in the water balance on all types of land, independent of how they are used. The green water stored as soil moisture must be more strongly integrated into water management, taking the effects of climate change into account.

Climate adaptation, water management and ecosystem protection should be better interlinked. In order to enable greater use of regulating ecosystem services for stabilizing the water supply, a key role in water management should be assigned to safeguarding the functions of water for ecosystems.

To make the local drinking-water supply more resilient, it is necessary to utilize various independent blue-water resources that are redundant and mutually complementary. Where necessary and technically feasible, greater use of alternative water resources such as desalinated seawater or effluents from municipal wastewater treatment plants is also recommended, provided that adverse effects, e.g. for ecosystems and human health, can be avoided. Multiple uses of water of different quality levels should be anticipated in the construction of the water infrastructure and buildings. Digital water-information systems should be established across the board which record withdrawals by private households, public institutions and industry, potentially even in real-time, so that the supply can be adjusted by the utility. Artificial intelligence should also be used in the future, although there is still a need for research in this area. Decentralized water storage and water reuse can be established for large consumers, contributing to more flexible water abstraction.

In order to deal in the short term with increasingly frequent extreme events, a broad range of adaptive, fast-acting and resource-efficient measures – from purely technical to more nature-based ones – should be used in combination with long-term effective measures to restore a climate-resilient landscape water balance. The selection and combination of measures should be based on the requirements outlined in Box 3.

In addition, approaches for assessment processes under conditions of uncertainty should be further developed and put into practice. In regions that are particularly at risk from water emergencies, transdisciplinary forums should be created to address the challenges faced and to collaboratively develop adaptation options. In order to promote agile policy adaptation, more research projects should be funded that examine timely technical adaptation measures and policy measures, as well as their (water-) efficacy. Technical adaptation measures, e.g. planning bases for infrastructure measures such as the occurrence of a once-in-100-years flood event (HQ_{100}), must be adapted.

Solution-space ecosystems

The restoration of wetlands such as swamps and marshes, river and floodplain landscapes or peatlands, as well as other water-relevant ecosystems such as forests, plays an important role in climate-resilient water management. Since the pre-industrial era, it is estimated that more than 80 % of the world's wetlands have been lost due to changes in land use and drainage, and most of the remaining wetlands have been degraded (UNEP, 2021). Restoration measures in wetlands can improve the retention of water in the landscape and thus increase local water availability for humans and nature, stabilize supplies of drinking water, contribute to flood protection and improve water quality and nutrient storage. Multiple benefits include e.g. the provision of habitats for diverse flora and fauna, improved soil quality and contributions to the livelihoods and culture of local communities. Furthermore, peatland rewetting is of great importance for climate-change mitigation. Whether the restoration of a wetland is feasible also depends on the regional availability of water with the corresponding water quality. Unintended consequences such as the spread of invasive species or a change in the local hydrological cycle, which can have an adverse effect on agriculture, for example, should be taken into account and avoided.

The WBGU recommends promoting at all political levels the restoration of ecosystems that are of major importance for the water balance. This explicitly includes water-related activities within the UN Decade for Ecosystem Restoration, the UN Water Decade, the 2030 Agenda for Sustainable Development, the Ramsar Convention, the EU Water Framework Directive, the EU Nature Restoration Law and the relevant national strategies. In addition, Germany's Federal Action Plan on Nature-based Solutions for Climate and Biodiversity, and related, relevant strategies such as the German Peatland Protection Strategy should be promoted over the long term and the measures contained therein promptly implemented in the interests of climate-resilient water management.

Box 3

Requirements for climate-resilient water-management measures

The WBGU proposes four requirements that should be taken into account when selecting, implementing and developing climate-resilient, socially balanced water-management measures:

Assess water-related efficacy on different time scales: The efficacy of measures should be assessed on the one hand with regard to specific water-related objectives and, on the other, with regard to their respective contribution to the restoration of a climate-resilient landscape water balance. Against the background of exacerbated water-related challenges, different time horizons, uncertainties, impact delays and adaptation limits must be taken into account.

Analyse feasibility in the respective context: The feasibility of measures should be assessed on a context-specific basis, taking into account the availability of technologies, financial resources, institutional capacities, their acceptance and their requirements in terms of land and resources – also with regard to their long-term operation and any adjustments that may become necessary over time.

Focus more on potential multiple benefits: Possible multiple benefits for climate and biodiversity protection and health, social and economic benefits of measures, and effects on the reduction of inequalities should be anticipated, evaluated and taken into account in the assessment of measures.

Avoid unintended consequences: In order to avoid maladaptation and other unintended water-related, ecological, health, social and economic consequences, all impacts of measures should be identified, evaluated and taken into account using a systemic and transdisciplinary approach.

In the spirit of an integrated landscape approach (WBGU, 2020), it is advisable to enter into a dialogue with land users, residents living near areas to be restored, and other stakeholders at an early stage. In this way, conflicts can be avoided, multiple benefits increased and societal acceptance for restoration enhanced. The measures should be implemented with a view to the multifunctionality of the entire ecosystem (e.g. a river and floodplain landscape) and take into account the mosaic approach in spatial planning (WBGU, 2024). This can result in diverse river and floodplain landscapes with high biodiversity which fulfil various functions such as water-level stabilization, water treatment, groundwater recharge, CO_2 sequestration, and the provision of habitats or recreation areas. Along the entire river catchment, its sustainable use for navigation, fishing, tourism and drinking-water supply, among other things, can be made possible and a near-natural, harmonious appearance restored.

The removal of barriers in river courses should be promoted in order to restore their connectivity and enable far-reaching ecological and water-related multiple benefits. The WBGU recommends entertaining the possibility of creating new ecosystems in restoration measures and spatial planning. This should lead to re-consideration of the legally regulated classification 'good ecological status' (EU Water Framework Directive). Under certain circumstances, this can even mean an addition that takes into account restoration aimed at increasing the resilience of ecosystems. Adaptive management incorporating regular monitoring using scientifically proven methods and robust modelling can help to anticipate the processes of ecosystem restoration and, if necessary, take timely follow-up measures.

In research, the perspective of the water supply and the protection and restoration of ecosystems, especially freshwater ecosystems, should be integrated or given greater consideration, for example in Germany's Future Research and Innovation Strategy. Research on swamp and river landscapes should be expanded: in order to do justice to different usage requirements of river courses and landscapes, more research is needed that analyses their diverse ecosystem services as a function of restoration measures. The findings should be incorporated into multifunctional spatial planning.

Long-term studies, research and monitoring projects have an important role to play and should be promoted: examples include studies on the diverse effects of dam removal, on comparing the initial state with the ecological state after dam construction and after removal, or on water input into upland bogs. There is a need for research into the typification and mapping of peatlands in order to effectively monitor, protect and restore peatlands and their contribution to climate-change mitigation and the conservation of specific biodiversity. Socio-ecological research should also be strengthened. For example, ecosystem services and the impacts of management and restoration should be comprehensively studied, and methods for the effective implementation of the integrated landscape approach for ecosystems of major importance for the water balance should be researched and made available.

Solution-space agriculture

On the one hand, climate-resilient water management in agriculture means adapting crops and cultivation methods (and irrigating where or when necessary) in order to deal with fluctuations in water supply and climate change as a whole. On the other hand, agricultural practices in turn also influence the water balance and water supply; agriculture must therefore contribute to a climate-resilient landscape water balance. Approaches to reducing water-related risks are diverse and locally specific, their effectiveness declines as climate change increases and is subject to uncertainties. Among the approaches under consideration, measures to maintain soil moisture and agroforestry are relatively effective even if warming intensifies. Often, however, individual measures will no longer be sufficient and combinations will be necessary (Caretta et al., 2022). In its report entitled 'Rethinking Land in the Anthropocene: from separation to integration', the WBGU made extensive recommendations for ecologically sustainable agriculture and its incorporation into an integrated landscape approach (WBGU, 2020). In addition to this, the following recommendations are made for climate-resilient, socially balanced water management in agriculture:

First, data and projections on water use and water supply should be improved and more knowledge made available on water-related adaptation measures in agriculture. Many measures are in the individual farmer's self-interest and, in principle, also within its sphere of influence. Advisory and training programmes or regional support teams should therefore provide farmers with knowledge and skills for climate-resilient water management and involve them in its practical further development. For overarching planning and regulation, abstraction and consumption data should be collected in real time wherever possible, data on water supply, groundwater aquifers, etc. should be improved and made available together with corresponding projections. This should be part of a broader digitization campaign for agriculture. Capacities should be built up for improving publicly available local projections and scientific monitoring of adaptation measures. Experience should be exchanged in international networks, including with low-income countries. In these countries, for example in Sub-Saharan Africa, the potential of local knowledge systems should be better used in local adaptation and transformation strategies for agriculture. Corresponding advisory services and networking activities could be further expanded internationally, for example by the GIZ, and in Germany by the Federal Agency for Agriculture and Food.

Second, agriculture should also be appreciated as 'green water management' and incorporated into integrated landscape and water-management approaches: adaptation measures that influence the water balance and water quality – e.g. by creating buffers, increasing groundwater recharge or maintaining ecosystem services – also benefit other water users or the general public. Land users should therefore be seen more as water actors, and farmers should be given more support in their role as 'green water caretakers'. This should be reflected in the political and societal treatment of agriculture, in its appreciation, in education and training and in its integration into water-management processes – such as an integrated landscape and water-balance approach and climate-adaptation strategies – and in financial incentives.

Third, financial incentives for farmers are required and transformation efforts should be safeguarded; in some cases, sufficient access to resources and capital must first be created in low- and middle-income countries. Compensating mechanisms, such as water funds, should be established between land users and water users for measures affecting water. Here, water-related agricultural subsidies can be integrated. In the EU, this concerns the next cycle of the common agricultural policy, which should be reorganized into a 'common ecosystem policy' (WBGU, 2020). As cooperation between farmers and the public sector is essential when it comes to water risks, new scope for negotiation could arise here. This should be flanked by the creation of transition programmes that secure livelihoods and mitigate the risks of the transformation for agriculture, e.g. by means of temporary income support or partial protection against possible reduced yields when testing new cultivation methods. Possible regulation or pricing of actual water abstraction and consumption (based on improved data) should be facilitated by the above-mentioned supporting measures, also with a view to social balance.

Research should develop new guiding principles for agriculture. The focus here is on learning from practical experience with adaptation strategies. Tools and metrics for evaluating adaptation measures should also be further developed. Options such as changes in behaviour or capacity-building measures often cannot be covered by current climate and impact models. Appropriately scaled models are needed that take into account economic, social, cultural and management aspects for different adaptation options, as well as multiple benefits and trade-offs for sustainable development. There are still knowledge gaps regarding the potential effectiveness of adaptation measures to reduce water-related risks, especially for climate scenarios predicting warming of 2 °C and more. In particular, the potential and limits of irrigation as an adaptation option should be better researched, since global modelling often does not sufficiently take local water availability into account. Tools also need to be developed to improve our understanding of interrelationships in the water-energy-food-ecosystem nexus and to project changing sectoral expectations in climate change.

Solution-space cities

By 2050, the global urban population will have grown to an estimated 6.6 billion people, with two thirds of humanity living in cities (UN, 2019). At the same time, the effects of climate change are being felt more and more acutely in many cities around the world. In addition to increasing pressure on natural resources, more frequent and longer periods of drought are leading to increasing water shortages, and the number of cities worldwide where a water emergency has already had to be declared is rising. More frequent and heavier extreme precipitation, intensified by urban surface sealing and overburdened drainage systems, is causing more and more flood damage. Increasing heat stress, exacerbated by the urban heat-island effect, is leading to a rising number of heat-related deaths.

The WBGU recommends establishing climate-resilient urban water management across the board in accordance with the guiding principle of water-sensitive urban development. Together with access to affordable, climate-adapted housing, it is of key importance for a sustainable urban design for all in the future. In this context, the urban infrastructure must be designed in such a way that it is more resilient to the effects of extreme events and strengthens the local hydrological cycle, enabling it to act as an efficient buffer against growing water extremes. Urban infrastructure should be integrated into the natural landscape water balance. It is essential to take medium- and long-term climate projections into account here. Synergies between water-sensitive urban development and the mitigation of the urban heat-island effect should be specifically targeted. In addition, the guarantee of urban quality of life and the reduction of social inequalities should always be considered and anticipated as essential contributions to improving urban climate resilience.

In view of the growing number of exacerbated challenges in the water sector in many places, there is an urgent need to accelerate adaptation to climate change in cities around the world. In addition to establishing climate-resilient water management, this includes in particular the development and expansion of a climate-resilient urban water infrastructure. It must be significantly accelerated, especially in fast-growing cities, in order to keep pace with rapid, often informal growth (especially in Africa and Asia). Special consideration should be given to informal neigbourhoods, where decentralized and non-piped sewage systems can be used, for example. The local population should be involved in planning and implementing these systems, informed about health benefits, and the capacities of previously informal service providers should be strengthened. Financing the development and expansion of climate-resilient urban water infrastructure in low- and middle-income countries should be increasingly promoted in bilateral and multilateral development cooperation.

In order to prevent maladaptation and an increase in vulnerability and existing inequalities, care should be taken to avoid negative social, health and environmental consequences when constructing and expanding a blue-green infrastructure in cities. Preventive measures should be taken to avoid displacement effects. The vegetation should be suitable for expected changes in the climate and have a low allergenic potential. Urban green spaces should be easy to reach, accessible and tailored to the needs of the local population.

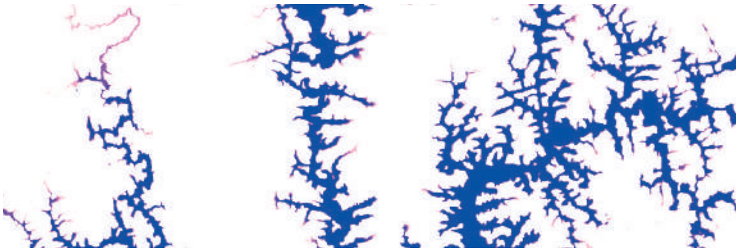
The WBGU further recommends developing emergency plans for urban water shortages. The number of cities that have declared a state of emergency due to water shortages is rising worldwide. If left unresolved, this growing global problem has considerable destabilization potential and therefore deserves greater attention in international sustainability policy.

Furthermore, it is important to recognize the water-related limits to urban growth. Climate change will confront many cities with existential challenges in connection with water, many of which are barely being addressed today. In particular, cities that will not be able to effectively solve the problem of water scarcity in the medium and long term with infrastructure measures alone should, after exhausting all other means, examine options for limiting urban growth or, in extreme cases, options for an orderly retreat in good time.

In this age of urbanization, more and more cities are facing seasonal or permanent water shortages. There is a need for research on the effective implementation of known adaptation measures, but also on how to deal with the above-mentioned hydrological boundary conditions.

Given the existing urban infrastructure, innovative approaches are needed for the integration of resilience-enhancing solutions in existing buildings in order to implement transformative adaptation measures. This raises the question of how new water-supply concepts can be realized in existing systems with as little invasiveness as possible and at low cost.

Especially in regions where the water supply is under pressure, there is a need for better temporal and spatial mapping of private and commercial demand, ideally in real time. To this end, research is needed into identifying the proper resolution of capturing water abstraction locations, ethical aspects of data collection, data processing, data security and provision, as well as possibilities for using artificial intelligence.



Protection of water quality

The quality of water resources is severely impaired worldwide by the release of pollutants and pathogens. In many cases, the use of water as a transport medium leads to considerable concentrations of pollutants in the water. This regularly over-stresses nature's self-purifying power. It is therefore essential to protect water quality in order to counteract the scarcity of water resources as a result of the exacerbated challenges described above. The European Green Deal already includes the goal of 'zero pollution' by 2050 (European Commission, 2021). Zero pollution means that pollution is reduced to a level that is no longer harmful to human health and the health of ecosystems. The zero-pollution objective is of great importance and requires the implementation of a circular economy.

Key elements for implementing these guiding principles are (1) the rapid implementation of the EU Urban Wastewater Treatment Directive, (2) contemporary testing procedures and methods for substance assessment that can better detect persistent and (water-) mobile pollutants and must be given more preventative consideration in the official approval process, (3) integrated approaches for recovering raw materials from wastewater, and (4) the flexible use of centralized and decentralized wastewater-disposal systems in the expansion of sanitary infrastructure in low- and middle-income countries.

Extend producer responsibility in the EU

The EU Urban Wastewater Treatment Directive is a significant landmark regulation for the preservation of water quality and should be implemented swiftly in the EU Member States once it has been adopted. The WBGU particularly welcomes the concept of integrated extended producer responsibility, according to which producers of pharmaceuticals and cosmetics should bear at least 80 % of the costs of constructing and operating an advanced treatment step in wastewater treatment plants required to remove trace organic chemicals. It should be examined to what extent it is possible to expand extended producer responsibility to cover further pollutant classes (e.g. toxic and persistent household chemicals and pesticides) and substance properties (not only toxicity but also persistence in the aquatic environment). When implementing the EU Urban Wastewater Treatment Directive, it is crucial to provide incentives to reduce the emission of environmentally hazardous substances, e.g. by grading the participation of companies according to the degree of environmental hazard of the substances placed on the market or produced, or by introducing exemptions for rapidly degradable products.

Expand the recovery of raw materials from wastewater

Wastewater is a valuable resource and should be used in three ways to close gaps in the circular economy. First, in addition to being returned to surface water bodies, wastewater should be treated and reused as required and depending on its intended use, e.g. for irrigation in agriculture. Second, the potential for recovering energy from wastewater treatment processes should be made greater use of. This can also help to achieve the energy neutrality of municipal wastewater treatment plants as envisaged in the EU Urban Wastewater Treatment Directive. Third, wastewater often contains substances that are sometimes considered harmful but can be used as valuable secondary raw materials, e.g. biopolymers and metal ions such as lithium and copper. The recovery of phosphorus, as laid down in the German Sewage Sludge Ordinance, could serve as a model for dealing with these substances. Successful reclamation could potentially reduce the need for primary treatment and the associated negative environmental impacts. However, not all wastewater is equally suitable for recovery in terms of economic efficiency and technical feasibility.

The WBGU sees great potential in technologies for raw-material recovery. Material recovery is becoming increasingly important. The energy transition is also a material transition, which is highly relevant for water. Research is needed into the risks associated with these materials (e.g. lithium), such as their behaviour in the environment and their effects on health.

Avoid the discharge of harmful chemicals

Adverse effects on water quality caused by industrial chemicals that spread along waterways and cannot be recovered can be avoided if substances are tested for health and environmental properties before they are registered and put on the market. Innovative biological high-throughput test procedures and simulations in substance development using artificial intelligence enable the manufacturing industry to carry out significantly faster and more comprehensive risk assessment and labelling. In this way, new substances can be put on the market more cost-effectively and nevertheless more safely; substances already on the market can be better characterized retrospectively. This can make a substantial contribution to achieving the zero-pollution objective and preventively protect water, ecosystems and human health.

Make flexible use of centralized and decentralized wastewater systems

The inadequate treatment of domestic wastewater in low- and middle-income countries is a major cause of the pollution of groundwater and surface waters with pathogenic microorganisms, organic carbon compounds, nutrients, and macro- and microplastics. Historically, the cost-intensive construction of centralized wastewater treatment with extensive sewer networks modelled on the high-income countries was favoured to counter this form of pollution. For many settlements, especially informal settlements in low- and middle-income countries, however, centralized wastewater treatment is not a suitable solution.

By contrast, the flexible use of centralized and decentralized wastewater systems such as the Citywide Inclusive Sanitation (CWIS) concept – which focuses on socially balanced access to water, sanitation and hygiene (WASH) for all population groups and all districts – is very promising. CWIS sees wastewater disposal and treatment as a service concept and not merely as the provision of infrastructure; different technical solutions can be considered on an equal footing and used flexibly. This includes the central sewage system but also decentralized sanitary facilities that are not connected to a sewage network (non-sewered sanitation) such as faecal sludge management. International donors (World Bank, Asian Development Bank) and sector associations (International Water Association) have already taken up the CWIS concept. The WBGU recommends promoting the provision of access to safe water and hygiene based on the CWIS concept instead of focusing exclusively on centralized wastewater treatment concepts. This requires a rethinking on the part of decision-makers, investors, planning engineering offices and universities to promote hygienic, decentralized, non-piped wastewater systems as a real alternative to centralized wastewater systems. Another prerequisite is the improvement and formalization of informal, existing (unsafe, unhygienic) decentralized, non-piped wastewater systems, the prioritization of WASH in political agendas and the assumption of leadership by national governments. As part of research, financing and business models for decentralized, non-piped wastewater systems must be developed and their technical advancement promoted.

Development of climate-resilient water governance

Forward-looking water governance that is capable of learning and adapting is required to avoid harming humans and nature and to prevent distribution conflicts.

Take responsibility internationally – develop an International Water Strategy

The WBGU recommends developing an International Water Strategy as a new impulse for water diplomacy (Fig. 3). The aim here is to contribute to institutionalizing the existing processes on water as an exchange and coordination platform. As there are numerous interfaces with other policy areas, e.g. climate, biodiversity and sustainable land-use governance, as well as regional (e.g. EU) and national water strategies, capacities at the interfaces should be increased. This will enable actors who are already working at the relevant interfaces and have water-specific networks and expertise to play an active role in negotiating and developing an International Water Strategy in the future.

The International Water Strategy should recognize the protection of water as a common concern of humankind and also address the use of green water and its possible regulation under international law. It should endeavour to better interlink the existing water conventions with other international water-related treaties. When organizing the process, care should be taken to begin with the less controversial topics. These include drinking water, integration, education, research and cooperation. To improve the prospects for a consensus, the strategy should initially rely on non-binding instruments. In the long term, the International Water Strategy should lead to an agreement under international law – comparable to the Rio Conventions.

The International Water Strategy could motivate and encourage states to join the existing international water conventions – the UN Water Convention and the UNECE Water Convention. What these water agreements lack is a focus on green water alongside blue water. In the future, their scope of application should therefore be expanded to also achieve a climate-resilient way of dealing with green water. The complex international interactions and interdependencies between green and atmospheric water – e.g. the effects of land-use changes on evaporation flows and precipitation in other countries – urgently need to be researched. The International Water Strategy can serve as a platform for corresponding scientific cooperation with a regular information exchange with a view to subsequent appropriate water governance. Governance of blue and green water could, for example, include information, consultation and approval obligations for projects and extensive land-use changes that have a significant impact on transboundary atmospheric water transport.

The WBGU continues to advocate state recognition and codification of a general human right to water, which includes not only access to clean drinking water but also the participation of civil society in water-related decision-making processes and access to environmental information and legal protection. This recognition should also make it clear that the human right to water is a manifestation of the human right to a healthy environment, which is not yet codified either (WBGU, 2023).

In order to improve the transfer of scientific findings on water to policy-makers, the WBGU advocates establishing a Water Mapping Initiative whose planning and implementation is internationally shared. It should consist of two units: a science platform and an expert panel. The science platform aims to bring together existing scientific expertise in order to identify imminent regional water emergencies. The expert committee governs the platform and feeds the results of its work into political processes (Fig. 4).

In order to recognize and limit water emergencies at an early stage and develop plans for dealing with them, global data and monitoring capacities need to be merged. This includes the IPCC and IPBES forecasts, long-term data series, monitoring and observation data from national monitoring organizations, and the results of regional and national research projects. Furthermore, the platform should integrate data and experience gathered in past emergencies, the results of national and supra-regional water research, and local data and experience of emergencies. This should be supplemented by high-resolution spatial and temporal data from observations and forecasting models at the local (river catchment areas), regional, national, international and global level. As soon as the Science-Policy Panel on Chemicals, Waste and Pollution Prevention called for by the UN Environment Assembly and currently under negotiation has started its work, its findings should also be taken into account.

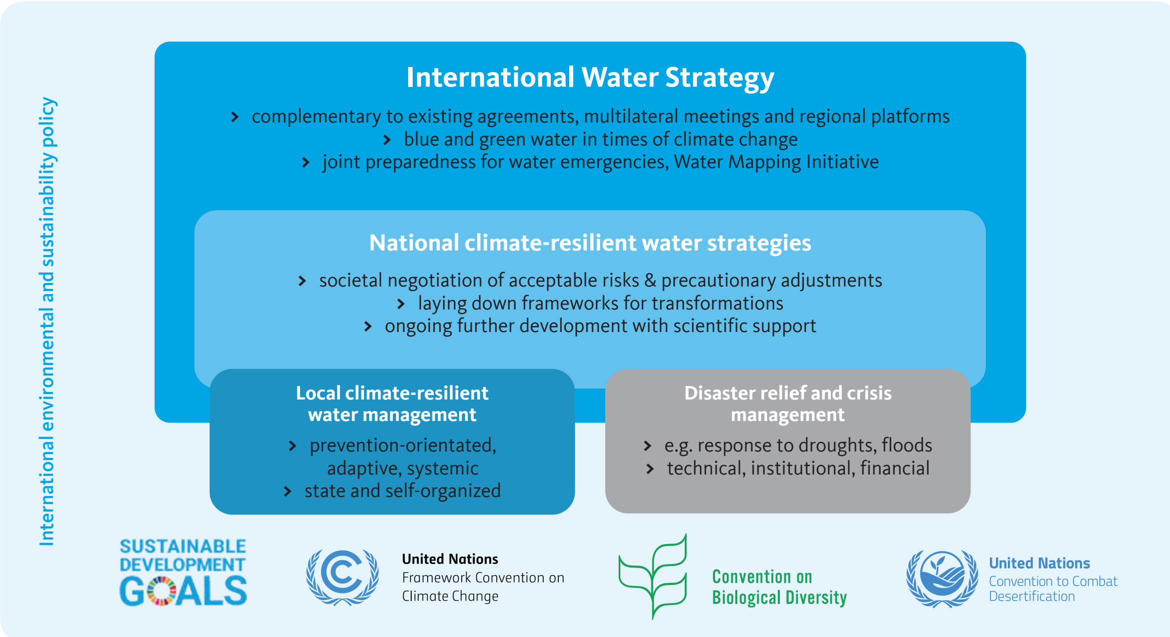


Figure 3
Proposal for an International Water Strategy. The International Water Strategy and national water strategies interact with local water management. Local water management involves the municipalities and all relevant actors, including self-organized structures. National water strategies should be formulated coherently with the International Water Strategy. They should initiate climate-resilient management measures at the local level and include emergency relief and crisis management.
Source: WBGU

An expert committee should be set up to oversee and manage the platform. Once imminent regional water emergencies with a planetary dimension have been identified, the committee would draw up forecasts for regions at risk. At the same time, it could promote the exchange of information between science, politics and stakeholders. At the international level, the expert panel should inform the UN Water Conferences. Moreover, the committee should inform water-related dialogue platforms in different regions of the world and in different country alliances, as well as policy dialogues on designing an International Water Strategy and the UN Water Conferences in 2026 and 2028. Locally, the committee should also support water authorities in the implementation of climate-resilient water management in the event of imminent emergencies.

In the context of global governance, further research is needed as a prerequisite for the work of the Water Mapping Initiative and for the fundamental handling of exacerbated water-related challenges. It is key to replacing or supplementing empirical knowledge in all regions of the world with data from scenarios, as climate change is already significantly altering the hydrological cycle. Data should therefore be generated not only at the local level but also at the level of the world's regions. There is therefore an urgent need for more climate-sensitive water research at the intermediate level. The impacts and interactions of global changes and local measures must also be available as a source of information for decision-making processes.

Climate-resilient planning can only be implemented if capacities for data collection and modelling are built up locally in low-income countries.

In order to consolidate the UN Water Conferences, a UN Water Secretariat needs to be established which, in future, could be headed by a Special Envoy for Water. An International Water Strategy should also include regular meetings both at the UN level and at the level of the various regions of the world. New regional research alliances could inform these regional platforms. The middle-level scenarios described above will be highly relevant here.

Comparable governance approaches have shown that it increases the motivation of countries to deal with global risks if their representatives can regularly exchange information at the regional level on targets, target achievement and imminent dangers and risks in their region of the world. This can be done as part of an International Water Strategy by strengthening regional organizations such as the EU. The strengthened regional organizations could coordinate regional water-governance platforms and thus enable countries to implement global and regional water targets as effectively as possible. Protection measures at the regional level could also be promoted by international funding or international cooperation. In Europe, a water strategy ('EU Blue Deal') could be based on the European Green Deal and relate to the European Biodiversity Strategy.

Create policy coherence internally and externally

As part of their international political actions, Germany and the EU should establish policy coherence between the various external policy fields related to water as well as between the external and internal fields. In the context of their international relations, they pursue a wide range of goals that result, on the one hand, from international agreements on climate and environmental policy and, on the other, from economic interests or geopolitical strategic interests and values. Political measures to promote these goals must be checked for compatibility and coherence. This can affect a wide variety of water-related areas, e.g. covering German energy demand, agricultural subsidies or investment agreements. Particularly against the backdrop of geopolitical power shifts, the importance of trusting partnerships and ensuring Germany's credibility in its own political actions is increasingly becoming the focus of political considerations. In preparation for the upcoming processes to renegotiate a post-2030 agenda at multilateral level, the promotion of European and German credibility in the eyes of strategic partner countries is also of key importance worldwide.

Shape trade and economic relations, hold the private sector responsible

International economic relations and trade policy should promote sustainable water use and not exacerbate water scarcity in regions suffering water stress. This requires better integration of water-related impacts and risks within the framework of international trade policy, for example within the World Trade Organization (WTO), regional trade agreements or investment-protection agreements.

EU trade relations should be analysed specifically for water-related spillover effects. False incentives that exacerbate negative spillover effects – e.g. from regulations in trade agreements or the long-distant effects of European regulation – should be dismantled. Furthermore, trade relations should be used to promote the switch to water-saving production and cultivation methods or alternative sources of income.

The WBGU recommends that the protection of water resources should be more firmly anchored in existing trade agreements. If possible, this should be done under WTO law in order to achieve coherent regulations for a maximum group of countries – but also in bilateral and multilateral agreements, since reforming WTO law

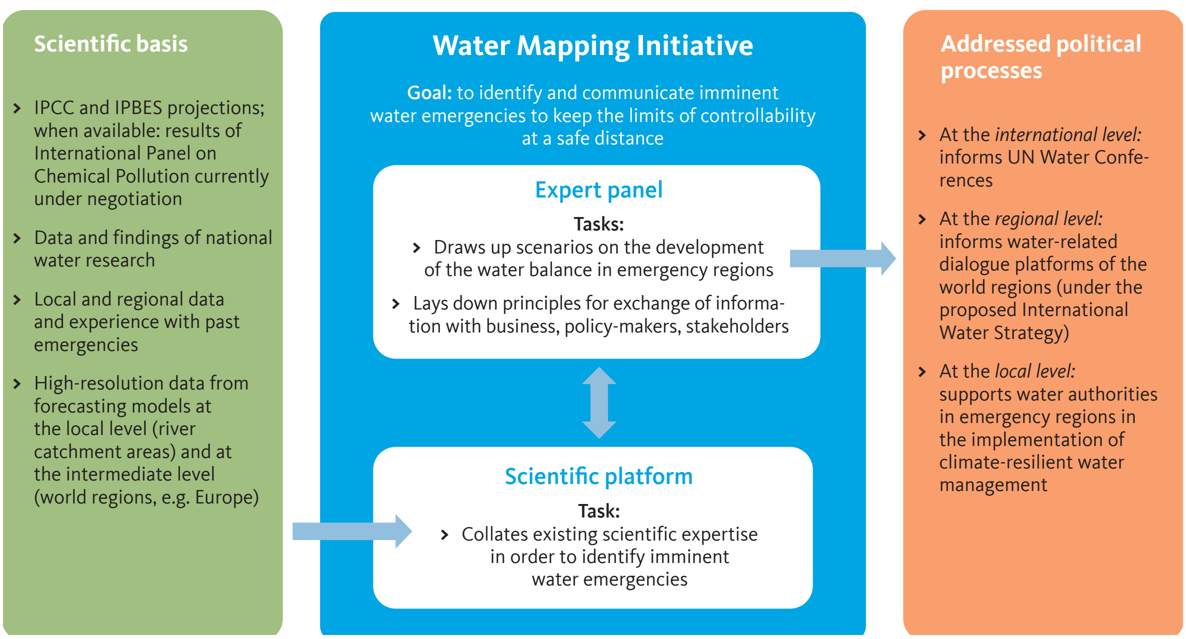


Figure 4
WBGU proposal for a Water Mapping Initiative to prevent imminent regional water emergencies. The scientific platform aims to recognize imminent water emergencies as early as possible by integrating scientific principles. On this basis, the expert panel would inform and support international, regional and local policy processes.
Source: WBGU

is likely to be difficult in the short and medium term (Zengerling, 2020).

Companies and investors should also be held more accountable internationally. Based on reporting on water use and water risks, companies and investors should be encouraged to take measures to avoid negative impacts of their activities on water resources. Low- and middle-income countries should be given support with the introduction of reporting obligations, e.g. via capacity-building measures. Germany should also examine the extent to which protecting water resources and recording water risks can be more closely integrated into the German Supply Chain Act.

The proactive state

The state should play a proactive role in the field of water governance. In order to do justice to the precautionary and polluter-pays principles, democratic processes are needed to negotiate, conceive and implement strategies and instruments for water policy. Cooperation with different actors is important ('with and not against society'), but this must not mean that the state withdraws and remains passive vis-à-vis the challenges of water governance. The WBGU recommends increasing administrative capacities and resources so that states can assume their role and responsibilities appropriately.

A future climate-resilient, socially balanced water-management regime requires controlled and planned interaction between the proactive state with all its framework-giving responsibility (top-down) and historically evolved self-organization (bottom-up) in water management, which is already practised in some cases; it does not arise out of necessity but from the opportunity for improved water governance, which can accelerate the implementation of the goals of climate-resilient water management.

Promote self-organization at the regional and local level

Especially in regions of the world that are severely affected by exacerbated water-related challenges, the WBGU advocates the targeted promotion of structures that (1) enable self-organization at the regional and local level (bottom-up), (2) compensate for weaknesses in formal water governance, which is often designed by the state, and (3) also acknowledge and address deficits in informal systems. In the past, the promotion of self-organization, especially in line with IWRM principles, has proved its worth in expanding participatory and inclusive forms of decision-making. Especially in times of growing autocratization processes at the political level in the majority of countries worldwide, this promotion of inclusive governance approaches at the local level and in the area of water management is important.

International alliances for climate-resilient water management

When drawing up funding lines in the field of water management and water research, specific attention should be paid to promoting cooperative research projects with countries facing increasing challenges in water management (e.g. droughts, floods), or affected by social polarization and political autocratization processes – or which are of high strategic relevance as partners and alliances for Germany and Europe at the level of geopolitical negotiation processes.

When supporting confidence-building measures, especially in conflict areas, it is important to pay attention to institutional capacities and a dialogue focused on common goals, and not to concentrate primarily on technological solutions and data availability. All too often, infrastructure projects are prioritized without also considering local needs for their long-term maintenance and for embedding them in both formal and informal societal systems of governance. It is more difficult to change norms, thought patterns and habits. What is needed, therefore, are confidence-building measures in institutions (e.g. on policy coherence, transparency, accountability), long-term partnerships and a genuine dialogue with partners – also in the funding of research projects. All too often, (research) projects are short-term and there is no real dialogue between donors and recipients.

The German and European science-funding landscape should specifically promote interdisciplinary and transdisciplinary projects in the field of sustainable water management in different regions of the world where there are different management challenges. This includes scientific preparation and locally adapted innovation development in the field of irrigated agriculture as well as urban water supply and disposal, waste-water treatment and hydropower generation. It is important to pay attention to transdisciplinary research designs in which the transformative co-production of water-management knowledge is promoted in close cooperation among scientists and practitioners.

Dialogue forums with deliberative elements should be institutionally established and interlinked as an instrument of sustainable climate-resilient governance. Participation has a preventative effect and helps to reduce the potential for conflict between different actors. This also promotes democratic practice and can contribute to peacekeeping both within countries and internationally. Dialogue forums also offer an opportunity to involve diverse forms of knowledge and actors (e.g. cities, associations, religious communities and companies) in the search for solutions.

Mobilize and organize funding also for local approaches

Safe access to drinking water and sanitary facilities, as agreed in the UN Sustainable Development Goals (SDG 6), has been improved worldwide, but even today 2.2 and 3.5 billion people respectively still have to make do without them. In 140 countries, investments would have to be tripled to a total of over US$100 billion per year in order to achieve SDGs 6.1 and 6.2 by 2030 (Hutton and Varughese, 2016), plus expenditure on water-resource protection and the reduction of water-related risks (including those caused by climate change). However, the respective benefits are estimated to be two and a half to seven times the costs (UNESCO, 2024; GCA, 2019).

Public and private investment is needed to finance this. More private capital in particular must therefore be mobilized, especially in low-income countries, where, for example, only 1.4 % of the private financial resources leveraged with development cooperation funds in 2012–2017 were allocated to the water and sanitation sector (OECD, 2019). Many strategies (e.g. of the World Bank, of the German Federal Ministry for Economic Cooperation and Development (BMZ) as well as the German National Water Strategy) are already aimed at making investment in the water sector more attractive and raising the creditworthiness of water suppliers. Skills and capacities need to be built up, especially in public companies and institutions for efficient planning, investment management and operation, as well as for supervision and regulation. However, because of the exacerbated water-related challenges described above, more attention must also be paid to the following three fields of action.

First, water-related risks should be made transparent in order to mobilize private and public investment. Only if companies, investors and municipalities pay more attention to the water-related risks and impacts of their activities will they invest more in mitigating them or participate in efforts such as the International Climate Adaptation Fund. The German government should work for a harmonization of non-financial reporting on SDG 6, for example by supporting the International Platform on Sustainable Finance, and with its own activities. Building on experience with EU taxonomy and the design of 'blue' financial instruments, Germany can play a pioneering role in this respect. Moreover, information and support services for assessing water risks should be improved. Better data and long-term projections on water availability, forms of water use and regional and sectoral linkages should be collected and made available in line with demand; the skills needed for the use of these data and projections should be taught, and other countries should also be supported in this endeavour. Climatological, meteorological and hydrological public services and research institutions must be strengthened and networked for this purpose. The establishment of a digital and free European access portal (European Access Point, ESAP) should be supported. Public support programmes such as the German Sustainability Code should be expanded and relevant experience exchanged with other countries.

Second, the water sector should be made more attractive by ensuring stable sources of income. The users of water or specific infrastructures (e.g. flood protection) should bear more of the costs, as should those who cause damage. On the one hand, the pricing of water should be comprehensive but socially balanced and cover environmentally related costs. Exceptions to water-abstraction charges should be abolished. On the other hand, distributors and users of water-polluting substances should participate more in waterbody protection. In Germany and the EU, there are already proposals of this nature within the framework of extended producer responsibility; these should be extended to other substance and product groups and properties. Germany should also advocate an EU-wide pesticide levy that takes environmental and health risks into account and charges more for substances with higher risks. The revenue can be used for waterbody protection, to mitigate exceptional burdens, e.g. for farmers, and for advice on alternative plant-protection techniques. The German government should support capacity building in low- and middle-income countries for the planning and implementation of price reforms as well as the introduction of producer responsibility and water-related environmental levies.

In addition, measures with multiple benefits for the general public should be better remunerated. Public co-financing, tax relief or subsidies can create more incentives for private investors. The EU's Common Agricultural Policy (CAP) should be reformed as from 2028 in such a way that it promotes the conservation of water resources and nature-based measures with multiple benefits and avoids disincentives. The eco-schemes provided for in the first pillar of the CAP should be expanded at the expense of the existing area-based direct payments. Indirect water-related subsidies should also fulfil minimum water-related standards and could, for example, be screened on the basis of the do-no-significant-harm principles of EU taxonomy. In the introduction of climate-resilient water management, low- and middle-income countries can be supported by water-related debt swaps, provided they fulfil the necessary institutional conditions.

Finally, revenue generation and use should be given a boost at the local level. However, revenue from centrally levied charges, e.g. on water-polluting products, should also flow to municipalities and cities on a pro-rata basis to enable them to carry out the tasks made necessary by these product (e.g. water treatment). This can be supplemented by horizontal equalization mechanisms if the costs and benefits of local measures are incurred in different municipalities. In low- and middle-income countries, more efficient revenue collection and use often requires institutional and structural reforms, a fight against corruption, and greater transparency and accountability.

Third, mediating institutions (intermediaries) and local cooperation platforms should be strategically strengthened or established: specialized banks, revolving water funds, NGOs or research institutions can 'pool' smaller projects or water and land actors as well as public and private investors, mediate between them and structure suitable financing. With the help of these intermediaries, the EU, national and sub-national governments should institutionalize local exchange and cooperation formats between stakeholders and donors across the board. These can be used to create a common knowledge base, coordinate strategies and measures, and organize financing. This should be accompanied by the development of public capacities and best-practice networks for implementing results-orientated blended-finance approaches and the planning, review and scaling of remuneration models for projects with environmental and social multiple benefits.

Research is required on (1) projections of potential water-related damage, adaptation costs and multiple benefits and on the modelling of uncertainties; (2) impacts of potential water-related damage on national economies and the financial sector; (3) opportunities for more participation of institutional investors in financing water-related objectives; (4) hybrid financing instruments and new business models for nature-based approaches; (5) the efficient assessment of local multiple benefits of nature-based approaches and their systematic use; (6) effects of an extended reform of levies and charges, including e.g. unintended burdens on third parties or the relocation of pollution-intensive economic activities.

Science and education for a sustainable WaterFuture

The science system has a key role to play in dealing with exacerbated challenges. Especially the non-stationarity of hydrological regimes caused by anthropogenic climate change requires the continuous production of knowledge and data, which must be taken into account in innovations to ensure that the water requirements of humans and ecosystems are secure. Non-stationarity means that the assumption that a system exhibits predictable variability that can be derived from empirical observations is no longer tenable. Furthermore, science has a growing advisory and supporting role to play in the political process. The complexity and speed of changes in socio-ecological processes, exacerbated by climate change, simultaneously demand forward-looking, reflexive and adaptive local and global water governance. Independent, critical science is essential as a basis for this.

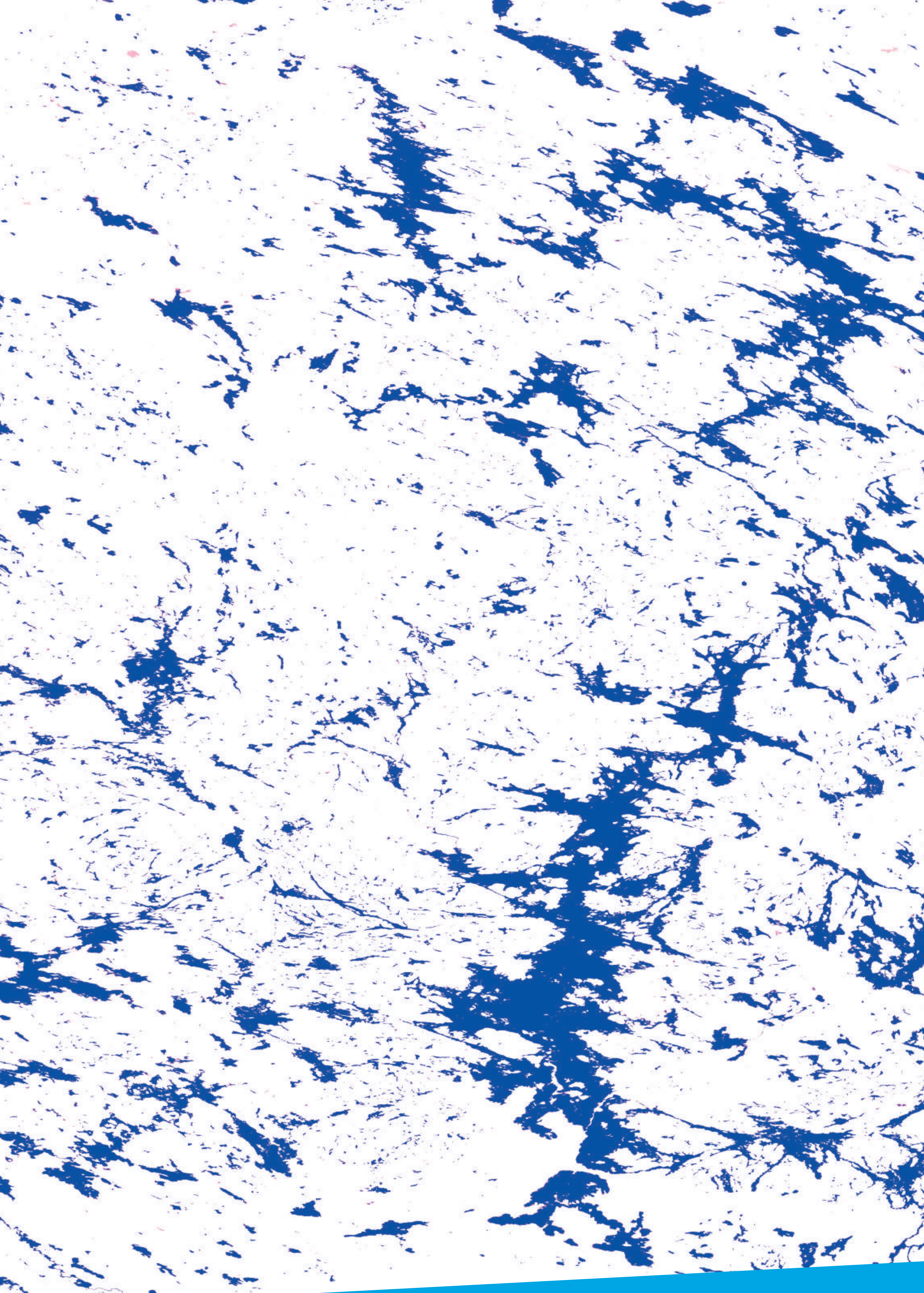
Scientific capacities in low- and middle-income countries should be strengthened. International research collaborations can contribute to their development. Up to now, the legal framework for international scientific cooperation has stipulated that all personnel, material and travel funds are managed in the scientific institutions of the donor countries. As a way of boosting scientific capacities, the WBGU recommends creating the legal conditions for direct fund management, including accounting and auditing in partner countries. This strengthens the role of the scientists conducting research there and generates skills in the administration of funds. Another measure would be to create the legal conditions for on-lending funds, with shared liability between the partner institutions involved and the donor.

Citizens can actively participate in scientific research projects in citizen labs. By involving the population in the decision-making process, citizen labs, like deliberative participation processes, can contribute to more resilient structures in municipalities; they can find customized solutions to local challenges – such as water shortages – which are accepted thanks to transparent decision-making. Citizen labs also improve the protection of water resources. The WBGU regards this form of public participation as very important for the protection of water and biodiversity and advocates its further expansion.

Education is essential for the transition to a sustainable society in general and for the prevention of water crises in particular. Measures such as information provision, education, and knowledge acquisition through practical experience or public dialogue raise people's awareness of the importance of water as a resource. Self-determined action and active participation in political processes are promoted by a better understanding of the connections between lifestyles, the economy and water quality, as well as by knowledge of the new, climate-change-related challenges in water management and the complex interrelationships of global governance. The WBGU recommends initiating more educational programmes at national and international level and launching an international discussion on new forms of economic activity and the appreciation of ecosystem services. Furthermore, advisory and training programmes – also based on the results of knowledge exchange – should be carried out at the regional level and tailored to local conditions in order to raise awareness of local water problems and enable actors to rethink and take targeted action. Real-life lessons on the topic of water enables children and young people to learn more about water cycles, the water supply, water's importance for people and nature, and the consequences of climate change. There is already a considerable amount of teaching material for all ages and school types. Because the topic of water is of such paramount importance, the WBGU recommends that it becomes obligatory for curricula to take up the topic on an interdisciplinary basis across the entire school spectrum.

Outlook

The issue of 'water in a heated world' has gained new international momentum with the UN Water Conference 2023 and the establishment of the G7 Water Coalition in 2024. The aim must now be to capitalize on this. In particular, the UN Water Conferences scheduled for 2026 and 2028 should be used to place the global importance of water higher on the political agenda and to adopt resolutions to anchor the topic more firmly in international sustainability policy. This report aims to make a contribution to this end.



Introduction

1

Summer 2024: Germany has already been affected by three severe floods in the last six months. February and March were the warmest since weather records began. The increasingly frequent occurrence of once-in-a-century extreme events is becoming the new normal in the water sector: in 2022 and 2023, drought emergencies were declared in 22 countries worldwide; more and more cities and regions are declaring a water emergency, at least temporarily; other regions have been hit by exceptionally severe (flash) floods. The main causes of these developments are the drastic transformations and large-scale destruction of natural spaces, as well as the continuing global urbanization, which have led to changes in the landscape water balance. Furthermore, water management is often inadequate and the effects of climate change are becoming increasingly noticeable. The pollution of water resources has by no means been overcome either: although efforts to ensure a safe water-supply and -disposal system have made significant progress in many regions of the world, a substantial proportion of the world's population still does not have adequate access to both services. In addition, synthetic pollutants are contaminating ecosystems, increasingly restricting various forms of water use and causing health problems. New regional water emergencies are developing, which are replicated in other regions of the world, thus becoming a planetary pattern – in some cases with effects that are far beyond the horizons of previous human experience. This is where the WBGU joins the debate and asks how we can keep our distance from the limits of controllability as large as possible and how the global community can adapt to the speed and force of these changes in the water sector.

There are many tried and tested cooperative approaches and activities for implementing sustainable water use, which have been strengthened by the agreement on the 2030 Agenda in 2015. In addition, there are international conventions on transboundary waterbody management, which have been making valuable contributions to safeguarding natural water resources for many years. In the meantime, however, climate change and its consequences for the global hydrological cycle have intensified the demands on global water policy. International water diplomacy is already beginning to respond: in 2023, a UN water conference was held for the first time in 46 years. The next World Water Conferences will take place in 2026 and 2028, as decided by the UN General Assembly. In 2026, the focus will be on implementing the Sustainable Development Goal on clean water and sanitation (SDG 6); in 2028, the conference will concentrate on promoting implementation measures in the water sector and taking stock of the UN Water Decade (2018–2028).

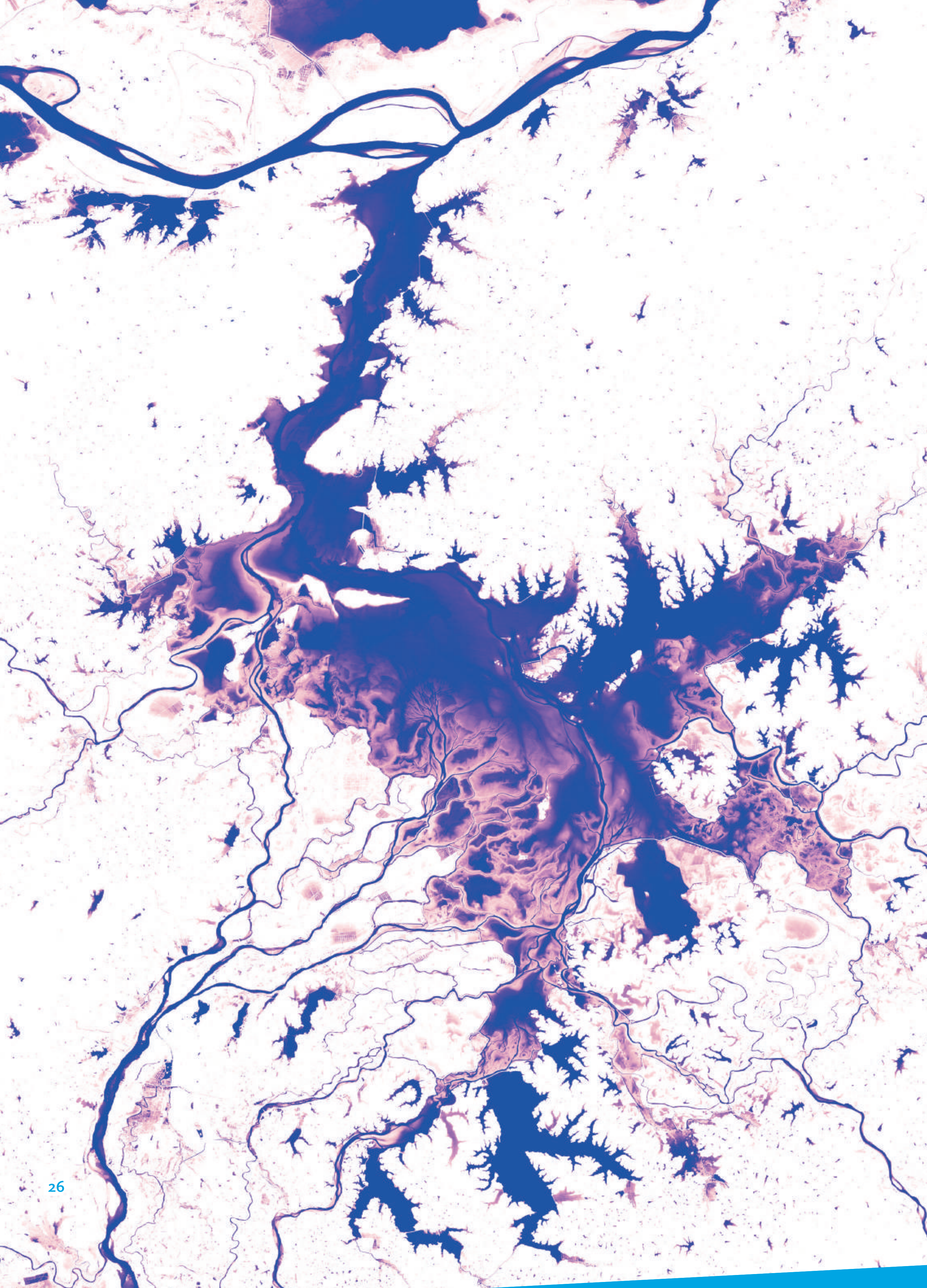
In 2024, the G7 countries launched a water coalition for the first time. The effects on the Earth's hydrological cycle are also playing an increasingly important role in international climate policy. An EU Blue Deal is being discussed at European level, proposed by the European Economic and Social Committee. Germany adopted its first National Water Strategy in 2023.

Overall, the question arises as to whether international water diplomacy and the strategies at different political levels do justice to the dimensions of the global water crisis today and in the future. Up to now, global water governance has appeared rather fragmented, underfunded and not very assertive. This is aggravated by the fact that the growing global challenges for political action need to be tackled with a multilateral system weakened by crises.

What role do the proactive state and social forms of self-organization play in climate-resilient water management? How can the intended political goals and measures be adequately funded and how can public and private actors make an appropriate contribution? Can the objectives be realized and implemented within the required time frame?

As humanity has already changed the global hydrological cycle to such an extent that experience-based knowledge is less and less adequate for solving the challenges, science too has a special responsibility when it comes to providing knowledge for action and orientation. Climate change will continuously alter the hydrological cycle and with it local water availability – it is therefore not a question of adapting to a new state, but of an ongoing adaptation process that must be constantly readjusted. This requires not only political but also societal advice: the management of water resources is often informal and local, based on cross-generational knowledge. This knowledge can and should be proactively integrated into the development of locally and regionally effective solution approaches. In order to cope with extreme events, greater use will have to be made of the support provided by forecasts and scientific scenarios of the future. Science is called upon to play a new, forward-looking and supportive role here: where do the possible limits of controllability lie in a region, and what options for precautionary action are available to keep the distance from intolerable developments as large as possible? This also gives rise to new research topics.

The aim of this report is to develop proposals for climate-resilient water management and international water governance that meet the challenges outlined above and point to new pathways for safeguarding peaceful cooperation. The UN Water Conferences in 2026 and 2028 offer an outstanding opportunity for raising the international profile of this globally important and highly urgent issue and to agree on long-term, common goals.



Status quo in dealing with water as a resource

2

Humans have a massive impact on the natural water cycle. Water is polluted, overused and unfairly distributed in many places. The effects of climate change on ecosystems and people are already being felt worldwide. Billions of people still have no access to clean drinking water or sanitation, are affected by flooding or suffer from water shortages. Use patterns are shaped by political framework conditions and the water infrastructure, which involve pronounced path dependencies that make course corrections and substantial changes difficult.

Water is the basis of life for humans, animals and plants, and a stable water cycle is essential for maintaining the functionality of water-related ecosystems. These functions are already impaired today – by the destruction of aquatic ecosystems, the historically evolved patterns of water use, changes in the global water cycle, and increasingly frequent extreme events such as flash floods and droughts. Water is wasted, overused and unfairly distributed in many places. Growing pollution by persistent substances is restricting water use further, so that a supply of safe drinking water is no longer guaranteed in many cases. Use patterns are shaped by political framework conditions and the existing water infrastructure which involve pronounced path dependencies that make course corrections and substantial changes difficult.

Globally, agriculture accounts for 72 % of all freshwater withdrawal, industry for 15 %, and municipalities and households for 13 % (AQUASTAT, 2024). However, the amount of water abstracted for agriculture as a percentage of total abstraction varies considerably by region and income level. In high-income countries it accounts on average for only 41 % of total withdrawals, whereas in low- and middle-income countries water abstracted for agriculture accounts for 80–90 % (Ritchie and Roser, 2017). The expansion of irrigation agriculture, the area of which more than doubled between 1961 and 2018 (UNESCO, 2024), and the water requirements of a growing urban population have led to the overuse of non-renewable groundwater (deep groundwater), and water tables have been falling increasingly in many regions and cities around the world (Herbert and Döll, 2019). The Middle East, North Africa, India, northern China and the southwest of the USA are particularly affected (Herbert and Döll, 2019; de Graaf et al., 2017; Wada et al., 2012). In most of these regions, water consumption for agricultural irrigation accounted for an average of over 90 % of total water consumption between 1960 and 2010, and at least half of that stemmed from non-renewable groundwater (Wada and Bierkens, 2014).

About 2.2 billion people have no safe access to clean drinking water – and above all low- and middle-income countries are affected (UNESCO, 2024). The supply situation is especially difficult in rural areas, where four fifths of people do not have safe access to clean drinking water. About 3.5 billion people have no access to adequate sanitation. Official Development Assistance (ODA) to the water sector in 2022 was US$9.1 billion, more than 4 % below its 2018 peak (UN Water, 2024).

Between 2002 and 2021, 1.6 billion people were affected by flooding and about 100,000 lost their lives. In the same period, 1.4 billion people suffered from droughts, which caused about 21,000 deaths (UNESCO, 2024). Approximately half of the world's population currently suffers from severe water shortages for at least part of the year (IPCC, 2023a).

In many regions of the world, efforts to ensure a safe water-supply and -disposal system have made significant progress, yet a substantial proportion of the world's

Poyang Lake (China)

population still have no adequate access to these services: for at least three billion people, water quality is uncertain because of a lack of monitoring (UN, 2022). The threat caused by pathogenic microorganisms in drinking water still affects two billion people worldwide.

In addition to local effects, there can also be telecoupling effects via the trade in goods whose production requires water. The water needed for producing goods and the water contained in the goods can be tracked as virtual water flows across the globe. Approx. 65–90 % of global virtual water flows originate from the trade with agricultural products, followed at a considerable distance by industry and the energy sector (d'Odorico et al., 2019; Hoekstra and Mekonnen, 2012). Thus, countries with high agricultural exports in particular also indirectly export their own water.

2.1 Water: essential resource for all life and the role of ecosystems

Water is the "bloodstream of the biosphere" (Ripl, 2003). All life originated in water; it spread around the world in the sea, on land and in fresh water, and in all habitats it is dependent on the availability of enough water of sufficiently high quality at least some of the time. Biologically active organisms consist to a considerable extent of water, and its percentage must be kept as constant as possible. In an adult human, this proportion is just under 60 %; in some organisms it can be more than 90 %. Water is more or less continuously absorbed by organisms and released again via excretions. The specific concentrations of minerals in water and body fluids and their exchange across the body's interfaces play a key role in maintaining cell and tissue functions; but they also represent limiting conditions beyond which survival is no longer possible. Marine organisms live in salt concentrations that are too high and often life-threatening for terrestrial and freshwater organisms. For an organism, therefore, the availability of sufficient uncontaminated or only slightly contaminated ('drinkable') water – with tolerable and, depending on the habitat, more or less stable concentrations of essential minerals – is a prerequisite for health and survival.

The availability of water characterizes different habitats, and the organisms are adapted to it. For example, there are life forms that have dry stages and thus passively survive periodic water shortages, while others can tolerate regular flooding. Especially in terrestrial habitats, survival is restricted by water-related extreme conditions such as prolonged droughts or flooding. Although humans have colonized a wide variety of habitats, they do not cope well with large fluctuations in water availability and are dependent on the regular availability of water. The dependencies range from individual survival and food security to economic and industrial activities that are threatened by extreme fluctuations in the water supply. According to Timmermann et al. (2022), in the history of evolution *homo sapiens* has prevailed over other human species i.a. due to its ability to cope better with dry conditions; even so, securing water supplies remains one of the existential constraints of humanity. Extreme water shortages and the deterioration of water quality, often in connection with changes in the climate at the time, have repeatedly contributed to the collapse of civilizations such as the ancient Mayan empire or the ancient Arab civilization (Falkenmark et al., 2019). Water-related threats to vital systems, such as the collapse of food systems as a result of prolonged droughts, have the potential to destabilize societies and trigger migration (Cissé et al., 2022). For example, four years of drought combined with an increase in food prices and malnutrition may have contributed to instability, migration and an intensification of conflicts in the context of the Syrian war (Gleick, 2014; Falkenmark et al., 2019; Cissé et al., 2022).

Ecosystems and their biodiversity are an important part of the global water cycle (Table 2.1-2). All ecosystems require and interact with water. They provide fresh water by transporting, filtering and storing water. The naturally occurring soil- and rainwater, which is absorbed and evaporated by plants ('green water', Section 2.2.1), is a critical variable for the conservation of ecosystems (Hoekstra et al., 2011; Wang-Erlandsson et al., 2022). An adequate supply of water is a hallmark of healthy aquatic and terrestrial ecosystems. Ecosystems such as peatlands and forests play an important role in storing water and carbon. In addition to the oceans, forests also influence the intensity and distribution of precipitation. In their function as buffers, forests and freshwater ecosystems also mitigate the effects of extreme events, e.g. by protecting against erosion and flooding (flood zones) or by regulating water runoff, for example during periods of drought. Ecosystems and their organisms can therefore provide a natural ('green') infrastructure that can help mitigate the impacts of extreme events (Smakhtin, 2018). Other important functions are natural groundwater recharge through infiltration and the associated improvement in water quality (Fig. 2.1-1), as well as the regulation of the local microclimate.

Water therefore has fundamental functions for the preservation of the biosphere. In addition to regulating ecosystem services, it also makes vital material ecosystem services possible such as the provision of drinking water. Water is also a habitat and harbours important food chains that ultimately provide food for humans. Non-material benefits include, for example, cultural-spiritual

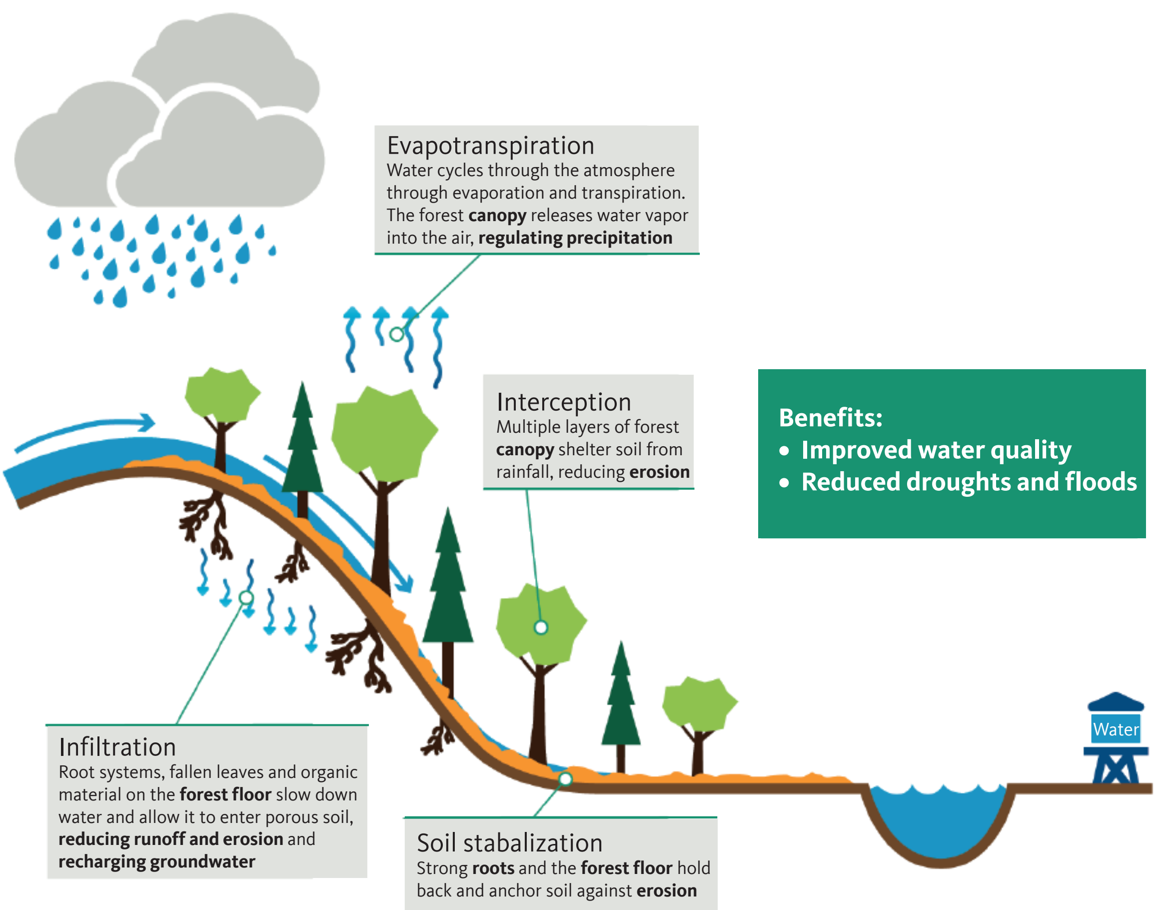


Figure 2.1-1
The influence of natural infrastructures on water security. Natural infrastructures such as wetlands or forests contribute to the water supply by purifying the water and replenishing groundwater reservoirs. They also regulate the flow of water and thus buffer the effects of floods or droughts, regulate precipitation, stabilize the soil and thus reduce erosion.
Source: Qin and Gartner, 2016

and identity-forming contributions (Vari et al., 2022; Wang-Erlandsson et al., 2022; Table 2.1-1).

Further important functions of water are non-material and cultural services provided by healthy ecosystems, such as the recreational value of such activities as hiking in water-rich environments, swimming or fishing, the spiritual significance and their symbolic and aesthetic value (Vari et al., 2022). Many of these functions are possible because of the biodiversity in the ecosystems. Despite their small proportion in relation to the earth's total surface area, freshwater ecosystems and inland water bodies in particular are home to many plant and animal species (Dudgeon et al., 2006). Freshwater ecosystems can also provide a habitat for specialized fauna and flora, e.g. in peatlands.

2.2 Global water cycle under human influence

Water passes through a continuous, global cycle which constantly provides freshwater in the form of precipitation over land. Its basic processes of evaporation and condensation are maintained by the sun, the earth's gravity, the distribution of the land masses, and the large-scale circulation of the atmosphere. Humans now influence

Table 2.1-1
Ecosystem services of freshwater ecosystems. The ecosystem services of freshwater ecosystems are shown with selected examples, grouped according to regulating, material and non-material services.
Source: WBGU, based on Vari et al., 2022; Lynch et al., 2023; IPBES, 2019a

REGULATING	**Creation and conservation of habitats** Provision of spawning/breeding grounds, plant habitats, nutrient recycling, oxygen production by photosynthesis
	Regulation of the climate Sequestration and storage of carbon; regional effect on the microclimate, e.g. by cooling settlements via blue spaces
	Regulation of the available quantity of fresh water Regulation of the quantity, location and timing of surface and groundwater runoff
	Regulation of the quality of freshwater resources and coastal waters Natural binding, filtering or microbial removal of pollutants or excess nutrients
	Regulation of risks and extreme events Mitigating the effects of floods or droughts
	Regulation of air quality Filtering particulate matter from the air via the vegetation, e.g. in alluvial or swamp forests
MATERIAL	**Materials for energy generation** Supply of firewood or peat
	Food and feed Supply of drinking water and foodstuffs such as fish, molluscs and freshwater algae
	Materials Provision of wood, reed fibres, including the soil for their cultivation
	Medical, biochemical and genetic resources Production of veterinary, medical or pharmaceutical ingredients from freshwater organisms, use of genetic information for breeding plants and animals
	Use of watercourses Transport routes for inland navigation or energy generation by hydropower
NON-MATERIAL	**Education and inspiration** Basis of religious and spiritual experience or social cohesion through the existence of spiritual places. Enables personal development, e.g. through education and knowledge acquisition and the development of skills for well-being, information and inspiration
	Physical and psychological experiences and recovery Landscape experience, e.g. during leisure time, with the associated positive health effects
	A sense of belonging Foundation for feelings of home, belonging and rootedness, which are conveyed, for example, by freshwater ecosystems, and serve as the basis for narratives, rituals and festivals

this natural cycle through a variety of activities in which water is extracted, used and discharged or flows back; this in turn changes evaporation, precipitation, groundwater recharge, runoff behaviour, etc. Global climate change influences the entire water balance from the global to the regional level (Section 2.2.1.2). Humans also have a direct impact on the water cycle by altering areas of land. This includes changes to the landscape as a result of agricultural and forestry uses, industrial production areas, mining, land sealing in settlements, roads and parking areas, as well as the reshaping of water bodies, e.g. river straightening, dams, dykes and reservoirs. As a result, evaporation, precipitation and runoff are redistributed both temporally and spatially (Fig. 2.2-1; UBA, 2017; GCEW, 2023b). Changes in land use also influence precipitation and river flows far beyond the local level (Wang-Erlandsson et al., 2018).

Other anthropogenic influences include the discharge of substances into surface and groundwater via inadequately treated wastewater from households, trade and industry, the disposal of waste or the over-fertilization of agricultural land. Emissions from various sectors such as transport, energy generation, industry and households lead to the direct release of substances into the water or the atmosphere, which can have adverse effects on vegetation, soil and groundwater after deposition.

2.2.1 A comprehensive view of water – blue and green water

The renewable water resources in a region, which result from precipitation, evaporation, inflows and outflows, determine the water supply and thus the amount of groundwater and surface water that can theoretically be used over time (BMU and UBA, 2017). The water supply is distributed differently from region to region and season to season and can result in water shortages or surpluses in relation to demand (Raskin, 1997; UBA, 2022c). Both the requirements for human use and the requirements for functioning ecosystems are relevant here (Section 2.2.2). The development of water stress due to scarcity therefore depends on the ratio between the total freshwater abstraction for all uses and the total renewable freshwater resources after taking into account the ecological water requirement (FAO and UN Water, 2021: 9). In the context of the 2030 Agenda, the FAO speaks of water stress when more than 25 % of freshwater resources in an area have been abstracted (FAO and UN Water, 2021: 9).

A more comprehensive view of a region's water resources is obtained by distinguishing between blue and green water (Fig. 2.2-2). Blue water includes all water resources in rivers, lakes, reservoirs and groundwater (Falkenmark and Rockström, 2006; Wang-Erlandsson et

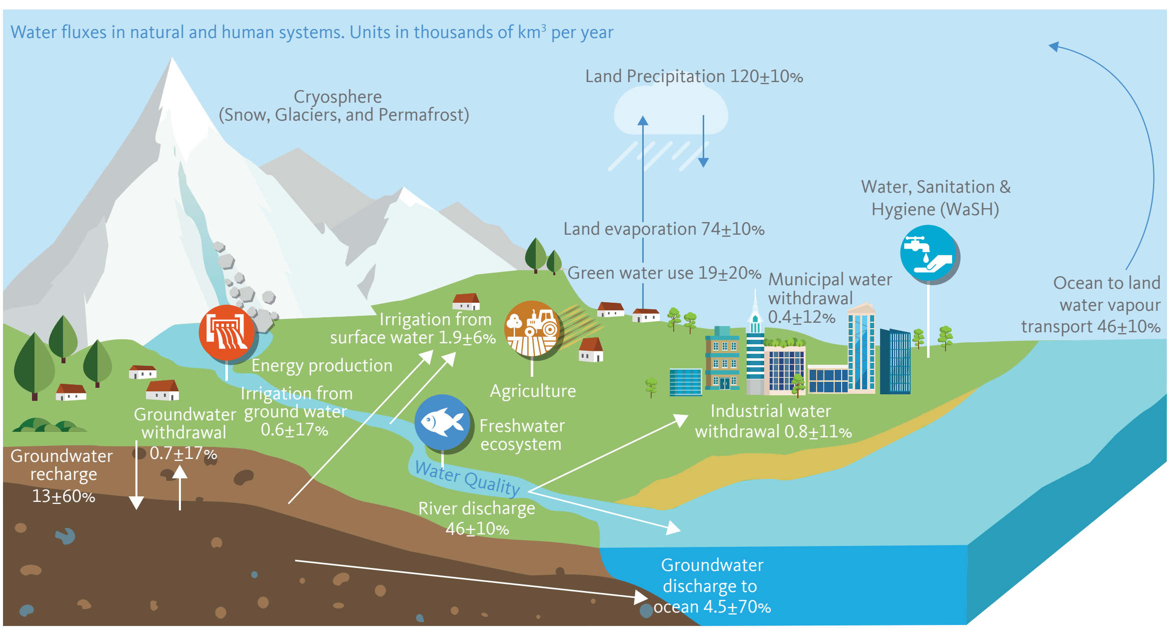


Figure 2.2-1
The water cycle including direct human interventions: the use of green water refers to the use of soil moisture; blue water is used for irrigation.
Source: Caretta et al., 2022: 565

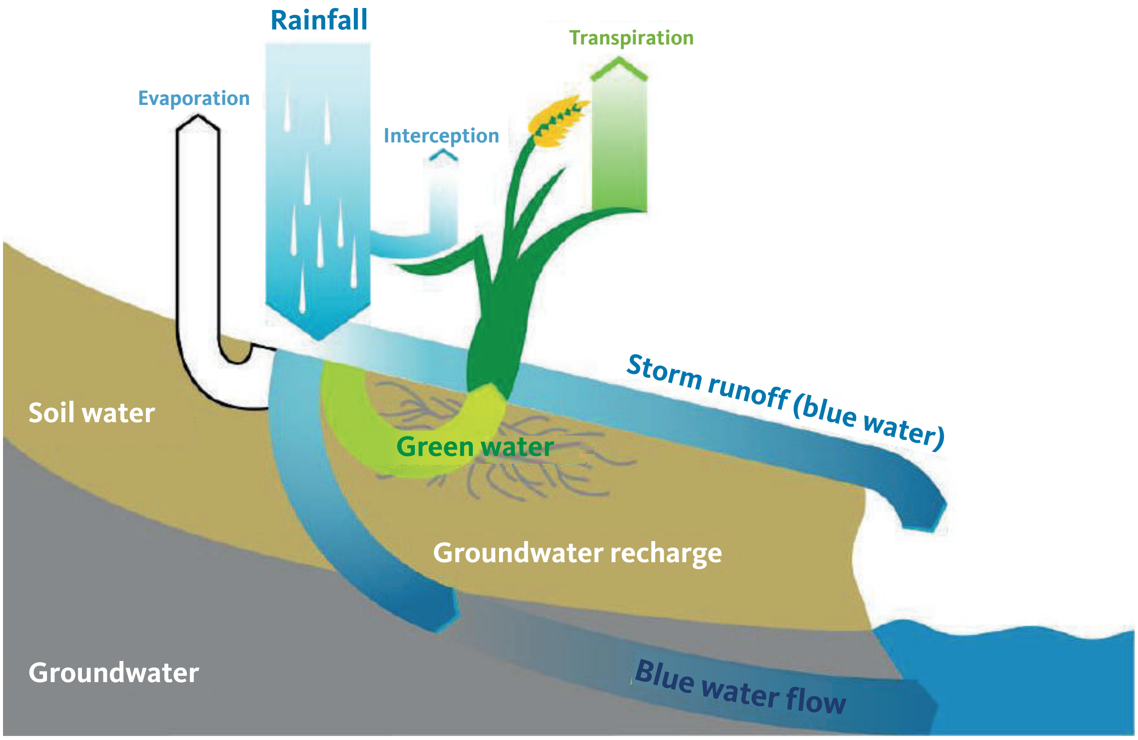


Figure 2.2-2
Division of precipitation into green and blue water. Some precipitation is absorbed into the soil, where it is then available to plants (green water). Plants release absorbed water into the atmosphere by transpiration. Another part of the precipitation evaporates unused from the soil or from the surfaces of the plants (interception). Finally, water also runs off the surface or into the groundwater (blue water).
Source: modified from Geertsma et al., 2009

al., 2022). Green water refers to the soil moisture available to plants; when it rains over land areas, some of the water is absorbed and stored in the soil and is then available to plants for the formation of biomass. The rest evaporates from the soil or plant surface or flows off and becomes blue water; this also enables subsequent use by humans downstream (Fig. 2.2-2; Falkenmark and Rockström, 2004; for details and, in some cases, differing definitions of the concept of green water, see Ringersma et al., 2003). Rockström et al. (2023b) estimate the proportion of precipitation over land that is available as blue water at 35 %. Both blue and green water make ecological functions and thus ecosystem goods and services possible (Section 2.2.2); they are therefore a prerequisite for human survival and societal development (Falkenmark and Rockström, 2006; Falkenmark and Rockström, 2004: 6; Rockström et al., 2023b). To regulate the global water cycle, a balance is needed between green and blue water, not only to ensure the amount of global precipitation or carbon fixation in soils and forests and other ecosystem services, but also to guarantee established water uses in different sectors (GCEW, 2023a; Rockström et al., 2024). A distribution of water that meets the needs of both natural areas and areas used intensively by humans thus contributes to the preservation of all life, and secures the water and food supply for humankind.

The need for a comprehensive view of water resources that also includes soil-bound water is also reflected in the supra-regional importance of the exchange of water between land and atmosphere. Up to 50 % of precipitation over land comes from evapotranspiration from land areas, the rest from evaporation from the oceans. In many countries, precipitation therefore also depends on evaporation in areas outside their own territorial borders (Rockström et al., 2023b). Countries that receive mainly air masses from the direction of the ocean are less dependent on water transport from surrounding countries for their precipitation. Landlocked countries and those that receive most of their air masses from over land are more affected by neighbouring countries' land uses that alter the water cycle. For example, deforestation in the Congo Basin influences the amount of precipitation in neighbouring countries (Fig. 2.2-3). Heavy irrigation of crops in India leads to increased atmospheric moisture transport and thus influences the runoff of the Yangtze River in China. Even a large country like Russia, 45 % of whose moisture is 'recycled' internally, receives 20 % of its moisture from neighbouring countries (Rockström et al., 2023b). These dependencies are also factors that make international cooperation in the water sector important (Rockström et al., 2023b: 796).

2.2.2
Observed impacts of climate change

Climate change is intensifying the global water cycle. Water and climate are inextricably linked by the exchange of water and heat between the atmosphere, the ocean and the land surface (Kundzewicz, 2008). A warmer atmosphere can absorb 7 % more water in a gaseous state for every 1 °C increase in temperature. This makes more and heavier precipitation possible (Douville et al., 2021). The average annual amount of precipitation has already increased in many regions worldwide, especially in the northern high latitudes (Caretta et al., 2022). By contrast, a decrease in average precipitation has been observed in the tropics (Caretta et al., 2022); however, drier summers have also been observed in the Mediterranean region, in south-west Australia and South America, in South Africa and in western North America (Douville et al., 2021).

Global warming also causes increased evapotranspiration (the sum of transpiration and evaporation, i.e. the water-vapor emissions from animals and plants as well as from soil and water surfaces). Together with the higher atmospheric water absorption and increasingly variable precipitation patterns, this reduces the moisture near the Earth's surface in many regions, and thus contributes to regional drought events (Douville et al., 2021; Caretta et al., 2022). Global soil moisture has already fallen slightly, particularly in the Mediterranean region but also in parts of North America and Australia, and this has increased both the frequency and intensity of drought events in recent decades (Douville et al., 2021). The changing precipitation patterns and the already altered runoff from snowmelt and glaciers are also changing the amount of water in the watercourses. Flooding or low water levels are the result, and the seasonal water volumes also change, which leads to an increasing irregularity of the runoffs (BAFU, 2012). The increasingly fluctuating natural runoffs are countered by a water infrastructure that is increasingly unable to cope with these changes.

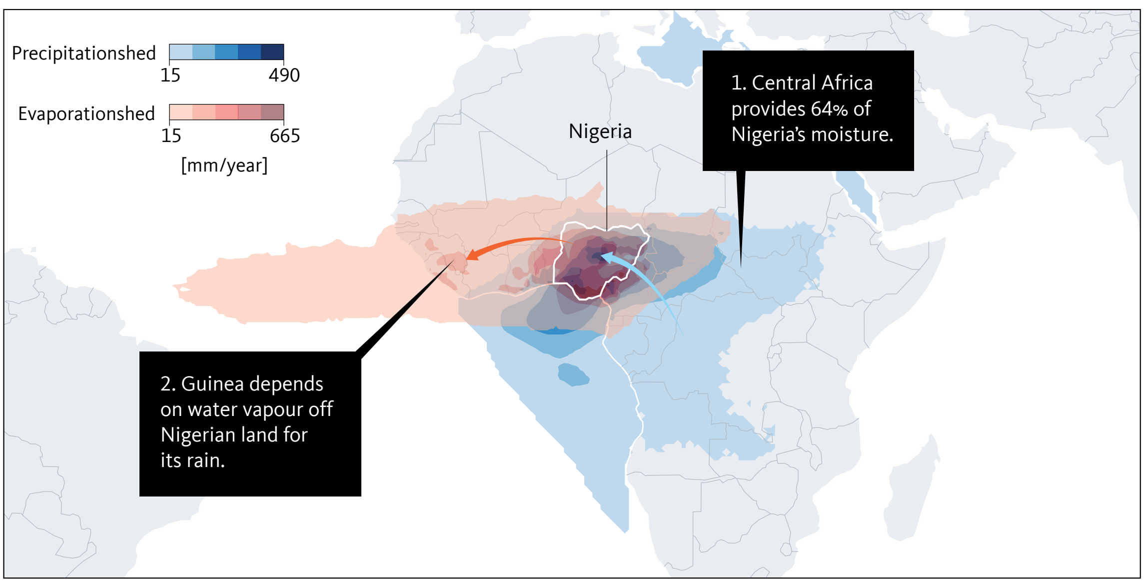


Figure 2.2-3
Nigeria as a producing and receiving area of moisture and evaporation. Nigeria receives 64 % of its moisture for rainfall from continental areas. Of these, 42 % comes from other countries, mainly from the Congo Basin. At the same time, Nigeria generates 43 % of the moisture that leads to rainfall in its neighbouring countries (Cameroon, Guinea and Ghana). This example shows the vulnerability of all these countries, since deforestation in the Congo Basin would very likely have an impact on the amount of rainfall.
Source: Rockström et al., 2023

Furthermore, there are local changes in the permafrost, especially in regions where the permafrost is thin and discontinuous, e.g. in southern Siberia, south-central Alaska, north-east China, or near the southern limit of the permafrost (Jin et al., 2022). A rising permafrost temperature has been recorded in all permafrost regions in recent decades; this is increasingly leading to the thawing or deepening of the active, unfrozen layer (Fox-Kemper et al., 2021). This not only leads to increased groundwater flows, but also changes groundwater recharge (spatially and temporally) and runoff, with effects on the groundwater balance and surface waters (Jin et al., 2022). The degradation of permafrost is also a potential further source of the release of substances and leads to changes in the landscape through erosion (Lafrenière and Lamoureux, 2019; Langer et al., 2023).

From a global perspective, extreme weather events such as prolonged heatwaves, droughts or heavy rainfall have also become more frequent and more severe (IPCC, 2019b, IPCC, 2021c), and they are also occurring more quickly and on shorter time scales (flash droughts, flash floods; Yuan et al., 2023;Yin et al., 2023). The increase in agricultural but also hydrological and ecological droughts worldwide (IPCC, 2021c; Yuan et al., 2023) particularly affects areas that are already suffering from a lack of precipitation (UNESCO, 2020).

In general, droughts have a significant impact on vegetation growth and therefore on agriculture and ecosystems (Yuan et al., 2023). They can also trigger compound events with cascading effects for humans and nature, e.g. the increased risk of forest fires, the depletion of water resources, the deterioration of air quality or a threat to food security (Christian et al., 2021; IPCC, 2022b). For example, the number and size of forest fires has been steadily increasing for around ten years (San-Miguel-Ayanz et al., 2022). This applies in particular to Australia, the USA and South America (Nolan et al., 2022), but also to southern Europe: between 2007 and 2016, forest fires in Portugal, Spain, France, Italy and Greece destroyed an average of 457,000 hectares every year – an area corresponding to almost twice the size of the Saarland (Dupuy et al., 2020). In Germany, there was a 'recovery pause' in 2021 before the fires raged all the more fiercely in 2022 (BMEL, 2023).

Flooding events are also becoming more intense. River floods claimed over 7 million lives in the 20th century (Merz et al., 2021), and around 58 million people worldwide are currently affected by river floods every year, more than half of them in Asia (Dottori et al., 2018). Due to the already increased frequency and intensity of heavy rainfall events worldwide, particularly in North America, Europe and Asia (Seneviratne et al., 2021, Caretta et al., 2022), the risk of flash floods is also increasing. This is particularly true in the arid regions of the world, including Africa (Fig. 2.2-4; Section 4.3; Yin et al., 2023). Worldwide, the number of flash floods in dry areas in the years 2000–2022 was already 20 times higher than in the last century (1900–1999; Yin et al., 2023). Flash floods can occur anywhere. Vulnerable areas are those with poor or insufficient natural and artificial drainage capacities.

On the coasts, storm surges also occur more frequently; they grow ever larger due to sea-level rise and the increasing intensity of storms. The sea level rose by about 20 cm between 1901 and 2018 (IPCC, 2023a). Low-lying coasts and islands in particular are already being affected by more frequent storm surges with historically severe flooding (IPCC, 2019a).

The current warming of the world's bodies of freshwater almost matches the warming of the atmosphere (Grant et al., 2021). The available habitat for freshwater organisms is shrinking (Kraemer et al., 2021). The warming causes a more stable stratification of the water and reduces vertical mixing in the water column. In combination with the higher water temperature, this causes a reduction in the amount of dissolved oxygen (Parmesan et al., 2022). The oxygen content in freshwater lakes is therefore falling rapidly – many times faster than in the oceans. In the last four decades, for example, the oxygen content in the deep waters of temperate lakes has fallen by around 18 % (Jane et al., 2021). Water quality is also negatively affected by the impact of higher water temperatures on biogeochemical processes (Capon et al., 2021), and the salinization of freshwater also poses a threat to vegetation, wildlife and entire freshwater ecosystems (Kaushal et al., 2021). Salinization reduces edibility or digestibility as a result of higher concentrations of minerals, especially sodium and chloride ions. Salinization of terrestrial and freshwater ecosystems therefore threatens their organisms and their functionality. Salinization also threatens human supplies of drinking water, as well as the food security of humans and animals, if food plants and animals are intolerant to increased salinity (Kaushal et al., 2023).

Water levels and volumes in rivers and lakes are also changing, and the surface area of wetlands worldwide has decreased. As a result of direct human influences (e.g. land-use changes), but increasingly also due to climate change, only 13 % of the wetlands that existed around 1700 were still present in 2000, for example; in more recent years the losses have been even more pronounced (approx. 0.8–1.2 % per year from 1970–2008; IPBES, 2019a). Also, on all continents and in all climatic zones, 51–60 % of watercourse stretches regularly fall dry, at least briefly; non-perennial rivers and streams are the rule rather than the exception (Messager et al., 2021). Many of the formerly perennial rivers and streams (e.g. Nile, Colorado) have also become intermittent due to land-use changes, water abstractions and climate change, and ever larger parts of the global river network are expected to stop flowing, at least seasonally, in the coming years (Messager et al., 2021). Here, too, habitats are increasingly disappearing; this is affecting not only nature but also a large part of the world's (human) population (Caretta et al., 2022). The effects of climate change, combined with habitat loss, changes in the global water cycle and pollution, are already having a lasting impact on the functionality of freshwater ecosystems, as well as their flora and fauna (Capon et al., 2021). The changes in seasonal water temperatures in lakes and rivers, for example, are causing a shift in the distribution areas of freshwater species, and impairing previous ecosystem functionalities (Caretta et al., 2022; Parmesan et al., 2022). Cold-water fish species are disappearing, while warm-tolerant zooplankton and fish species, invertebrates and aquatic plants are spreading (Parmesan et al., 2022). About 81 % of freshwater species populations are already in decline or threatened with extinction (Parmesan et al., 2022), mainly due to the increasing loss of habitats and the spread of invasive species and pollution, extreme events such as heatwaves, but also the loss of glaciers (Parmesan et al., 2022). In western and central Europe and the western parts of Eastern Europe, for example, at least 37 % of freshwater fish and around 23 % of amphibians are currently threatened with extinction (IPBES, 2018b; Sections 3.4.5, 3.4.6.2, 3.4.8).

The biodiversity of freshwaters is particularly sensitive to climate change, which has a particularly strong impact here compared to marine habitats. In inland waters and freshwater ecosystems, the loss of biodiversity has already progressed much further in recent decades than in terrestrial or marine ecosystems as a result of the lower water volumes and smaller habitats, geographical fragmentation and greater proximity to human civilization (Tickner et al., 2020; Capon et al., 2021; Albert et al., 2021; Costello et al., 2022), and many services provided by freshwater ecosystems (Table 2.1-1; Section 2.1) are already severely restricted today (Parmesan et al., 2022).

2.2.3 Importance of land use and climate change for green water

More than 75 % of the Earth's land surface has been altered by humans (Kaushal et al., 2017). Agriculture is the predominant type of land use worldwide, covering almost 50 % of cultivable land (Schürings et al., 2022).

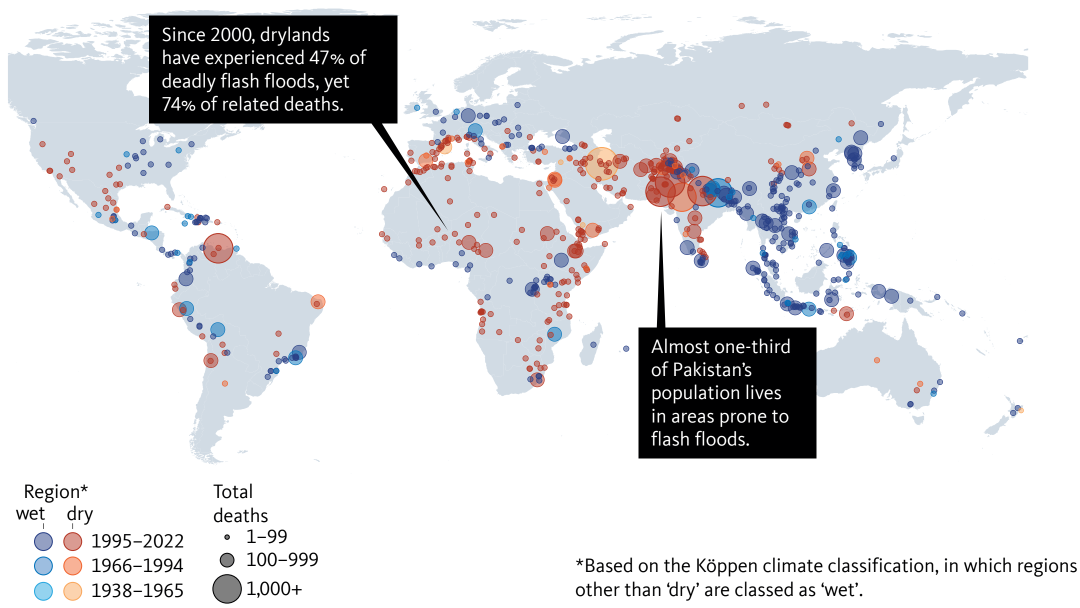


Figure 2.2-4
Global overview of the occurrence of flash floods. In general, flash floods seem to cause more deaths in dry regions (dark red: 1995–2022, red: 1966–1994, and pale red: 1938–1965) compared to more humid regions (dark blue: period 1995–2022, blue: 1966–1994 and pale blue: 1938–1965) because dry soils can absorb less water, and the people living there are often less prepared. The size of the circles represents the number of deaths.
Source: Yin et al., 2023

Land-use changes, e.g. the conversion of fields into urban settlement areas, the increasing soil compaction of intensively used agricultural areas, or the logging of forests and a lack of vegetation cover are changing runoff regimes, thus having a direct impact on the water cycle (IPCC, 2021c; WBGU, 2020). How water is absorbed into the ground, how quickly it runs off over surfaces, streams and rivers, to what extent the land surface is flooded, or how strong evaporation is, depends, among other things, on the surface conditions. Increasing surface sealing heightens the risk of excessively rapid and rising runoff with the consequence of extreme flooding (Caretta et al., 2022). Soil erosion, nutrient depletion and other forms of soil degradation (primarily due to agriculture) also affect the availability, quality and storage of water far beyond the respective region (IPBES, 2018a; IPCC, 2019b). Moreover, around a third of the world's watercourses run through agricultural, industrial or urbanized regions, with significant impacts on water quality (Section 3.1.3) and negative effects on the health of freshwater species and ecosystems (Albert et al., 2021).

Prolonged dry periods and drought years over several years significantly change soil moisture and are directly related to changes in land use and climate (Haerdle, 2018; Samaniego et al., 2018). Reduced soil moisture, exacerbated by soil degradation, not only leads directly to yield losses in the vegetation, but also prevents the infiltration of precipitation for groundwater recharge. Prolonged heatwaves and droughts, such as those that occurred in Europe in 2018–2023, led to higher evaporation, a sustained decline in soil moisture, even in deeper soil layers, and significantly reduced discharges in many watercourses (WMO, 2023). This led to drought-stress damage in the vegetation and aquatic ecosystems, as well as significant yield losses in agriculture, but also to restrictions in shipping and the shutdown of power plants due to a lack of cooling water (Box 7.4-1).

2.2.4
Overuse of blue water

The changes in water availability are often associated with unsustainable water use (Section 2.2.4.1). Seawater desalination is one approach to expanding the supply (Section 2.2.4.2), but like other technological approaches (Section 2.2.4.3) it involves undesirable side effects and risks.

2.2.4.1
Trends in water use

Global water abstractions increased by 700 % between 1900 and 2010 (Wada et al., 2016). Irrigation for food production in particular has contributed to this, but water consumption by industry and households has also increased sharply since the beginning of the 20th century, especially between 1950 and around 1990 (FAO, 2022b), even though there have been efficiency gains in irrigation and innovations in water treatment and the operation of water-distribution infrastructures.

Globally, agriculture accounts for 72 % of all freshwater abstractions, industry (mining and extraction of raw materials, manufacturing, supplying electricity, gas, steam and air-conditioning plants, and construction) for 15 %, and municipalities and households for 13 % (AQUASTAT, 2024). Agriculture is thus the world's largest consumer of freshwater. However, the amount of water abstracted for agriculture as a percentage of total abstraction varies considerably by region and income level. In high-income countries it makes up only 41 % of the total abstractions on average, whereas in low- and middle-income countries it accounts for between 80 and 90 % (Ritchie and Roser, 2017). Agricultural water withdrawals accounted for approx. 2.2 % of total abstractions in Germany in 2019, since rainwater usually supplied enough for agriculture's needs (UBA, 2022a). However, data on agricultural abstractions are subject to a high degree of uncertainty. Furthermore, Germany, too, has seen a regional increase in the need for irrigation in agriculture, particularly in recent years with prolonged dry spells (HBS, 2023). Global and regional averages therefore mask regional and local differences (UNESCO, 2023). According to the FAO, irrigated farmland accounts for only about 20 % of the total area but is the source of over 40 % of total produce in terms of value. In some regions, irrigated land contributes more than 50 % of the value of agricultural production (FAO, 2020b: 58).

The trend towards abstracting more groundwater to expand agricultural irrigation in semi-arid areas is particularly problematic for securing water supplies (Bierkens and Wada, 2019; Llamas and Martínez-Santos, 2005; Wada et al., 2010; Siebert et al., 2010; Marston et al., 2015). Groundwater is also being abstracted at increasing rates in urban areas, especially megacities, to supply the growing urban population who have no access to clean surface water or piped drinking water (Bierkens and Wada, 2019). The growing abstractions of groundwater for irrigation and urban drinking-water supply have led to the increased use of non-renewable groundwater (deep groundwater). The result is that the groundwater table is falling more and more (Herbert and Döll, 2019); this has been observed especially in countries in the MENA region and southern Europe, as well as in major aquifers in India, northern China, the Middle East, North Africa and the south-west of the USA (Herbert and Döll, 2019; de Graaf et al., 2017; Wada et al., 2012; Caretta et al., 2022; Bierkens and Wada, 2019). In most of the regions mentioned above, water consumption for irrigation accounted for an average of over 90 % of total water consumption between 1960 and 2010, and around half of this came from non-renewable groundwater (Wada and Bierkens, 2014).

Analyses of local monitoring data from groundwater-abstraction points indicate that the local management of groundwater resources can play a role in slowing or even reversing the decline in groundwater levels (Jasechko et al., 2024; Chávez García Silva et al., 2024). Examples of successful groundwater management can be found in the La Mancha Oriental aquifer in southern Spain (Chávez García Silva et al., 2024), in the eastern Saq aquifer in Saudi Arabia and in the Bangkok Basin (Jasechko et al., 2024). However, groundwater levels only rose in 6 % of the aquifers analysed by Jasechko et al. at the beginning of the 21st century (at a rate of more than 0.1 m per year). Furthermore, groundwater levels often recover relatively slowly. By contrast, 36 % of the aquifers analysed revealed falling groundwater levels (of more than 0.1 m per year). In 30 % of the aquifers for which a comparison with the years 1980–2000 was possible, the decline in groundwater levels accelerated in the period 2000–2022. According to Jasechko et al. (2024), existing management practices, particularly in arid agricultural regions, are often inadequate, either conceptually or in terms of implementation, to slow down or reverse a decline in groundwater levels.

2.2.4.2 Seawater desalination

Freshwater – i.e. new blue water – can be obtained from seawater or brackish water with the help of energy-intensive technological treatment processes such as seawater desalination using high-pressure membrane processes (reverse osmosis) or thermal distillation and evaporation processes, especially in coastal regions or island states. Over the past 20–30 years, desalination plants have become an important alternative source of freshwater for countries in the Middle East (e.g. Saudi Arabia, Israel, United Arab Emirates, Qatar), Australia, Spain, South Africa, the USA and, increasingly, India and China (Eyl-Mazzega and Cassignol, 2022). The cumulative treatment capacity of existing desalination plants worldwide was around 99 million m^3 of freshwater per day in 2022 – enough to supply water for around 800 million people (EU Blue Economy Observatory, 2024). However, the further expansion of seawater desalination plants is hampered by their high energy requirements and negative ecological effects. Compared to the treatment of conventional freshwater resources with less than 1 kWh/m^3, the energy requirement for seawater desalination using reverse-osmosis systems is three times higher at approx. 3 kWh/m^3 (Drewes and Horstmeyer, 2016). Thermal processes require as much as 10 kWh/m^3. The expedited expansion and use of renewable energies is therefore also of great importance for this sector (Bundschuh et al., 2021).

The abstraction of seawater also has a significant impact on the aquatic environment (e.g. death of larvae, juvenile fish), as does the disposal of concentrated salt solutions (due to the large differences in density). Furthermore, because the level of demineralization achieved is so complete, the water produced has to be chemically treated to make it fit for human consumption. Despite these measures, some long-term studies indicate adverse health effects that can lead to a demonstrably higher risk of cardiovascular disease (Shlezinger et al., 2018).

2.3 Economic and social aspects of water use

2.3.1 Virtual water

The quantities of water consumed or polluted in the production of goods or services are sometimes referred to as the virtual water content of goods and services. A country's water footprint records the virtual water content of the goods and services consumed there (i.e. the sum of direct and indirect water consumption in the country itself, and for the production of imports, minus the virtual water content of exports; Hoekstra and Hung, 2002). In many regions and countries, a large proportion of the water footprint comes from products that are produced outside the region or country and then imported (Hoekstra and Hung, 2002; Hoekstra et al., 2011). For products and services consumed in Germany, this share is around 86 % (UBA, 2022b). The quantities of water consumed or polluted in the production of traded goods and services can be tracked as virtual water flows across the globe (Allan, 1998). Figure 2.3-1 illustrates the complexity of such flows for quantities of blue water that can be associated with the trade in food. Companies are linked to water consumption abroad via international supply chains. In this way, consumer and corporate decisions have a fundamental impact e.g. on the availability and quality of water resources and food security in exporting and importing countries; vice versa, they can also be affected by changing levels of water availability abroad, for example. Whether these effects and dependencies are critical depends on the situation in the respective countries.

Negative socio-economic and environmental impacts possibly connected with the production of the traded

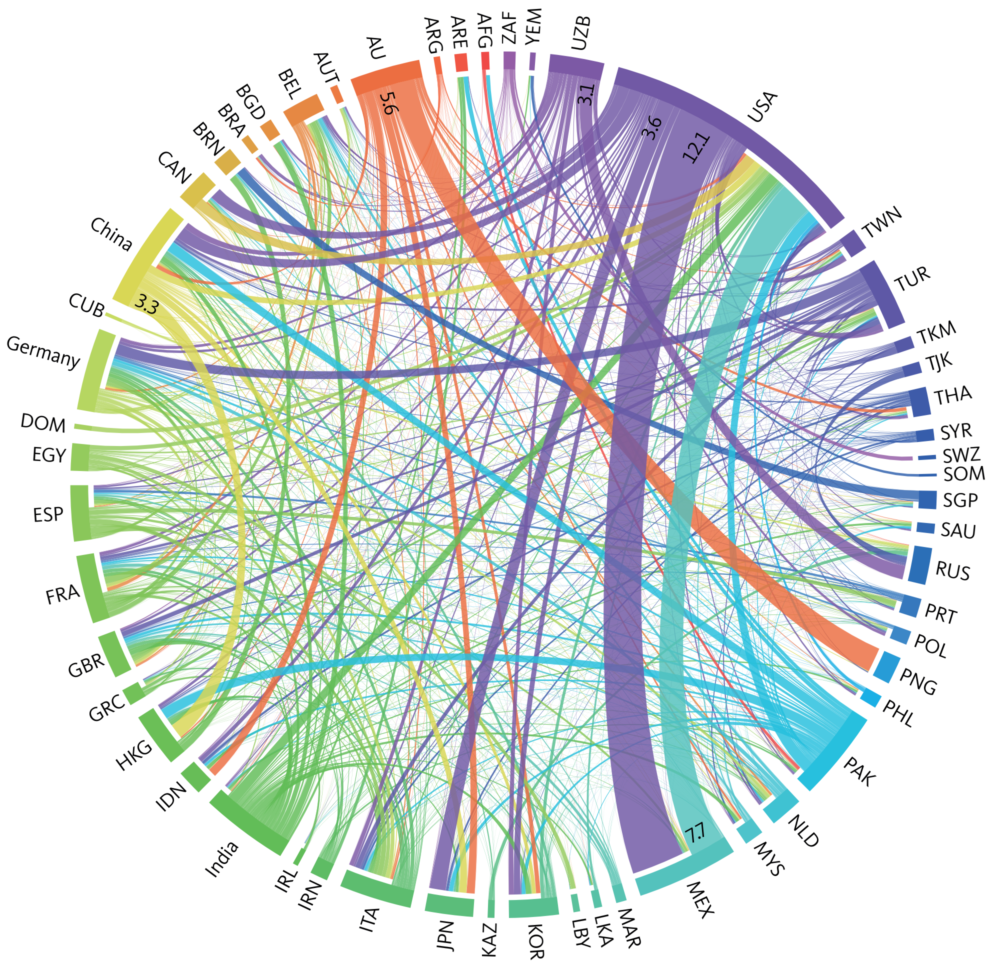


Figure 2.3-1
Flows of virtual blue water via the trade in food (1996–2005). The diagram shows virtual flows of blue water between countries (in km^3 per year) from the period 1996–2005. The colours of the connections indicate the exporting country. Data and country abbreviations can be found in Table 8a in Scanlon et al., 2023. Country codes according to ISO 2166 ALPHA-3.
Source: Scanlon et al., 2023

goods – both through the required amounts of water or the overuse of water resources and through pollution, e.g. from chemicals in industry and pesticides in agriculture – occur in the exporting country and are thus externalized by the importing country. Pollution 'traded' (or 'contained' in products) in the form of virtual water and its effects have hardly been determined to date, partly due to methodological challenges (d'Odorico et al., 2019; UBA, 2022b). The following sections therefore focus on the quantitative water consumption associated with trade and its effects.

Over 65–90 % of global virtual water flows originate from trade with agricultural products, followed at a considerable distance by industry and energy (d'Odorico et al., 2019; Hoekstra and Mekonnen, 2012). Accordingly, virtual water flows from the trade in agricultural goods and their impacts are particularly well documented in the scientific literature. The literature cited in this section also focuses primarily on trade in agricultural goods. There is a need for research into the effects of non-agricultural virtual water flows – e.g. in connection with the trade in industrial and energy products or textiles – on the quantity and quality of water resources. Yet studies have shown that non-agricultural virtual water flows should not be neglected. The traded water footprint of energy products increased by 35 % between 2012 and 2018. In 2018, virtual water flows from energy products accounted for around 7–9 % of total global virtual water flows. Firewood, crude oil, biofuels and electricity account for the largest share. Firewood and biofuels are water-intensive energy sources, but the trade in them is generally concentrated in industrialized countries in

North America and Europe (Peer and Chini, 2020). On the other hand, the trade in agricultural products and its impacts often affect low-income countries.

The opportunities and risks arising from the trade in virtual water for local water resources in importing and exporting countries and for food security in importing countries are outlined below.

Virtual water trading offers water-poor regions an opportunity to conserve scarce water resources. From a global perspective, it can lead to water savings if water-intensive products are imported from regions where water is used more efficiently (Maroufpoor et al., 2021). Some scientific studies document water savings through trade on a global level, albeit in different orders of magnitude (d'Odorico et al., 2019). Water savings through trade, particularly as a result of the spread of water-saving technologies, have also been documented for individual countries (d'Odorico et al., 2019; Dang and Konar, 2018).

However, it also happens that water-scarce regions are exporters of water-intensive products (Vallino et al., 2021). Germany, for example, sources rice from Pakistan and nuts from southern Europe, Iran and the USA (Finogenova et al., 2019). The countries of origin of such products are often low- and middle-income countries, while the importers are high-income countries (Vallino et al., 2021). Accordingly, water savings through trade in virtual water are more likely to be realized in rich countries than in poor ones (Distefano and Kelly, 2017).

Export-orientated production in water-scarce regions can lead to the local ecological boundaries (based on planetary boundaries according to Rockström et al., 2009b; Rockström et al., 2009a) being exceeded in these regions. The Federal Environment Agency (2022b) estimates that this is the case for almost 10 % of the foreign contributions to Germany's consumption-related blue-water usage. Particularly important here are Spain and countries in South Asia but also the USA and countries in North Africa and the Middle East (UBA, 2022b).

Water stress jeopardizes food security in many regions around the world (Maroufpoor et al., 2021). Trade in virtual water can contribute to food security in regions where it is difficult or impossible to supply the population from local agricultural production (d'Odorico et al., 2019; Tamea et al., 2016). At the same time, importing countries that (have to) rely heavily on global trade links are vulnerable to localized shocks to water availability or food production in exporting countries (d'Odorico et al., 2019). The literature comes to different conclusions regarding the influence of trade on food security in importing countries (Sartori and Schiavo, 2015; Distefano et al., 2018; d'Odorico et al., 2019).

Water-scarce countries with a low domestic agricultural production that are highly dependent on food imports, e.g. in the MENA region or the Middle East, are especially vulnerable (Tamea et al., 2016). As a result of the Russian war of aggression against Ukraine, around 30 countries, including Eritrea, Kazakhstan and Mongolia, recorded a drop in direct grain imports of more than 50 % (Liu et al., 2023). In Lebanon and Libya, a net deficit in calorie intake of 13–28 % compared to regular consumption was expected in 2022 (Bertassello et al., 2023). Low and middle-income countries that are heavily dependent on food imports suffer particularly from a decline in their imports, which appears to be due not only to a lack of purchasing power but also to a lack of access to the market or insufficient market power (Distefano et al., 2018). Although high-income countries, e.g. in Europe, can also be exposed to negative import shocks (Tamea et al., 2016), they appear to be better able to compensate for them.

2.3.2
Water, poverty and social inequality

Despite the increase in global access to clean drinking water from 62 % of the world's population in 2000 to 74 % in 2020, there are still major differences between countries in different income groups (Fig. 2.3-3, 4; UN, 2023: 12). About 1.3 billion people (19.1 % of the world's population), half of whom are children, are multidimensionally poor. They live with multiple deprivations in terms of health, education and material living standards (in 2021; UNDP, 2022; UNDP and OPHI, 2022; Fig. 2.3-2).

A significant proportion of all multidimensionally poor people (470.1 million people in 111 countries) are undernourished and lack access to clean drinking water, reliable sanitation and hygiene facilities. Their susceptibility to infectious diseases is high (UNDP and OPHI, 2022: 2; Balasubramanian et al., 2023). Furthermore, even in societal groups with access to drinking water, wastewater disposal and sanitary facilities, this access is often unequally distributed, or else the lack of access has a varying effect on life chances, depending on age or gender (Huinink, 2022; Calow and Mason, 2014).

For example, women and girls bear a larger burden from the water and sanitation crisis than men and boys, as they are often responsible for fetching water and thus have less time e.g. for education, and have to expose themselves to physical dangers in the process. In the case of children, the lack of access to clean drinking water has a more serious impact on development and health status than in adults; in older people, on the other hand, it has a different and often faster life-shortening effect than in young adults. For example, the gender-specific poverty index 'Global Correlation Sensitive Poverty Index' of the German Institute of Development and Sustainability shows that in 95 % of all countries, female poverty

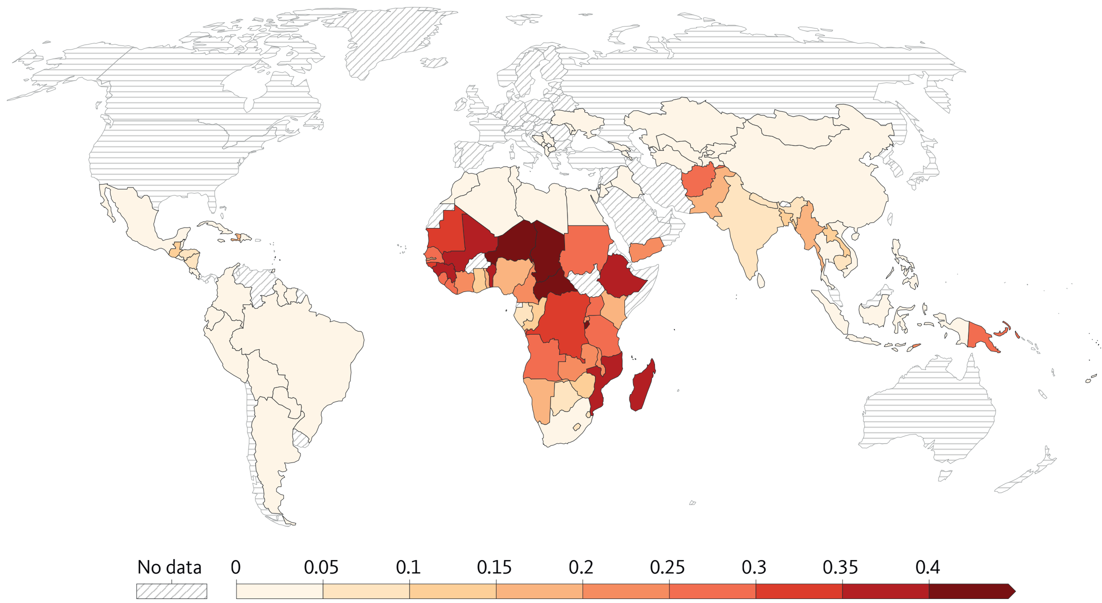


Figure 2.3-2
Multidimensional Poverty Index, global 2010–2020.
Multidimensional poverty is defined as being deprived in a range of health, education and living-standard indicators. The Multidimensional Poverty Index is a measure that reflects both the prevalence and the intensity of multidimensional poverty.
Data from: Our World in Data, 2023

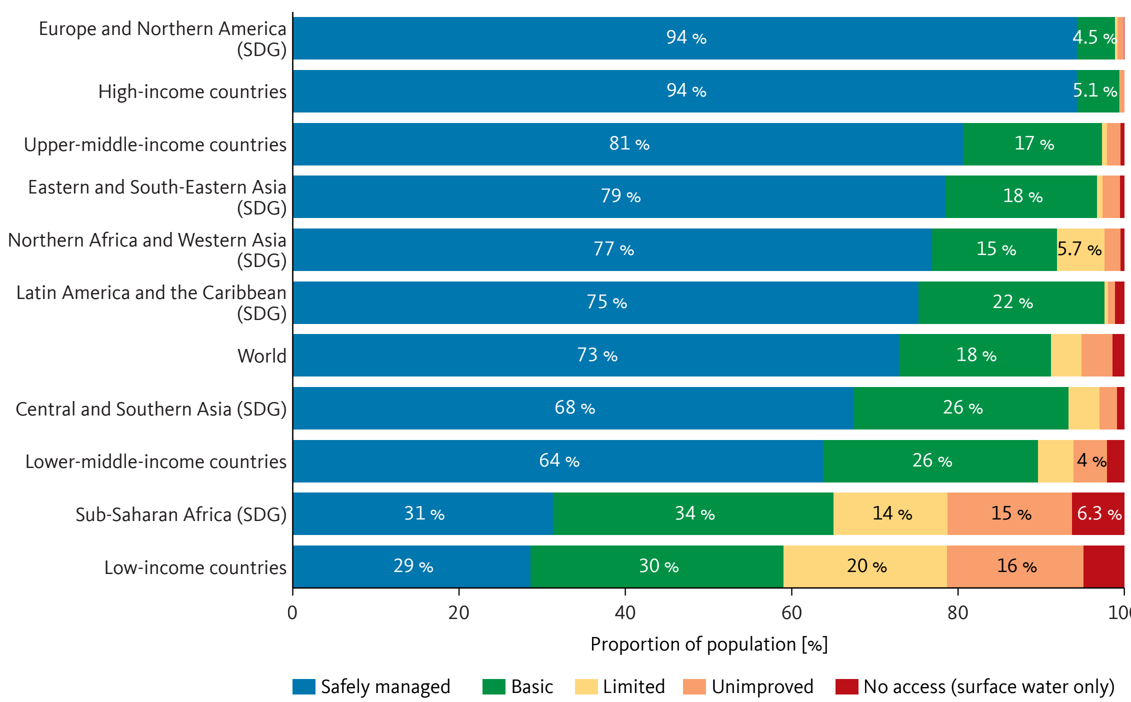


Figure 2.3-3
Share of the population with access to drinking-water facilities by region and income class (2020). Graded as follows: no access (surface water only), unimproved access, limited access, access to basic supply and safe access to drinking water.
Source: Ritchie et al., 2019

is on average twice as high as male poverty. The biggest gender-specific differences in poverty can be found in the Middle East, North Africa and South Asia (Burchi and Malerba, 2023). These regions of the world are also among the most arid regions on Earth.

Disparities in the supply of clean drinking water also exist between urban and rural areas and between groups with high and low incomes (UNICEF and WHO, 2023; Fig. 2.3-3). However, not only low-income and vulnerable population groups are disadvantaged when it comes to access to clean drinking water and sanitation. Water scarcity and increasing extreme events also hinder economic growth and jeopardize development goals such as poverty reduction and education (Section 3.2.1.3).

2.3.3 Pollution as a challenge for humans and ecosystems

Today, the water quality of water resources, including groundwater, is severely impaired by many anthropogenic substance inputs (Fig. 2.3-4). Especially pollution with persistent and harmful pollutants causes permanent damage to aquatic ecosystems and, via drinking water and the food chain, also to health risks for humans. For at least three billion people, water quality is uncertain because of a lack of monitoring (UN, 2022). According to Tozer (2023), water sources for up to 5.5 billion people could be contaminated by the year 2100.

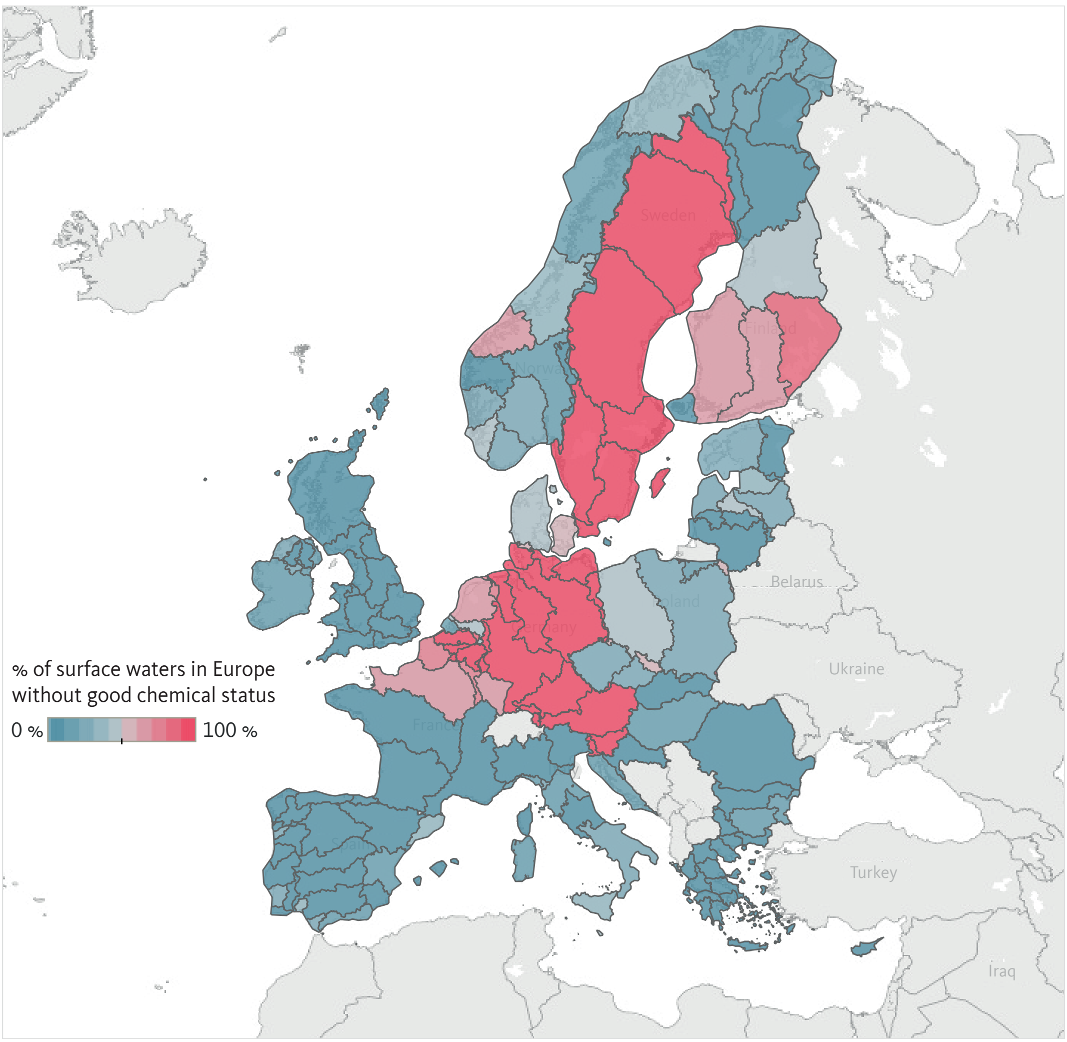


Figure 2.3-4
Proportion of surface waterbodies in Europe failing to achieve good chemical status. The assessment of the chemical status includes ubiquitous, persistent, bioaccumulative and toxic substances.
Source: WISE, 2021

2.3.3.1
Path dependencies caused by centralized water infrastructures

Many people today still have inadequate access to safe drinking water that is free from pathogens and pollutants (Fig. 2.3-3). This, combined with or caused by a lack of or inadequate wastewater treatment, significantly impairs the health of the people affected (WBGU, 2023). In the course of industrialization at the beginning of the 19th century, the contamination of water with pollutants already led to a massive burden on aquatic ecosystems, as well as unacceptable hygienic conditions and a significant increase in health burdens in cities. The growing awareness of the link between polluted water and the spread of epidemics such as cholera focused the attention of city planners on the centralized supply of clean water and the disposal of wastewater (Gallardo-Albarrán, 2020). Partly for this reason, life expectancy in England rose from 40 to 70 years between 1850 and 1950, with the biggest increase occurring at the beginning of the 20th century (Haines and Frumkin, 2021). In addition to the creation of a centralized drinking-water supply, the decisive factors here were the introduction of the waterborne sewerage system for the collection and orderly discharge of wastewater and the treatment of wastewater in central treatment plants. The development of these structures over several decades, particularly in high-income countries, resulted in a high degree of path dependency of the water infrastructure due to high capital intensity and long amortization periods as well as high fixed operational costs. In addition to the high investment costs, the ongoing maintenance of this infrastructure also required appropriate planning and operating expertise, financing by corresponding charges, and effective structures for enforcement, e.g. discharge bans, in order to achieve adequate water quality. Although the solution approach of centralized water supply and disposal was also adopted by low- and middle-income countries, it often resulted in an incomplete development of these structures with major deficits in operation due to a lack of long-term financing, trained personnel or effective official monitoring (Section 2.3).

Despite the existence of centralized wastewater-disposal structures, the pollution level in a large proportion of rivers and lakes is high even in Europe – measured against the good chemical status required by the EU Water Framework Directive. This pollution is primarily the result of the long-term effects of industrial chemicals such as polycyclic aromatic hydrocarbons (PAHs) or tributyltin and pollution from diffuse inputs such as mercury (Fig. 2.3-5; EEA, 2015; Liess et al., 2023). Even where wastewater collection and treatment are well organized, pollutants from industry, households, healthcare facilities or agriculture can only be removed from wastewater at great expense (civity Management Consultants, 2018; Toshovski et al., 2020; Fig. 2.3-5).

2.3.3.2
Nutrients and pesticides

Especially in high-income countries, substance inputs from agriculture into ground and surface waters are a serious problem (UNESCO, 2024). Organic fertilisers can pollute water bodies with nitrates and pathogenic microorganisms, while synthetic fertilisers pollute them with nitrates and phosphates and lead to eutrophication (Bijay and Craswell, 2021). In Germany, the nitrate contamination of many groundwater bodies has exceeded the limit value of the drinking water ordinance for years, in some cases by more than 700 %. The latest figures from the 2024 Nitrate Report show only slight improvements in groundwater quality (BMEL and BMUV, 2024). The level of anthropogenic nitrogen discharge into rivers is too high in many parts of the world (Mekonnen et al., 2015; Fig. 2.3-6). The over-fertilization of water bodies has far-reaching consequences for biodiversity and health (Section 2.3.4.3).

Conventional agriculture is also the biggest user of pesticides and other biocides. These can have neuronal and hormonal effects and influence embryonic development (Fukuyama and Tajiki-Nishino, 2020; Gangemi et al., 2016; McKinlay et al., 2008; Syvrud et al., 2021). Insecticides are also used in forestry. In Germany, according to a study by the Federal Environment Agency, over 80 % of water bodies in the agricultural landscape are contaminated with pesticides above the regulatory acceptable concentrations, and the biodiversity in these water bodies is therefore unacceptably threatened (Liess et al., 2023).

2.3.3.3
Pathogenic microorganisms

The spread of microorganisms via contaminated drinking water affects two billion people worldwide. The main route of entry is the discharge of untreated wastewater contaminated with faeces into water bodies. Especially in low- and middle-income countries, children suffer from malnutrition due to recurrent diarrhoea caused by pathogenic microorganisms in drinking water (Sameh, 2023; WHO, 2023). Pathogenic microorganisms and parasites can also be ingested via personal hygiene and in bathing water through the skin, mouth and lungs. Table 2.3-1 shows the number of deaths due to inadequate sanitation and drinking-water supply (WHO, 2023). People in sub-Saharan Africa and Central and South Asia are most affected.

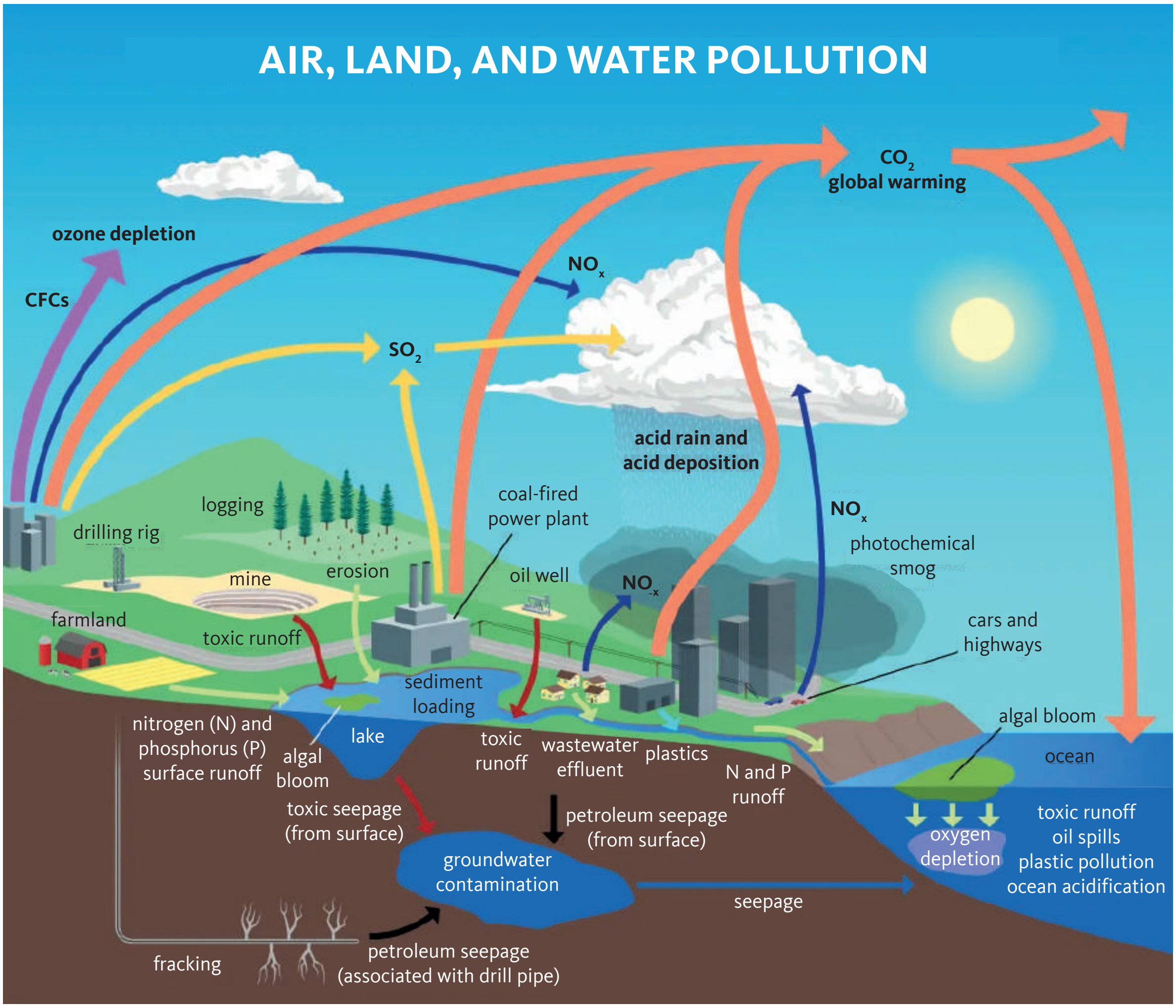


Figure 2.3-5
Air, land, and water pollution: major pollution pathways.
Source: Nathanson, 2023

2.3.3.4 Pharmaceutical drugs

A particular risk to healthcare is posed by the formation of antibiotic-resistant germs when bacteria are exposed to antibiotic residues from households and livestock farming (Sections 2.3, 4.5; Sanganyado and Gwenzi, 2019). Resistance to various antibiotics has been detected along receiving waters, i.e. rivers with a high proportion of wastewater effluent (Hiller et al., 2019; Biggel et al., 2021).

Numerous studies show pharmaceutical residues in the inflows and outflows of wastewater-treatment plants. It is undisputed that the usual treatment steps in the municipal treatment of wastewater are not enough to remove most of them (Duarte et al., 2021; Lipp and Lipp, 2022; Oaks et al., 2004; Sharma et al., 2022; Toshovski et al., 2020). Studies have repeatedly shown high residues of painkillers (e.g. diclofenac, ibuprofen, paracetamol), antiepileptics, antidepressants, hormones (oestrogens) and antibiotics (Fig. 2.3-6; Castillo-Zacarías et al., 2021; Lipp and Lipp, 2022). The main sources of inputs of pharmaceutical drugs into wastewater are healthcare facilities and households. In many low- and middle-income countries, wastewater from settlements is discharged directly into water bodies without wastewater treatment; in many cases, few or no studies are carried out on this, and the available data is sparse (Barcellos et al., 2022; Kairigo et al., 2020; Waleng and Nomngongo, 2022). Elsewhere too, however, livestock farming on land and in bodies of water leads to the direct entry of antibiotics and other veterinary medicinal products into water bodies and aquifers.

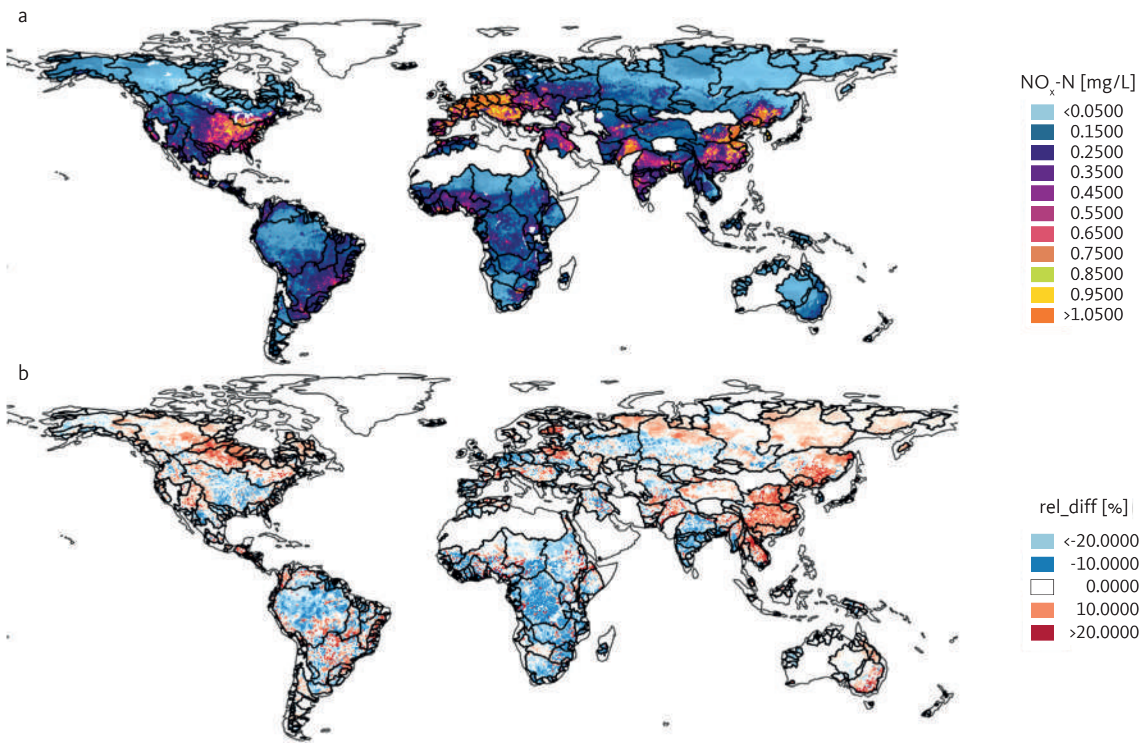


Figure 2.3-6
Simulation of nitrogen pollution in the world's major river basins. The study focuses on nitrate-nitrite-nitrogen (NOx-N), the predominant water-soluble nitrogen compounds. (a) shows the simulated global map of average NOx-N concentrations for the years 1990–2013. (b) shows the spatial pattern of changes in NOx-N concentrations from the 1990s (1990–1999) to the last decade (2000–2013).
Source: Sheikholeslami and Hall, 2023

Table 2.3-1
Worldwide deaths due to inadequate sanitary conditions and drinking-water pollution
Source: WHO, 2023

Health outcome	Population-attributable fraction	Deaths (thousands)	DALYs (thousands)
Diarrhoea	69 %	1,035	54,590
Acute respiratory infections	14 %	356	16,578
Undernutrition	10 %	8	825
Soil-transmitted helminthiases	100 %	2	1,942
Total	**N/A**	**1,401**	**7,3935**

2.3.3.5 Industrial chemicals and microplastics

A large number of industrial chemicals have been brought onto the market in recent decades without a full assessment of the health risks to humans and the environment. Large quantities of these chemicals are produced in order to guarantee certain features of consumer goods. It is now scientifically proven that many of these chemicals can be released from the end products, enter the environment and also accumulate in the human body Kumari and Pulimi, 2023). Contamination with industrial chemicals can be found worldwide – some substances are already ubiquitous. These industrial chemicals are discharged into wastewater e.g. via manufacturing processes, tyre, brake and metal abrasion, commercial or household textile cleaning and the use of cosmetics or plastic articles.

Some of the industrial chemicals act as endocrine disruptors (like hormones). They affect reproductive capacity and the neuronal development of unborn babies or children, or increase the risk of asthma and allergies (Abraham and Chakraborty, 2020; Eales et al., 2022; Richardson et al., 2019).

More and more studies show a global contamination of freshwater and drinking water, as well as of the oceans, with microplastics (particles from 1 µm up to 5 mm; Koelmans et al., 2019; Mishra et al., 2023; Sharma et al., 2023). Microplastics are produced i.a. directly by the decomposition of plastic waste in bodies of water and are distributed over a wide area (Koelmans et al., 2019; Li et al., 2020;Mishra et al., 2023; Sharma et al., 2023). Microplastics are persistent and harbour risks for the environment, animals and humans. The additives contained in the plastic and adsorbed contaminants such as polycyclic aromatic hydrocarbons (PAHs) can also have a toxic effect (Anik et al., 2021; Dusaucy et al., 2021; Sharma et al., 2023; Talbot and Chang, 2022; Zadjelovic et al., 2023). However, studies on their effects on health are hitherto insufficient. PAHs are often formed as unwanted by-products of production processes. Many compounds in this substance group are considered carcinogenic, mutagenic and teratogenic (DFG, 2023). While PAHs hardly pose a challenge for wastewater treatment in Germany because the levels in wastewater are relatively low (Toshovski et al., 2020), in other countries they enter wastewater or groundwater via industrial wastewater, especially from the oil, coal and steel industries, or through open fires in households, and pose a potential contamination risk to drinking water (Ambade et al., 2021; Mojiri et al., 2019; Zhang et al., 2019).

Emissions of highly complex chemical mixtures, soot and microplastics from brake, metal and tyre abrasion in road traffic (Alves et al., 2020; Grigoratos and Martini, 2015) and subsequent leaching by precipitation are sometimes released directly into surface waters. After uptake by aquatic organisms, humans are bioaccumulators of pollutants at the end of the food chain. Many of the substances are persistent and can be detected many years after they were banned, even in the remotest locations on Earth. In addition to microplastics, further examples include pesticides on the Zugspitze mountain (Levy et al., 2017), perfluorinated substances in the Canadian Arctic (Stock et al., 2007), and biocides and drug residues in the Antarctic (Duarte et al., 2021).

EU Directive 2008/105/EC (amended by 2013/39/EU), has identified substances in the group of industrial chemicals (including PFAS; WBGU, 2023: 177 ff.), PAHs and biocides, as well as heavy metals (Section 2.3.4.6) and their compounds, as priority hazardous substances and made them subject to mandatory monitoring for the EU member states (Toshovski et al., 2020).

2.3.3.6 Pollution from raw-material extraction and industrial activities

Due to inadequate wastewater treatment, metals, so-called heavy metals and their salts, as well as other chemicals used in the degradation process pose a health risk to billions of people in many regions of the world. The term “heavy metals” is used inconsistently and often includes elements that are also assigned to other terms, e.g. semi-metals such as arsenic (Duffus, 2022). Some of these substances are vital as trace elements, but in higher doses they can contaminate drinking water. When they accumulate in the food chain, they pose a threat to entire ecosystems and human health (Chowdhury et al., 2016; Lee et al., 2023; Rehman et al., 2018). Wastewater from mining operations contains quantities of some toxic, soluble metal salts, e.g. lead, cadmium, copper, lithium or mercury compounds, which are problematic for ecosystems and human health, and are often discharged directly into surface waters.

The extraction of materials such as ores, lithium salts, rare earths and copper is very water-intensive and results in considerable restrictions on water quality. Two thirds of the largest mines are located in countries with severe water shortages (Madaka et al., 2022; Bogardi et al., 2021). Figure 2.3-7 shows an example of the ‘water scarcity footprint’ of lithium, copper and coal mining for the production of lithium-ion batteries.

By-products of raw-material extraction, e.g. from the ores, process chemicals and the mined substances themselves, can enter water bodies through leaks or waste material and have a negative impact both on the environment and potentially on human health (Obasi and Akudinobi, 2020; Adeel et al., 2023; WBGU, 2023). One example is water pollution caused by arsenic-containing waste material from cobalt mining in Morocco (Blum et al., 2023).

Cobalt, lithium and phosphorus are found in the process wastewater from the recycling of lithium-ion batteries. Some of these are toxic even in low concentrations, and no limit value has yet been set for lithium for industrial wastewater discharged into water bodies or for drinking water (Adeel et al., 2023; Mrozik et al., 2021; Wagner-Wenz et al., 2023). Lead, cadmium and copper compounds also enter water bodies through (agricultural) livestock farming and fertilization. In other countries, arsenic often comes from natural sources, from industry and from mining, e.g. in the lithium mining described above; then it represents a continuous source of contamination for drinking water (Srivastava, 2020).

The health effects of heavy metals and their compounds range from developmental disorders, neurological diseases and organ damage to cancer. In many low- and middle-income countries, contamination of drinking

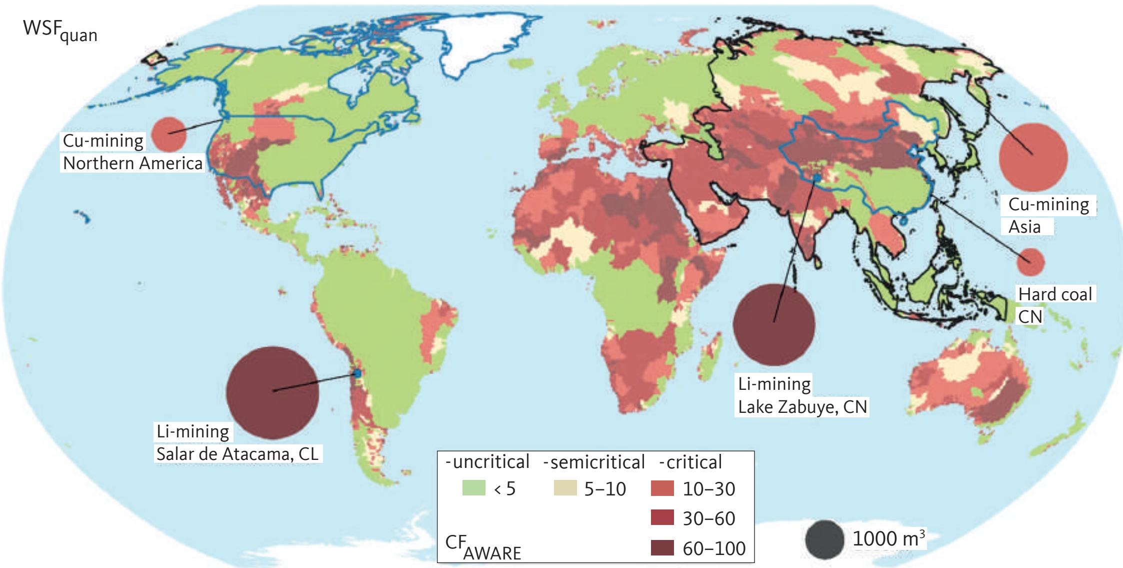


Figure 2.3-7
Water footprint of the mining processes of raw materials for lithium-ion batteries. The map describes the quantitative water-scarcity footprint WSFquan of the most relevant processes along the supply chain of lithium-ion batteries. The map is based on the risk definitions according to the DIN EN ISO-compliant AWARE (Available WAter REmaining) approach, which compares water consumption by humans and the water requirements of the environment with hydrological water availability. The circles represent the quantitative water-scarcity footprint (WSFquan) at the locations of the respective processes. The colour of the circles represents the AWARE characterization as non-critical, semi-critical or critical. The blue and black lines outline the regions and countries analysed in the balance sheet; blue dots represent point coordinates. CL: Chile; CN: China; Cu-mining: copper mining; Li-mining: lithium mining.
Source: Schomberg et al., 2021

water or surface water is practically unknown due to a lack of monitoring and investigations (Kumar et al., 2019; Wołowiec et al., 2019). Worldwide, 80 % of industrial wastewater is discharged untreated into bodies of water (GCEW, 2023a). The heavy metals and other chemicals they contain pose a serious health risk to ecosystems and, via drinking water and the food chain, to humans.

2.4 Political and legal aspects of water

This section outlines the diversity of different water-governance approaches. It deals with the genesis of three approaches to water management at the interfaces of ecosystem-related and societal challenges that are most widely discussed internationally. This brief overview is followed by a discussion of state (formal, *de jure*) governance using some examples at the regional level, and non-state (informal, *de facto*) water governance using examples at the local level, with a particular focus on the interaction between the two. In addition to formal (*de jure*), i.e. legally binding forms of water governance, informal institutions and rule interpretations also play an important role in implementation. In this context, institutions are understood as guidelines that structure interactions, i.e. rules and norms that are institutionalized by organizational structures, as well as their enforcement and compliance (North, 1991). A distinction must be made here between formalized, i.e. written institutions with legal status (e.g. constitutions, laws), and non-formalized but real-life institutions (e.g. taboos, traditions, rules of conduct; North, 1991: 97). This binary classification is a simplification, i.e. 'formal' and 'informal' are not always clearly distinguishable (Greif, 2006; Mielke et al., 2011; Hodgson, 2006).

Not all globally relevant issues can be analysed here – e.g. who the water belongs to, who is allowed to use it and how, or who is responsible for water quality and availability. These questions are only briefly addressed, but not answered, below. That requires comparative legal research (Thomashausen et al., 2018; Civic, 1998; Araral and Yu, 2013).

2.4.1
International guiding concepts

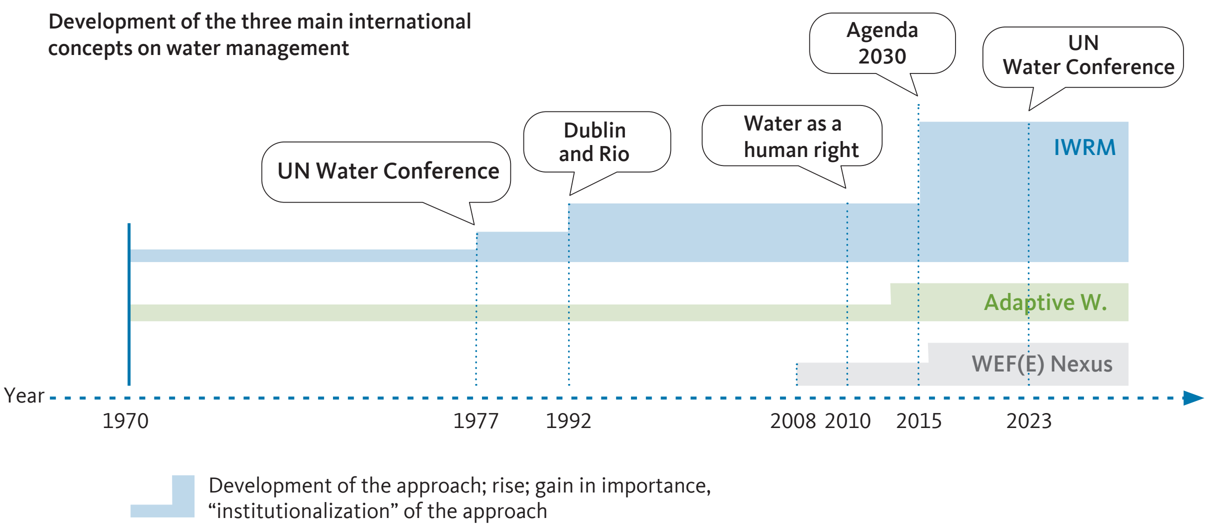
At the international discourse and policy level, there are three major trends in water governance: integrated water-resource management (IWRM), the Water-Energy-Food-Ecosystem Nexus (WEFE Nexus) and adaptive water-resource management (Fig. 2.4-1).

These approaches overlap. They all address the management of water as a resource and the associated conflicts of use between different sectors – such as water, energy and food – taking into account ecosystems and the management of water pollution and water-related extreme weather events. When it comes to implementing these solutions, there are many difficulties, particularly of an institutional, political/administrative and financial nature. However, the approaches also differ in their focus, their actors and their areas of application.

2.4.1.1
Integrated water-resource management

Integrated water-resource management (IWRM) is a paradigm that is used worldwide (Hack et al., 2017). The approach aims to achieve a fair and participatory distribution of the scarce resource of water between different sectors.

Today's understanding of IWRM as a holistic approach is based on both the Dublin Principles of 1992 and the Agenda 21 (Meran et al., 2021). The four IWRM principles are: (1) Water is a finite and vulnerable resource. (2) Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels. (3) Women play a central part in the provision, management and safeguarding of water. (4) Water is a public good and has a social and economic value in all its competing uses (GWP, 1996).



APPROACH	FOCUS	ORIGIN
IWRM	Coordination in the water sector	Administration, planning
Adaptive Water Resource Management	Iterative crisis adaptation	Ecology
WEF(E) Nexus Interdependencies between sectors	Interdependencies between sectors	World Economic Forum, context of the financial crisis 2007/08

Figure 2.4-1
Overview of international guiding concepts for water governance. The timeline illustrates the development and growing importance of the concepts of IWRM, adaptive water management and the WEFE Nexus. The concepts overlap in terms of content, but differ in focus and origin.
Source: WBGU

IWRM aims to achieve a systemic system of management of water, land and related resources, and takes equal account of the social and ecological dimensions alongside the economic dimension. The inclusive participation of a variety of actors from different sectors (as well as from local communities) characterizes the approach. IWRM is defined as a "process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Agarwal et al., 2000: 22). As part of the 2030 Agenda, the implementation of IWRM is an indicator for SDG 6.5 (IWRM progress), making the concept highly relevant internationally. The IWRM approach with its Dublin-Rio principles and instruments needs to be interpreted for implementation in the respective contexts (GWP, 1996). The Global Water Partnership (GWP) has developed a toolbox to support the application of IWRM principles in practice. The four core elements are an enabling environment, institutional structures, management instruments and infrastructure development. Figure 2.4-2 illustrates the role of IWRM in the implementation of water governance in a simplified manner.

The cycle shows the steps that a state can take to manage its water resources in a sustainable and integrated manner. The process begins with the formulation of political goals (in the context of current global goals) and first requires empirical data collection. This is followed by the formulation of an IWRM plan or a water strategy and the implementation of measures, as well as ongoing monitoring and evaluation of implementation (GWP, 2024b).

While IWRM has some conceptual strengths compared to traditional water management, there are often deficits in its implementation. The United Nations Environment Programme has identified major differences in the global implementation of IWRM between low- and middle-income countries on the one hand and high-income countries on the other (Fig. 2.4-3).

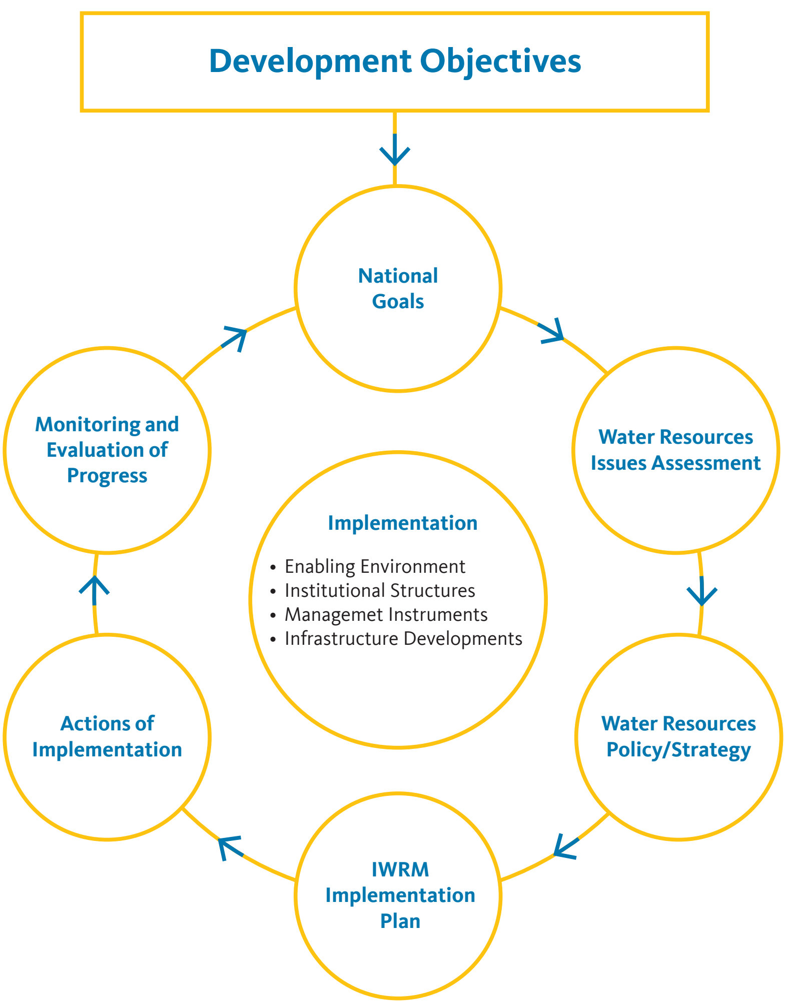


Figure 2.4-2
Policy cycle with planning and implementation phases of Integrated Water Resources Management (IWRM). National development goals, e.g. as part of the 2030 Agenda, give countries an opportunity to document their water resources and formulate a strategy for their integrated use. In an IWRM implementation plan, measures can be formulated from which actions can be derived. The implementation of the actions should be systematically reviewed and evaluated.
Source: GWP, 2024b

The implementation problems are based on a considerable lack of institutional capacity, a lack of political will for cross-sectoral governance (Horlemann and Dombrowsky, 2012; Kim and Hornidge, 2016; Pahl-Wostl, 2019), a lack of financial resources, rivalry between sectors (e.g. water for food or for energy), and their differing political support (Houdret et al., 2014). IWRM is orientated towards hydrological boundaries (Kurian, 2017) and not political-administrative boundaries, which makes control across all governance levels more difficult.

The IWRM approach is also criticized for not stipulating what is to be 'integrated' how and by whom (Biswas, 2004), and is described as requiring too much coordination and therefore too many resources. In addition, donors tend to implement blueprints, especially in low- and middle-income countries, instead of incorporating local opportunities. One example is the donor-supported, state-run establishment of water-user communities in large parts of Central Asia towards the end of the 1990s and in the 2000s (Kim and Hornidge, 2016).

In addition to the deficits in implementation, another weakness of IWRM is the lack of consideration of the effects of climate change and the end of stationarity. IWRM does not yet provide for the standardized inclusion of projection data that take changes caused by climate change into account.

The BMBF-funded funding measure 'Global Resource Water' (GroW) combines global analyses with local solutions. The 'STEER' project in particular addresses challenges in the implementation of IWRM (BMBF, 2024a).

2.4.1.2
Adaptive water-resource management

Due to increasing uncertainties and instabilities as a result of the more pronounced effects of climate change, new discussions on adaptive approaches have been initiated, especially in the last 15 years (Pahl-Wostl, 2007, 2008; Pahl-Wostl et al., 2006, 2007). Unlike previous approaches, which aim to stabilize systems and minimize natural fluctuations, adaptive water management does not resist changes in the water balance. Adaptive approaches argue in favour of social learning and flexibility in order to respond quickly and appropriately to changing environmental conditions and their impact on water availability and management, but also to keep pace with changing environmental conditions, e.g. precipitation patterns, in the longer term.

The complexity and associated uncertainty are recognized and attempts are made to live with change – in the sense of acting in the face of uncertainty and learning from controlled experimentation – and to strengthen the resilience of socio-ecological systems in such a way that they can 'absorb' unforeseen events. By addressing problems of ecological resilience with technical solutions, societal integration and the promotion of societal resilience (Allan et al., 2008), the approach of adaptive water-resource management is a response to the rather linear IWRM practice (Herrfahrdt-Pähle, 2010).

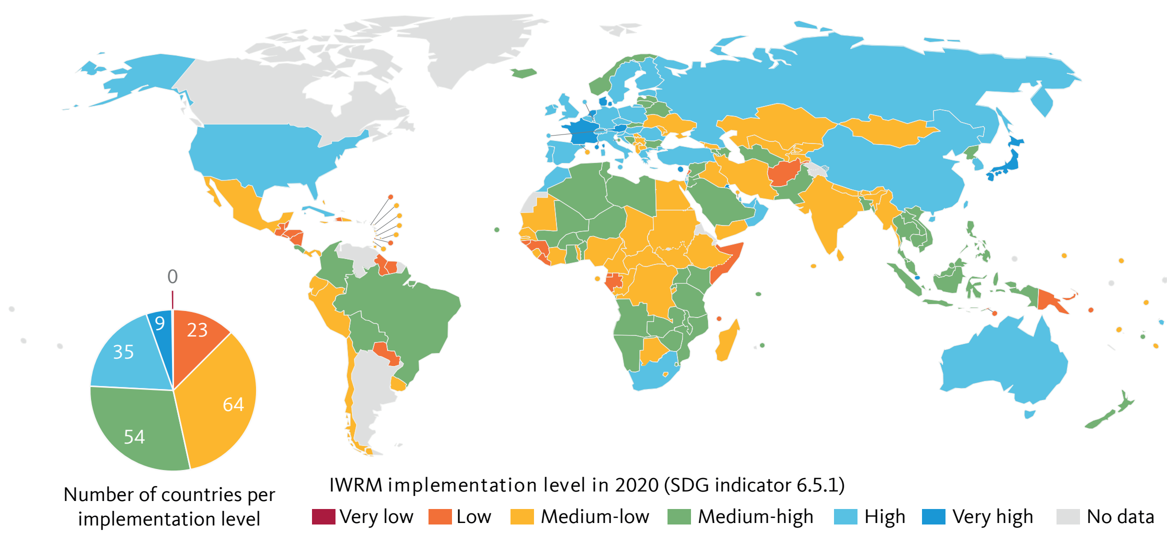


Figure 2.4-3
Implementation of Integrated Water Resources Management in individual countries, measured using the SDG 6.5.1 indicator in 2020.
Source: UNEP, 2021b

2.4.1.3
Water-Energy-Food-Ecosystem Nexus

The Water-Energy-Food (WEF) Nexus was originally developed largely by private-sector actors and as part of the food, energy and financial crises of 2007–2008; it was presented at the World Economic Forum in 2008. In subsequent years, the concept was expanded to take sufficient account of ecosystems (Water-Energy-Food-Ecosystem or WEFE Nexus). IWRM and the WEFE Nexus are closely related. They differ primarily in that IWRM begins with the water resource, while nexus approaches regard all elements as a coherent system from the outset (GWP, 2024a).

With the aim of improving policy coherence and better understanding, and managing the interdependencies between the Sustainable Development Goals (Srigiri and Dombrowsky, 2021, 2022), the WEFE Nexus has emerged as a useful concept over the last ten years. In addition to the IWRM approach, it is being implemented by the BMZ as a second important guiding principle of German development cooperation in the water sector (BMZ, 2023). However, this approach faces its own implementation challenges, particularly with regard to the complex measurement of impact. For example, in most water-management contexts, it is not possible to quantitatively ascertain and measure conflicting objectives arising from the complex interrelationships between the sectors due to the data situation and methodological challenges (Albrecht et al., 2018). This also complicates the further dissemination of the approach in political practice in many countries, as Dombrowsky et al. (2022a) describe for Jordan.

2.4.2
State water governance

The interplay between (inter-)state governance (de jure) and non-state, self-organized actors and real-life practice (de facto) shapes the implementation of water governance. The following section outlines agreements and guidelines relevant to water law at the global, regional and national level that characterize the status quo in dealing with water.

2.4.2.1
Binding conventions under international law

In addition to numerous bilateral treaties, two conventions regulate the use of water at the international level: the Convention on the Law of the Non-Navigational Uses of International Watercourses of 1997 (UN Water Convention) and the 1992 Convention on the Protection and Use of Transboundary Watercourses and International Lakes (or UNECE Water Convention).

Both reify and extend the three main rules of international law in the area of transboundary water bodies: (1) equitable and reasonable utilization; (2) the no-harm rule, and (3) the duty to cooperate (Mbengue and Cima, 2023). The no-harm rule restricts state sovereignty in such a way that the use of one's own territory must not lead to a significant impairment of foreign territory. The principle of equitable and reasonable use entitles a riparian state to a fair and reasonable share of the uses or benefits of the respective watercourse, thus obliging it to weigh up the interests of all user states (Laskowski, 2010) and, as a cornerstone of international water law, it is now also part of customary law (ICJ, 1997). Furthermore, the conventions commit states to the sustainable use of transboundary water bodies and contain environmental-protection regulations (McCaffrey and Sinjela, 1998), which, however, are not very detailed compared to national regulations or the EU Water Framework Directive (Directive 2000/60; Section 2.4.2.2) and have been criticized as inadequate (Dellapenna and Gupta, 2009). The UN Water Convention, for example, provides for the obligation to preserve ecosystems and the obligation to prevent pollution, whereby quality standards and indicators are yet to be defined by the respective riparian states in subsequent agreements. The aspect of pollution prevention is more strongly emphasized in the UNECE Water Convention, which also establishes an institutional structure with a secretariat, unlike the UN Water Convention. The signatory states were also able to agree on a supplementary protocol on water and health, which commits them to taking measures to prevent, control and reduce water-related diseases (UNECE, 1999).

The regional nature of water aspects is reflected in the character of both conventions as framework conventions which also expressly allow for the possibility of concluding further bilateral and multilateral agreements that observe the principles of the conventions, but may deviate from them depending on the circumstances of the individual case. Both agreements can therefore be seen as platforms for the formation of intergovernmental cooperation at the regional level, and for the creation of programmes and strategies for water protection. Both conventions contain positive approaches, such as the guiding principle of sustainability and – for treaties with a potentially global scope – appropriate principles and instruments. However, their effectiveness is diminished by the fact that not many states have ratified them (UN Water Convention: 38; UNECE Water Convention: 52); large and influential countries such as the USA, China, India and Brazil are missing. The reason for this is the tension between the rules of equitable and reasonable use on the one hand and the no-harm rule on the other. There is disagreement over how far the right to use natural resources in the sense of equitable use extends, and at what point a violation of the no-harm rule occurs, for example when building a dam. In case of doubt, upstream states will always emphasize the former, while downstream states will have a broad understanding of the no-harm rule (Tanzi, 2020). For this reason, the minimum number of ratifications for the UN Water Convention was not achieved until 17 years after its adoption (Mager, 2015) and has stagnated; only three further ratifications have been added since it came into force in 2014. By contrast, the trend in the UNECE Water Convention is towards an increase in ratifications. After ratification was initially limited to European states, non-European states are now increasingly joining in.

2.4.2.2
EU Water Framework Directive: Approaches for multi-level governance

The EU Water Framework Directive (Directive 2000/60) is an example of a legally binding organization of river-basin management that covers not only rivers but also inland surface waters, transitional waters, coastal waters and groundwater.

The EU Water Framework Directive regulates targets, instruments and procedures, but requires further specification. It aims to protect inland surface waters, transitional waters, coastal waters and groundwater by preventing deterioration (no-harm rule), enhancing the status of aquatic ecosystems (including water quality), promoting sustainable water use (water quantity), enhancing the aquatic environment (improvement requirement), reducing the pollution of groundwater and mitigating the effects of floods and droughts (Article 1). Both the improvement requirement and the no-harm rule with regard to good water status are binding and can also be enforced with regard to individual project authorizations (Durner, 2019: 3). The member states are obliged to comply with environmental quality standards, which are specified in Article 4 in conjunction with Annex V and define what qualifies as good chemical, good ecological and good quantitative status of the water. Ecological status refers to the quality of the structure and functioning of aquatic ecosystems associated with surface waters, and is measured using indicator organisms. The chemical status refers to the concentration of certain chemical pollutants. The quality standards for ecological status are specified by the member states and those for chemical status by the EU (Ginzky, 2009: 244). As an instrument for achieving the objectives, an official planning regime for water management is also introduced, which refers to catchment areas of river basin districts as the relevant geographical size (Art. 3, 11, 13 in conjunction with Annex VII). The management of water resources at river basin level aims to administer and manage hydrological catchment areas across political boundaries (Dombrowsky et al., 2014). Great importance is attached to the involvement of civil society actors and all groups directly affected by water management. Studies show that the type of involvement differs considerably in various parts of Europe (Rimmert et al., 2020). This may be the reason why interest groups from agriculture and environmental organizations are generally more involved, while less well-organized citizens seldom take up much space in the participation process.

This focus on river basin districts contrasts with the previously prevailing regulation of individual sources of pollution at local level, which did not result in an effective systemic protection of water. The same applies to the development of a monitoring network for water bodies and to public participation within the EU member states (UBA, 2021b: 4). Nevertheless, even 20 years after the EU Water Framework Directive came into force, there are still considerable deficits in achieving its targets. While almost all groundwaters (e.g. in Germany) have good quantitative status and around two thirds have good chemical status, no surface waters have good chemical status and only 9 % have good ecological status BMUV, 2022: 17). Across Europe, only three member states achieve 70–100 % of the targets for their river basin districts (Europäische Kommission, 2021b: 4). The reasons for this are implementation deficits and the lack of a legally coherent approach.

Although one of the aims of the EU Water Framework Directive is to eliminate the previous patchwork of different directives, a series of daughter directives to the EU Water Framework Directive have been issued since 2006, each with their own regulatory approach, which affect different water areas (surface water, groundwater, bathing water, drinking water). Although the EU Water Framework Directive provides a framework that enables further differentiation in secondary legislation and the specification of quality standards, this framework is fragmented within water law and is not very coherent with other standards that are also relevant for water protection (Breuer and Gärditz, 2017: margin number 135). In other words, the objectives of the EU Water Framework Directive cannot be achieved through water-management measures alone (Durner, 2019: 11 f.) and must be better integrated into other policy areas such as agriculture, energy and transport (Europäische Kommission, 2021b: 1).

In addition, there are implementation deficits, mainly due to insufficient financial resources of the member state administrations (Europäische Kommission, 2021b: 17 f.). In a review of the EU Water Framework Directive and several daughter directives, the EU Commission identified the following obstacles to achieving the objectives more effectively: many member states focused primarily on technical solutions for isolated sources of pollution, while diffuse sources were hardly addressed.

Furthermore, ecosystem-restoration measures are often required to achieve improvements in water status. The complexity of the challenges was another factor hindering the enforceability and responsibility of the member states.

Due to its approach, which is nevertheless predominantly assessed as positive, the EU Water Framework Directive is being taken up as a governance approach in other regions of the world (Zeitoun et al., 2013; Molle, 2009; Mostert et al., 2007; Wester and Warner, 2002), although local adaptations are necessary (Heldt et al., 2017). Compared to approaches outside the EU, e.g. the IWRM approach (Section 2.4.1.1), the EU Water Framework Directive emphasizes water quality and relies on fairly detailed binding regulations for this purpose.

2.4.2.3
Urban Waste Water Treatment Directive

In January 2024, the EU Parliament and the Council agreed on a revised version of the Urban Waste Water Directive (91/271/EEC), which contains important new approaches. This agreement was also formally adopted by the EU Parliament at first reading in April 2024 (Europäisches Parlament, 2024). The Council has yet to adopt it and is expected to do so in autumn 2024. Four of these approaches should be emphasized.

First, the polluter-pays and precautionary principles are to be taken into account by the introduction of extended producer responsibility (Art. 9, 10; Annex III). Manufacturers of pharmaceuticals and cosmetics must contribute to the costs of a fourth purification stage, depending on the quantities and toxicity of the products placed on the market. Mechanical wastewater treatment takes place in treatment stage one, biological wastewater treatment with the removal of nutrients such as nitrogen and phosphates in treatment stages two and three; the fourth treatment stage is intended to remove trace substances by means of ozonation or activated carbon adsorption. Levying charges not only serves the purpose of financing, but should also have an indirect preventive effect in terms of lower-emission production. The German Environment Agency even suggests involving all manufacturers of water-polluting products, as this can lead to greater acceptance of the Directive (UBA, 2023d: 8).

Second, large wastewater treatment plants are to be obliged to be greenhouse-gas and energy-neutral (Art. 11): The renewable energy they generate must at least match their consumption by the end of 2045. However, this system-wide approach is likely to be difficult to implement in specific individual cases, and is potentially associated with higher costs, as energy consumption increases with rising purification requirements, and there is only limited capacity to generate renewable energy.

Third, according to Article 20, the member states must ensure that the disposal routes of sewage-sludge management correspond to the waste hierarchy pursuant to Article 4 of the Waste Framework Directive (2008/98/EC), which is intended to improve waste prevention, reuse and the recycling of resources. Fourth, the mandatory introduction of the above-mentioned fourth purification stage, which is intended to remove micronutrients, also serves the implementation of the 'Zero Pollution Action Plan' (Art. 8). Together with Switzerland, which was the first to introduce a mandatory fourth purification stage, the EU would play a pioneering role worldwide.

2.4.2.4
Water Reuse Regulation

The regulation on minimum requirements for water reuse (Regulation (EU) 2020/741, OJ L 177, 5.6.2020, pp. 32–55) aims to recycle water. It lays down minimum requirements for water quality and monitoring for all EU member states, as well as risk-management rules for the safe use of treated water for agricultural irrigation as part of integrated water management. It is thus responding to regional phases of water scarcity, which are becoming more acute as climate change progresses. The regulation has been in force since 26 June 2023. As part of risk management (Art. 5), the operators of treatment plants are obliged to draw up risk-management plans for water reuse, which require authorization by the member state authorities. The plant operators determine and assess the risks involved in reuse and determine suitable precautionary measures. Although the Water Reuse Regulation is to be welcomed in principle, further specification is required in order for it to be applicable in the member states. For example, minimum requirements and risk management must be regulated in part by the member states (e.g. the drafting by the technical regulations DWA M-1200) and in part by the Commission in delegated legal acts. With regard to the minimum requirements, the member states have a great deal of room for interpretation when specifying the requirements for reprocessing, monitoring and risk management. This carries the risk that the member states' standards will vary widely and could ultimately lead to enforcement deficits (UBA, 2023a).

2.4.3
Self-organized water governance

Particularly in the context of natural resource governance issues, it is essential to understand both state governance (top-down) and practices that are actually in use at the local level (bottom-up), even if this binarity represents a simplification (Greif, 2006; Mielke et al., 2011; Hodgson, 2006). While state governance is usually the focus of political debates and social-science research, everyday practices and informal structures receive comparatively little attention, although they play a key role in implementation. The effects of everyday practices and informality on water governance are ambivalent (Sengupta, 1980; Bardhan, 2004; Bjornlund, 2004). While experience, knowledge and self-organization exist at different levels of water governance, depending on the context they can complement state governance, e.g. in traditional, self-organized irrigation systems, or work against or conflict with it, e.g. in the case of water theft (Helmke and Levitsky, 2004). One risk of self-organized, informal governance is that parallel power structures can undermine state water management and possibly discriminate against minorities. In Jordan, for example, the informal norm of 'wasta', the preferential treatment of one's own clan members, often makes it impossible to collect water-abstraction charges (Oberhauser et al., 2023). However, informal rules can often be more effective for water use or coordination when setting rules than government rules (Bardhan, 2004: 27). For example, traditional systems can sometimes guarantee a more sustainable water supply than formal water management by preserving traditional cultivation techniques and thus also ecosystem services. One example of this is the cultivation of oases in North Africa (Santoro, 2023; Mustapha, 2016). Secondly, everyday practices can be applied outside the legal framework. Particularly in societies with weak or inadequate state institutions, for example in water management, informal, neighbourly or historically evolved and used institutions often take over water-management tasks (Bardhan, 2004: 27; Balasubramanya and Buisson, 2022). Finally, informal institutions, such as neighbourhood-based organizations, are repeatedly recruited and promoted by state institutions, for example in dealing with extreme weather events, water scarcity or other water-related challenges (Bjornlund, 2004).

The water mismanagement that can be observed in many places is based on a strict separation of state-regulated and self-organized water management. The official, formal policies do not work if they do not consider, address and integrate water-management practices that are already in use. As a study on an approach to participatory groundwater management in Morocco shows, this did not lead to the desired results due to the exclusion

Box 2.2-3

Participatory governance and intermediary structures in the implementation of the EU Water Framework Directive: examples from Sweden and Germany

The interplay between a proactive state and local structures is a key element in the implementation of the EU Water Framework Directive. In addition to its environmental objectives of achieving good ecological and chemical status in all EU water bodies, it also requires member states to actively involve affected and interested actors ('stakeholders') at the local level. To this end, there is a formalized three-stage process, the procedures and criteria of which are defined for members, as well as an informal process, the implementation of which is characterized by discretionary powers with regard to the format and the actors involved (Art. 14). Experience to date has shown that participation and 'intermediary organizations', e.g. networks and partnerships, have the potential to promote local knowledge and understanding (Moss, 2009).

One example of such an interface in the context of the EU Water Framework Directive are the local water boards in Sweden. They have promoted dialogue within a water district, been involved in gathering local knowledge, and provided a forum for discussions about current and future water use (Söderberg, 2016). The 125 local water authorities have incorporated the real-life practice and experience-based knowledge of actors, such as members of the Indigenous Sami people in northern Scandinavia, but also of established interest groups such as the fisheries organization and municipalities. In various case analyses of the EU Water Framework Directive, researchers found that the involvement of affected and interested actors led to the process being dominated by interests that were already well-organized. For example, the fishing organizations had more influence than the Sami representatives (Söderberg, 2016). A survey of water authorities in the six largest EU countries (France, Germany, Italy, Poland, Spain and the UK) on the implementation of the EU Water Framework Directive and participation revealed that state authorities, agriculture and environmental-protection organizations were the most strongly represented. The influence of agriculture and industry was perceived as too strong, particularly in France and Germany (Rimmert et al., 2020). In Germany, the implementation of the EU Water Framework Directive has also established participation structures and triggered participation and learning processes. One example at the local level involved three interactive workshops motivated by the EU Water Framework Directive. State and non-state actors came together here to discuss the discharge from a dam. The study concluded that an effective participation process needs both a formal framework and flexibility in its organization to accelerate experimentation and learning. It should also be an integral part of management structures, so that the results of the process can have an influence on future management decisions (Moellenkamp et al., 2010).

The management and monitoring of current water quality and quantity is key to the implementation of the EU Water Framework Directive. An example from Lower Franconia shows that even in many places in Germany, however, no record is kept of how much water is abstracted each time, as abstraction by agriculture or private wells is often based on the principle of personal responsibility. This indicates that even in highly formalized institutional contexts, water abstractions are handled with varying degrees of flexibility from case to case (Kohler et al., 2023).

of informal structures and power relations (Houdret and Heinz, 2022). One of the factors for the difficulties in implementing Integrated Water Resources Management (IWRM) in South Africa is the lack of consideration of the role of traditional structures in water governance (Dombrowsky et al., 2022b; Stuart-Hill et al., 2020; Lukat et al., 2022). The example of India illustrates that the implementation of the Water-Energy-Food (WEF) Nexus is made more difficult when sectoral policies on water, energy and agriculture, as well as different laws at the federal and state level, sometimes conflict with informal norms (Beisheim, 2013: 56). As an element of an analytical framework for the WEF(E) Nexus, consideration of both formal and informal institutions is recommended (Srigiri and Dombrowsky, 2021: 56). New Delhi, for example, has a highly fragmented water infrastructure with little public infrastructure reach, making unplanned, informal infrastructure the norm, e.g. in water supply and sanitation. However, these supposed boundaries between state and society are not perceived as such by the people living in informal settlements. Here, infrastructure is rather the result of a hybrid form of infrastructural power (Truelove, 2021), i.e. there is a dynamic, everyday interplay between state and self-organized forms of (discursive) water-infrastructure governance.

As an important component of adaptive water-resource management, social learning encompasses not only formal but also informal structures in which different actors work together. Formal and informal institutions can be both effective and ineffective for adapting water-resource management (Pahl-Wostl et al., 2007).

As a result of strong state control and regulation of the public water supply, informal practices play a less important role in high-income countries than in countries in South Asia, Latin America and Africa. Although it is important to emphasize that water governance in middle- and low-income countries is mostly informal, this does not mean that there are no such practices in place in high-income countries.

2.4.4 Water governance at its limits

Water scarcity caused by overuse, the effects of climate change and water pollution are key challenges of the 21st century. They are already causing conflicts, migration and displacement, but they also offer opportunities for multilateral cooperation. The political and legal response to this has so far mostly taken the form of national or regional water management, which is highly diversified in terms of content, and whose implementation is often characterized by fragmented responsibilities. Water governance is becoming increasingly important at the global level, as the 2023, 2026 and 2028 UN Water Conferences show – yet the long-term development of these important processes is still uncertain (Section 8.1). Water also plays an important role in related policy areas, such as climate and biodiversity governance. However, the growing amount of work involved in coordination and the need to identify synergies at the interfaces are a challenge.

The current management regime at the state level is aimed at controlling separate sectors such as industry, agriculture, households and water supply and disposal.

A transboundary, climate-resilient form of water management that takes a systemic view of all water bodies and simultaneously aims to improve the quality, quantity and equitable distribution of water is largely lacking. Although good approaches exist (IWRM, EU Water Framework Directive, Zero Pollution), effective implementation is lacking. Three elements are particularly promising for making implementation more effective in the future: coordination, inclusion and adaptability (GWP, 1996).

2.4.4.1 Coordination

Close coordination across sectors and governance levels, as well as coordination with climate and biodiversity governance, are crucial. Recent water-governance research shows that this is more likely to succeed if hierarchical, market-based and network-based governance approaches and coordination mechanisms are applied simultaneously, and if sufficient consideration is given to forms of self-organized governance in addition to state governance (Lukat et al., 2023). Coordination across control levels in vertically hierarchical and centralized systems takes a different form than in decentralized, polycentric systems (Pahl-Wostl and Knieper, 2023). Internationally coordinated governance could develop along supply chains (virtual water; spillover). Water scarcity and pollution along supply chains have hardly been addressed to date, if at all. Novel, selective instruments – such as producer responsibility and liability, as contained in the reformed EU Urban Waste Water Directive – or approaches to water reuse (EU Reuse Regulation) have been partially enshrined in law, but their effectiveness has not yet been sufficiently researched.

2.4.4.2 Inclusion

Inclusion ranges from purely informative involvement to tough negotiations between the different interests of environmental organizations and economic actors. Water management is characterized to a large extent by an interplay between state and self-organized governance. The latter refers to everyday, often informal, neighbourhood-organized water-management practices, for example in smallholder farming contexts. Integrated water-resource management therefore always requires operationalization at the regional, national or local levels, as well as the further development of the regulatory framework, in order to promote this multi-level integration (Ibisch et al., 2016a). This requires enabling institutions and traditions of participatory management, technical infrastructures and water-management levels that allow water to be managed according to local needs and with a high level of trust from water users in the system with regard to future water availability (Hornidge et al., 2011). The political economy of inclusion and its 'winners' and 'losers' are decisive for the design of the different water-management approaches. Competing interests should therefore be made transparent and comprehensible for all user groups in the interest of a model for sustainable and socially balanced water management that is fit for the future.

2.4.4.3 Adaptability

Finally, there is also a lack of adaptive and long-term management of water resources. It is therefore not surprising that water emergencies (Chapter 4) have hardly been addressed preventively to date. The adaptability and agility of the systems in dealing with climate and environmental change-related emergencies with regard to (sudden) water surpluses and shortages depend on the quality of the technological infrastructures, personnel capacities, communication systems and awareness-raising in the societies themselves. Lock-ins and path dependencies make adaptation more difficult, as they limit flexibility in planning and decision-making processes (Box 2.4-4). To date, there has been a lack of structures to scientifically inform water-governance processes at the global, regional and local levels and to continuously monitor them empirically.

Overall, current water governance is too fragmented, not socially balanced and not adequately prepared for future water emergencies due to a lack of adaptive and long-term management.

2.5 Investment requirements and financing challenges

In both high-income and low-income countries, there is a massive funding gap in the provision and maintenance of water infrastructure. Based on a wide range of cost estimates for water-related infrastructure (WWC and OECD, 2015), the World Bank estimates the global financing gap at US$6,700 billion by 2030 and US$22,600 billion

Box 2.4-4

Water-related path dependencies and lock-in

The term path dependencies is used where – for various reasons – stipulations, experience or events in the past influence today's decisions and decision-making options. A lock-in represents an entrenchment of historical structures that slows down or impedes change (Goldstein et al., 2023; Helmrich et al., 2023; Unruh, 2000). This can have technological, infrastructural, institutional or behavioural reasons and have a positive or negative impact on the way water is handled and on water governance. Infrastructural lock-ins result, for example, from falling average costs due to increasing economies of scale of capital-intensive water infrastructure (Seto et al., 2016; Section 2.5.1). Institutional lock-ins can arise from entrenched governance structures (Pierson, 2000; Seijger et al., 2017). An institutional lock-in at the global level results, for example, from the considerable fragmentation of water governance. In addition, there are discursive lock-ins, such as the prioritization of efficiency over equity in water-policy arguments (Boelens and Vos, 2012; GCEW, 2023b; Meehan et al., 2023).

However, behavioural path dependencies and lock-ins, which have their roots in social structures or norms, also have a considerable influence on water governance and its results (GCEW, 2023b; Nhim and Richter, 2022). Behavioural effects such as familiarization, routines and risk avoidance can lead to planning and governance processes being stuck in previous ways of thinking and failing to meet new challenges (Simoens et al., 2022).

However, path dependencies can also be positive. For example, experience in dealing with water, such as that of Indigenous communities, can give rise to path dependencies in a positive sense. Many indigenous peoples, such as the Anishinaabek in Canada, have a spiritual relationship with water, and moral principles that guide their actions and are orientated towards the well-being of people and water (Taylor et al., 2019). However, instead of seeing the inclusion of these different forms of knowledge as an opportunity to reflect on and further develop existing behaviour, influential water-governance actors (OECD, UN, World Bank) often do not sufficiently understand or incorporate them, which reinforces inequalities and increases the risks of mismanagement (GCEW, 2023b). Incorporating this experience-based knowledge could make a significant contribution to improving the quality of water management and managing risks better in the future (GCEW, 2023b). Positive path dependencies can also result from collectively developed rules for water management (Abarzúa and Glückler, 2023; Ostrom and Gardner, 1993).

From the experts' perspective, entrenched thought patterns that imply that solutions to water problems should be as centralized and large-scale as possible often have a negative effect (Gerten, 2018). Behaviour-based path dependencies also result from resistance to change when influential actors profit from established systems, defend their own interests and thus also prevent socially beneficial change.

by 2050 (Khemka et al., 2023). In order to achieve the SDG targets in the area of WASH alone, the 140 countries analysed by the World Bank will lack an estimated US$114 billion or 0.39 % of these countries' GDP in the period 2017–2030 (Hutton and Varughese, 2016).

Pricing instruments can make an important contribution to financing the infrastructure for drinking-water supply and wastewater disposal, and to meeting local water needs by generating revenue and redistributing costs (Grafton et al., 2023). However, in many countries the price of water bears little relation to water's value (UN Water, 2021). Water prices and consumer costs usually do not adequately reflect real scarcity conditions, externalized costs from environmental and ecosystem damage or the costs of provision (Grafton et al., 2023; Damania, 2020).

2.5.1
Water infrastructure investment

Investment in water infrastructure is key to ensuring a stable and sustainable water supply. Measures to be financed affect all stages of the use cycle (supply, provision, distribution, treatment). These include measures for the conservation of surface waters, the construction and operation of storage and transport infrastructure (e.g. reservoirs, pipelines, canals), sanitation, wastewater collection and treatment, connections to households and agricultural consumers, flood protection and drainage measures on sealed surfaces (OECD, 2022a).

The centralized drinking-water-supply and wastewater-disposal solutions favoured for many generations have tied up considerable financial resources in many countries due to long planning and amortization periods (BMUB, 2017). Due to uncertain planning conditions and maintenance work that has not yet been carried out, there is a considerable investment backlog in these sectors, which is increasingly causing technical failures and putting a growing burden on the environment (EIB, 2023a). However, where the boundary conditions for planning are shifting because of population growth, demographic changes and the effects of climate change, there is resistance to moving away from previous problem-solving approaches, which means that resource-intensive infrastructure solutions continue to be favoured (Box 2.4-4).

To date, water-related infrastructure has mainly been financed from public funds or via user charges or fees, as well as by international financial institutions. However, the water sector accounted for less than 2 % of total public spending between 2009 and 2020. This only covers a fraction of the financing requirements in some regions. In sub-Saharan Africa, for example, expenditure of over 4 % of GDP would be necessary between 2017 and 2030 to achieve access to clean water and sanitation for all (Khemka et al., 2023).

Private capital can help close the financing gaps in the water sector (Khemka et al., 2023; OECD, 2022a). However, greater involvement by the private sector is often viewed sceptically (Khemka et al., 2023). This is due to examples from the past in which the complete outsourcing of public services to the private sector had negative social and ecological consequences (Heller et al., 2023; Bayliss, 2014). With the privatization of public companies, especially in Anglo-Saxon countries in the 1980s, some governments hoped to build and finance a reliable water infrastructure at a lower cost. However, experience has shown that the privatization of the water supply has in some cases led to high levels of debt for the companies concerned and high consumer costs (Thames Water, UK; Laville et al., 2023). Nevertheless, a World Bank study also cites examples of successful participation by private actors (Khemka et al., 2023: 57 ff.), e.g. the Guerdane irrigation project in Morocco, in which a consortium built irrigation infrastructure for lemon farms on the basis of a thirty-year concession, co-financed and operated it for the duration of the concession.

However, the water sector is not very attractive for private investors. One reason for this is low and unstable yields, partly due to the inadequate pricing of the value of water (Section 2.5.2) and benefits that are difficult to quantify and monetize, e.g. in connection with nature-based solutions (Khemka et al., 2023; OECD, 2022a; Sections 6.1, 8.3.2). Furthermore, private companies still do not take enough account of the risks of water shortages or water-related extreme events such as flooding for their own areas of business; as a result, they underestimate the benefits of investing themselves in the conservation and sustainable use of water resources (Section 8.3.1).

In addition to low and unstable yields, the incentives for private investment are reduced by the need for high initial investments, combined with long repayment periods for traditional water infrastructure, the low creditworthiness of its operators, and the absence of a favourable political, institutional and legal framework (Khemka et al., 2023; OECD, 2022a).

There are also other reasons why investors and projects find it difficult to come together (OECD, 2022a; Section 8.3.3). Many water-related projects are implemented at a local level and are small and context-specific, while investors favour larger projects due to the lower transaction costs. Investors also often lack knowledge about the water sector and the methods and data for assessing risks and evaluating projects, while actors in the water sector have difficulties developing projects that satisfy investors' requirements.

In addition to the funding gap for the provision and maintenance of water infrastructure, another problem in many countries is the inefficient use of existing financial resources (Khemka et al., 2023; UNEP, 2021b). These do not necessarily reach the projects that offer the greatest benefits (Laubenstein et al., 2023). The lack of efficiency can have various causes, e.g. a lack of coordination between actors, a lack of transparency, inadequate accounting, or corruption (UNEP, 2021). As an example, Laubenstein et al. (2023) cite misguided subsidies in the water- and wastewater-supply sector (Andres et al., 2019; UNESCO, 2021). Technical, institutional or social path dependencies can also hinder the efficient use of existing resources.

The underfunding of water infrastructure has negative health consequences for society because of poor drinking water quality, lack of access to sanitary facilities and inadequate wastewater disposal (Section 2.3.4). Water scarcity and water-related extreme events also jeopardize growth and development, particularly in low- and middle-income countries (Section 3.2.1.3). A change of direction is therefore urgently required (Section 8.3).

2.5.2
Water prices and control instruments

Pricing instruments such as water-abstraction fees and drinking-water or wastewater charges are the backbone of water management in most countries around the world. Water prices that do not reflect the value of water or take externalized costs into account (e.g. due to ecosystem damage as a result of overuse) encourage high consumption and inefficient forms of use (Das et al., 2022) and threaten the financing of essential infrastructure. The price that consumers pay for water or water-intensive goods is determined by several factors, including the costs of extracting and treating water, operating distribution networks and connections, price elements such as taxes, fees and contributions, and the willingness of private actors to pay. In the EU, according to the Water Framework Directive (Section 2.4.2.2), water tariffs must cover the costs of providing and operating the necessary infrastructure and be sustainable with regard to the consideration of externalized costs (e.g. environmental impacts). The aim is to create incentives for the efficient use of water resources. Cost coverage should also include environmental and resource-related costs (Berbel and Expósito, 2020).

In many EU countries, as well as in numerous low- and high-income countries worldwide, such cost coverage has not yet been achieved. It is particularly low for the operation of irrigation infrastructure in agriculture. According to the OECD (2022a), only nine out of 39 countries achieve full cost coverage for both the capital costs and the operation and maintenance of irrigation.

Obstacles to the implementation of higher prices include political and economic barriers (e.g. resistance from influential industries, corruption), institutional hurdles (e.g. allocation of water rights), administrative obstacles (e.g. resources of authorities, monitoring and legal enforcement), technical and methodological problems (e.g. lack of metering for abstractions, unclear recording of non-monetary costs and uses) or social considerations (e.g. burden on low-income households or businesses in the absence of compensation and adaptation measures).

For example, appropriate pricing of water is made more difficult not least by the fact that it can lead to unwanted price increases (e.g. for food) or to structural changes that could jeopardize the livelihoods of those affected, and thus have not only economic but also societal consequences. It can be observed that the productivity of, and value added from, the use of water varies greatly across different economic sectors and regions. According to UN Water (2021), the productivity of water use measured by income in 2019 was US$3 per m^3 in low-income agricultural countries, for example, but over US$50 in service-based economies. If these differences are due to variations in the productivity of water use (e.g. due to outdated technologies), higher pricing can reduce the competitiveness of affected businesses and jeopardize their existence. The discussion about pricing water use must therefore always be integrated into a discussion about mitigating the associated hardships, rather than simply dispensing with water pricing altogether (Section 8.3.2).

In many countries, however, there are exceptions or cuts in the regular tariffs for certain economic uses, which reduce incentives to save water. Agriculture especially should be mentioned here, which is only charged for water abstraction in 44 % of the countries analysed in a study by the OECD (2021). In Germany, energy production, manufacturing, mining and agriculture account for almost 80 % of water abstraction. Nevertheless, in some cases low or zero charges apply to these sectors. It is up to the federal states to lay down the fees. Bavaria, Hesse and Thuringia generally do not levy any abstraction charges. Where they are levied, their level varies greatly (0.5–31 ct per m^3; BUND, 2019).

Institutional and technical requirements also pose challenges for enforcing higher prices, particularly in low- and middle-income countries. According to a World Bank survey, households in Uzbekistan that were not connected to the water mains were willing to pay twice the existing tariffs for a secure and good-quality water supply. However, such a supply can often not yet be guaranteed. A lack of technological equipment also makes a price reform difficult. For example, Uzbekistan does not have a nationwide metering system for household water consumption (World Bank, 2016b). In Germany, a fact that water abstraction in agriculture is often not recorded is an obstacle to enforcing abstraction charges (Sections 6.3, 8.3).

In addition to their financing function, water prices have a steering function in many countries in order to promote economical behaviour by consumers, limit negative environmental impacts and finance water-protection measures. This applies to high-income countries, e.g. in the EU, but also to low-income countries, e.g. Tajikistan, which introduced a fee for electricity-producing companies in the hydropower sector in 2009 to tax returns from the use of natural resources (OECD, 2018).

By linking production and water consumption in water-intensive sectors of the economy, such as agriculture and parts of the energy sector, selective incentives to save water charges can be undermined by measures to promote production, for example by subsidies in the energy sector. Following an increase in water-abstraction fees in the energy and industrial sectors of Bulgaria in 2012, consumption fell in some sectors, but at the same time abstraction for thermal cooling and hydropower use rose as a result of subsidies for electricity production (Sharkov, 2022). The GCEW (2023a) estimates the amount of subsidies that run counter to a reduction in water consumption at US$700 billion globally.

Price-effective instruments are supplemented by regulatory measures in the water sector, especially to maintain water quality. For example, most industrialized countries stipulate the conditions under which grey water may be returned to the cycle (OECD, 2021). Wastewater charges on the discharged volume or pollutant load provide additional incentives to minimize material pollution and enable reuse, e.g. for irrigation purposes.

Regulatory measures are also needed to compensate for the limited effectiveness of price-orientated instruments, for example to limit consumption or pollution levels. In times of severe shortages, restrictions on use for certain purposes have been imposed in France and Japan in the past in order to secure the basic needs of other consumers, e.g. bans on washing cars, watering gardens or filling private swimming pools (OECD, 2021).

To ensure the cost-effective and sustainable use of water resources in the long term, some countries and regions are focusing on limiting consumption locally and establishing water markets in which private actors such as farmers can trade water-abstraction rights, similar to European emissions trading. Experience from Australia's Murray-Darling Basin shows that water markets have the potential to increase the efficiency of water use, secure funding for the necessary infrastructure, and limit consumption in line with ecosystem needs (e.g. Wheeler et al., 2020). In view of the high institutional, legal and technical requirements, however, the introduction of water markets is difficult for many countries (Meran et al., 2021b; Section 5.1.1).

Exacerbated water-related challenges in the future

3

Advancing climate change is causing extreme events of an intensity and frequency that have never been experienced before. Warming, droughts and rising pollution result in reduced water availability and poorer water quality. Along with increased water use this leads to societies and ecosystems reaching the limits of adaptability. In addition, poverty, social inequalities, geopolitical tensions and autocratization are weakening the resilience of societies. This reflects the limits of controllability and the urgency of climate-resilient water management.

Today there is already either too much or too little water, or it is too polluted; inequalities in the distribution of water are also on the increase (Chapter 2). Humankind, ecosystems and the planet are moving towards a future in which the quantities and quality of water available to humans and nature are subject to increasing change. This chapter is devoted to the exacerbated challenges of the global water situation that humans and nature will have to reckon with in the future.

The WBGU uses the term 'exacerbated challenges' to describe regional or global developments in water availability and distribution, extreme events and water quality that significantly worsen water-related problems. Drivers of the exacerbated challenges can be, for example, climate change, land-use changes and ecosystem degradation, pollution and increasing pressure on water resources from human use, or imbalances that are difficult to control due to geopolitical destabilization. Depending on regional contexts, exacerbated challenges can lead to water emergencies, which are becoming increasingly common worldwide (planetary dimension; Chapter 4), and even to situations in which the limits of controllability are exceeded (Chapter 5). In this sense, water is the common 'currency' of many global developments and the mutually reinforcing environmental and health crises (Fig. 3-1; Section 3.4).

Progressive warming is driving global and regional changes in precipitation and evaporation, shifting the balance from frozen to liquid water, increasing the water content in the atmosphere and leading to an increase in extreme events such as floods and droughts (Section 3.1.1). Infrastructures are not prepared for these changes (Section 3.1.2). Water quality, too, will continue to decline in the future if the discharge of inadequately treated wastewater – currently about 80 % of the world's wastewater – and with it pathogens, persistent chemicals, nutrients and solid waste continues. As a result, groundwater, many bodies of freshwater, coastal zones and seas are becoming dead zones uninhabitable for animals and plants due to toxic blooms and a lack of oxygen; the self-purifying power of the waters is being lost (Section 3.1.3). In future, unless effective actions are taken, water use – and thus the risk of overuse – will continue to rise, depending on the region. Global geopolitical and societal developments are likely to exacerbate the situation (Section 3.2). These interacting exacerbated challenges cause direct strains on the health of nature and humans (Section 3.3).

3.1
Exacerbated challenges as a result of climate change and pollution

Climate change and water pollution will continue to increase in the future and, without effective countermeasures, will significantly jeopardize an adequate supply of drinkable water for nature and humans.

Mekong Delta (Vietnam)

3.1.1 Advancing impacts of climate change on the global hydrological cycle

Climate change has already been leading to changes in the global hydrological cycle since the middle of the 20th century (Section 2.2). Depending on whether and to what extent the global community succeeds in implementing the goals to limit climate change agreed in Paris in 2015, these changes will continue to intensify and manifest themselves in every region (IPCC, 2023b).

3.1.1.1 Changing precipitation patterns and quantities

Global average precipitation is rising; every 1 °C added to global warming increases average precipitation worldwide by 1–3 %, whereby the extent and direction of the changes – and therefore their effects – vary greatly from one region to another. The amount of precipitation could increase by up to 13 % by the end of the century compared to the period 1995–2014 (IPCC, 2021a: 19). Projections of regional changes in precipitation quantities depend on the extent of future global warming (Figs. 3.1-1, 3.1-2) and vary as a result of uncertainties that can be considerable (Caretta et al., 2022: 598).

In its Sixth Assessment Report, the Intergovernmental Panel on Climate Change states that an increase in the average amount of precipitation per year is to be expected, particularly for the Ethiopian highlands, East, South and North Asia, southeastern South America, northern Europe, parts of North America and the polar regions (Douville et al., 2021: 1110; IPCC, 2023b). By way of contrast, a decline can be expected for southern Africa, West Africa, Amazonia, southwest Australia, Central America, parts of South America and the Mediterranean region. In the Arctic, snowfall will decrease further in the future and be increasingly replaced by rain (Douville et al., 2021: 1110). The changing precipitation patterns and quantities will continue to lead to more frequent and more intense extreme events such as heavy rainfall or droughts in the future (Section 3.1.1.5; IPCC, 2019b: 9 f.).

3.1.1.2 Decreasing soil moisture in many regions

For the future, forecasts expect a further increase in mean global evaporation over large parts of the ocean and an increase in global atmospheric water uptake, combined with potentially increased evaporation and loss of water from the Earth's surface. This will result in an increase in evapotranspiration, i.e. the sum of direct evaporation from soil and water surfaces (evaporation) and water release by plants and animals (transpiration), in most land areas – except in those regions that are already very dry (Douville et al., 2021: 1058, 1117). Due

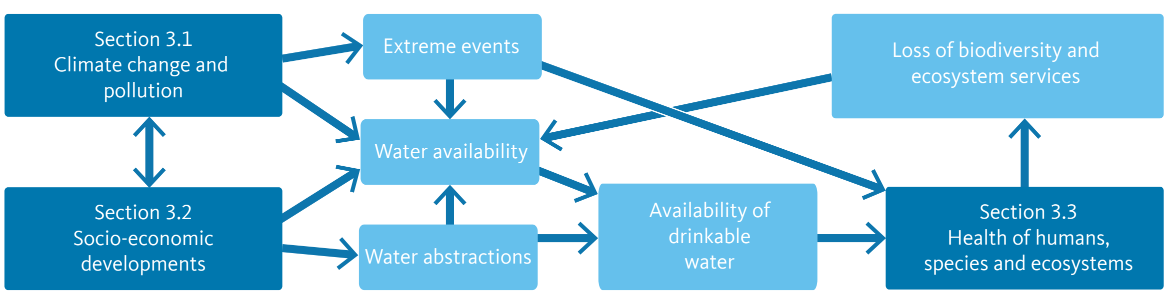


Figure 3-1
Causes and mechanisms of exacerbated water-related challenges. Climate change is altering the global hydrological cycle, resulting in an increase in extreme events such as droughts and floods. Some regions of the world are increasingly affected by pollution. Both can influence the water availability. At the same time, water abstraction is increasing worldwide due to the growing demand from agriculture, industry and households. As a result, the pressure on the availability of drinkable water is growing. Water-related problems are being exacerbated, for example through damage to human health and its socio-economic impacts, competition for land use or increasing damage caused by extreme weather events, such as the destruction of settlements and infrastructure, crop failures or biodiversity losses due to adverse health effects on species and ecosystems. The resulting loss of ecosystem services can in turn have a negative impact on the water supply.
Source: WBGU

to additional falls in precipitation, soil moisture in regions such as the Mediterranean, South Africa and the Amazon basin, as well as in parts of North and South America and Australia, will most likely decrease further, while it will increase in other regions (Fig. 3.1-3; Douville et al., 2021: 1121 f.; IPCC, 2023b).

The change in soil moisture will increase with every degree of warming. Global warming of 4 °C could reduce soil moisture by up to 40 % in some regions such as the Amazon, southern Africa and western Europe (Caretta et al., 2022: 601). Together with the significant influences of land-use changes on hydrological processes such as evapotranspiration and soil moisture (Zhang and Schilling, 2006), this will have an impact on precipitation, groundwater recharge, ecosystem properties and functions, as well as on agriculture and forestry via the decrease in green water (Section 3.2). In other regions, however, an increase in soil moisture is also expected (Fig. 3.1-3).

3.1.1.3 Fall in global freshwater reservoirs: groundwater and cryosphere

The amount of freshwater stored as groundwater has already decreased globally, largely due to irrigation measures (Section 2.2.3.1; Caretta et al., 2022). Our understanding of the effects of advancing climate change on groundwater is still limited due to restrictions in data collection (Caretta et al., 2022). However, groundwater abstraction, e.g. for irrigation, will increase as a result of climate change and is expected to deplete the non-renewable

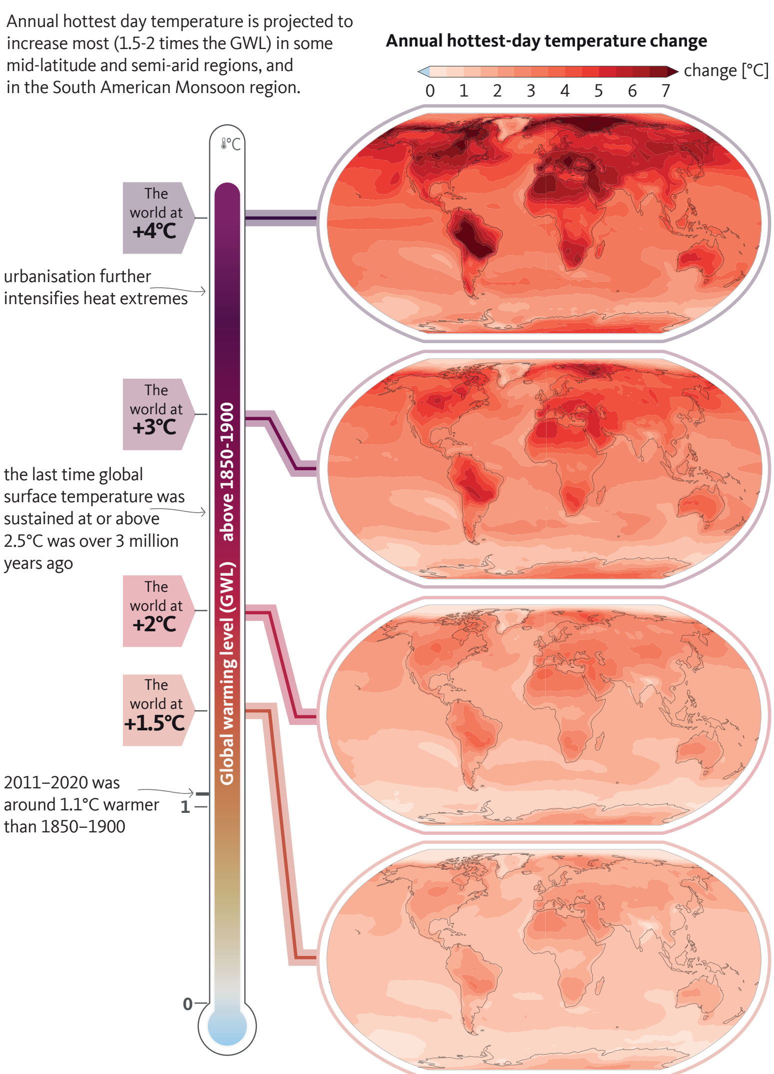


Figure 3.1-1
Changes in temperature on the hottest day of the year. The diagram shows the projected changes in the annual daily maximum temperature if global warming reaches 1.5 °C, 2 °C, 3 °C or 4 °C compared to 1850–1900.
Source: modified according to IPCC, 2023a

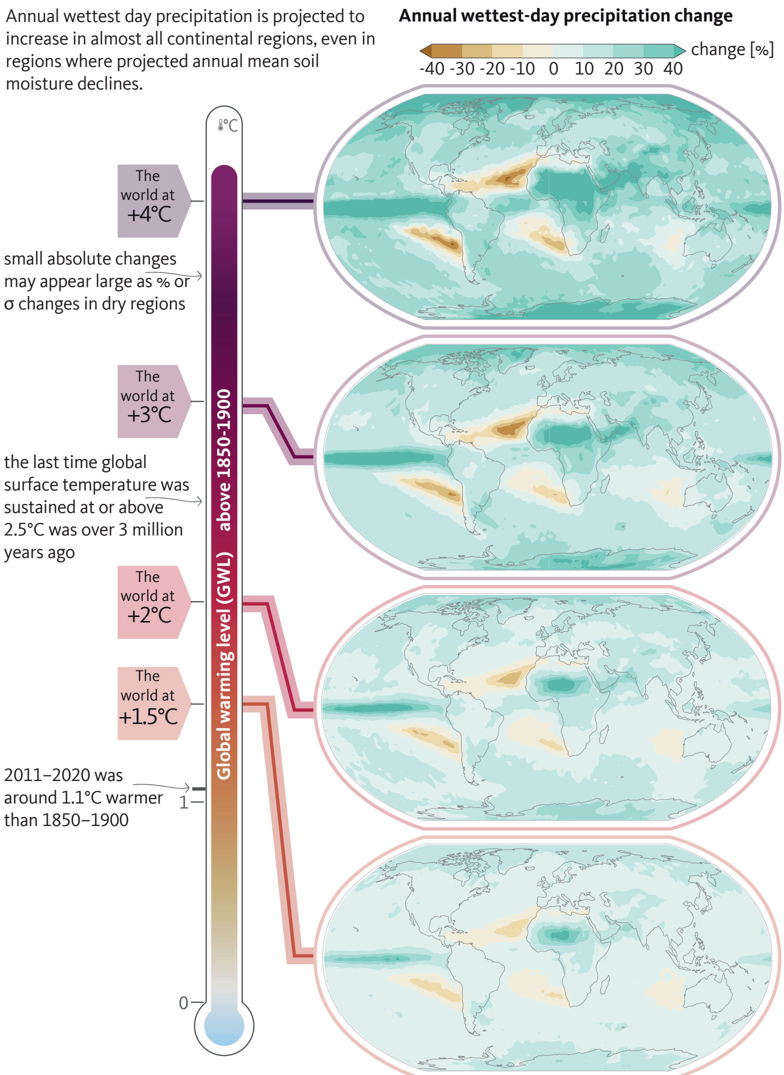


Figure 3.1-2
Changes in precipitation on the rainiest day of the year. The diagram shows projected changes in annual maximum daily precipitation if global warming reaches 1.5 °C, 2 °C, 3 °C or 4 °C compared to 1850–1900.
Source: modified according to IPCC, 2023a

groundwater resources worldwide (Caretta et al., 2022: 611). Aquifers in the tropics and semi-arid regions will be episodically replenished by the expected increase in (intense) precipitation in the future, which could boost their resilience. In semi-arid regions, however, there is a risk that replenishment will be cancelled out by excessive abstraction (Caretta et al., 2022: 611). An increasing loss of groundwater can intensify hydrological droughts, cause groundwater salinization and damage groundwater-dependent ecosystems such as forests (Section 4.6; Caretta et al., 2022). Other consequences include wells running dry, a loss of vegetation, reduced biodiversity and the infiltration of wastewater into aquifers (Liu et al., 2022; Huggins et al., 2022). However, one of the most serious impacts of permanent groundwater abstraction is a lowering of the land surface (ground subsidence). Increasingly vulnerable are areas in which human intervention, natural runoff and low recharge over a long period of time lead to water-storage losses and a compaction of vulnerable aquifer systems. Potential subsidence areas include densely populated and irrigated areas with high groundwater stress i.a. in Asia (e.g. in the North China Plain) and North America (e.g. in the coastal plain of the Gulf of Mexico), in coastal and river delta areas (e.g. in Vietnam, Egypt or the Netherlands) and in inland sediment basins, e.g. in Mexico, Iran and Mediterranean countries (Herrera-Garcia et al., 2021). Ground subsidence leads to earth cracks, which can cause extensive, direct damage to buildings and infrastructure in urban and densely populated regions, and can also increase

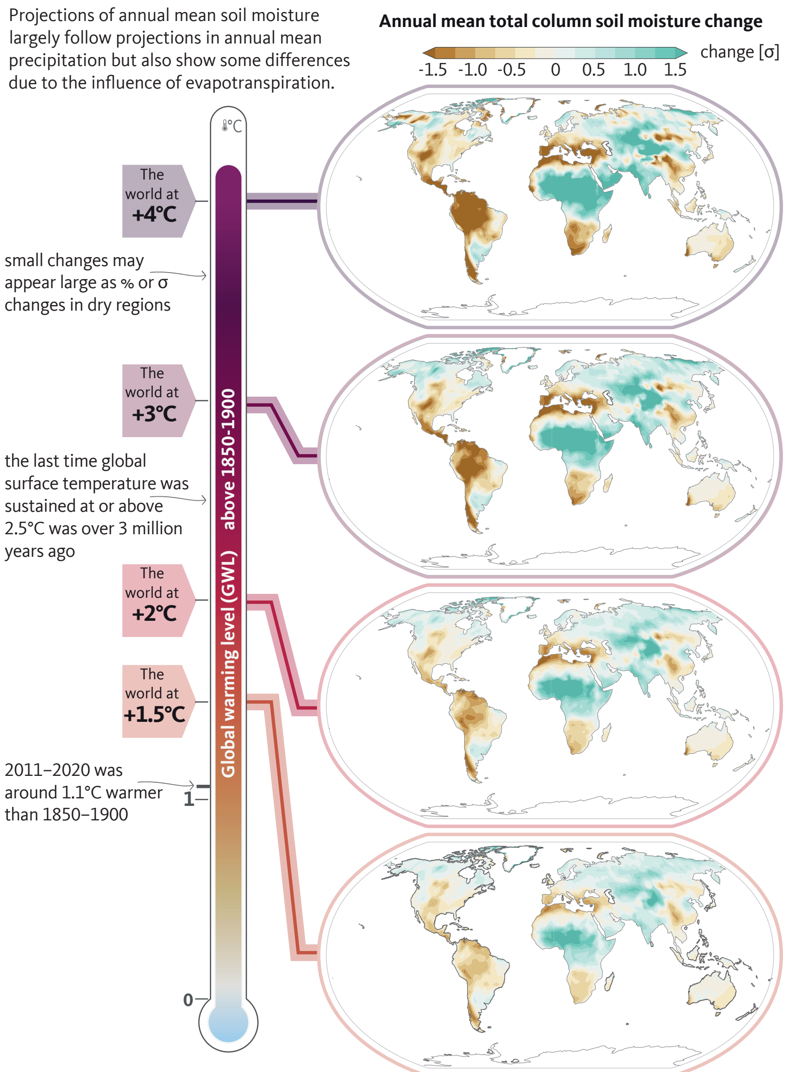


Figure 3.1-3
Changes in annual mean soil moisture. The diagram shows projected changes in the annually averaged soil moisture over the entire soil column if global warming reaches 1.5 °C, 2 °C, 3 °C or 4 °C compared to 1850–1900.
Source: modified according to IPCC, 2023a

the risk of flooding from watercourses or precipitation in inland areas (Herrera-Garcia et al., 2021). According to Herrera-Garcia et al. (2021), approx. 2.2 million km^2 or 1.6 % of the world's land area, around 19 % of the world's population and about 12 % of global GDP are affected by potential subsidence worldwide. While the largest share of economic losses is borne by high-income countries, the majority of the exposed population is to be found in low-income countries.

The melting of the cryosphere – ice sheets, glaciers and snow cover – due to global warming will continue. In the course of the 21st century, an increasing loss of global glacier mass is to be expected, accompanied by a declining area and mass of snow cover (IPCC, 2021c: 134). The global declines in glacier mass for the period between 2015 and 2100 are projected to be between 22 % and 44 % (RCP2.6) and between 37 % and 57 % (RCP8.5; Hock et al., 2019), although these changes as a result of climate change vary greatly from region to region. Increased glacier melting and changes in the extent, quantity and seasonality of snow cover will lead, at least temporarily, to changes in the associated snow- and glacier-fed rivers, including river flooding (IPCC, 2019a: 134; Caretta et al., 2022: 556). While the total runoff volumes will initially increase as a result of glacial melting, the proportion of glacier meltwater will decrease after reaching the so-called 'peak water' (i.e. the time of maximum total annual runoff of a glacier) until the glacier has completely melted. Particularly in warm and dry phases, this development can increasingly contribute to water shortages in glacier-fed river basins (Fig. 3.1-4). Globally, the timing of peak water varies, depending on the region and the size of the glaciers, but is expected by the middle or end of the 21st century at the latest (Hock et al., 2019). These changes will have far-reaching direct and indirect consequences for the ecological and human communities served by these river systems. However, the expected effects of glacier melt on the total runoff in the catchment area are highly (regionally) variable and influenced by precipitation runoff, groundwater runoff and snowmelt, among other things (Nie et al., 2021; Section 3.1.1.4). Added to this is the progressive loss of ice cover on lakes and rivers and a reduced duration of ice cover, leading to an increasing number of years in which year-round or seasonal ice cover is completely absent. Globally, the ice cover of rivers has already fallen by 25 % (1984–2018; Parmesan et al., 2022).

Global warming will also lead to further losses in the volume and extent of permafrost: for every 1 °C of global air temperature change, the volume in the upper three metres will decrease by around 25 %. In the alpine regions in particular, the permafrost will increasingly thaw and degrade over the course of the century (Fox-Kemper et al., 2021: 1216). In addition to hydrological changes (Section 2.2.1), this will also lead to the release of CO_2 and methane (Canadell et al., 2021: 677), although the projections on the repercussions on climate change are not yet fully clear (Jin et al., 2022). Overall, less and less meltwater will be available from long-term frozen storage, and this will impact on the seasonal supply of freshwater, both at peak and minimum levels (Section 3.1.1.4).

3.1.1.4
Changed runoff regimes

Further-rising temperatures, changing precipitation patterns (Section 3.1.1.1), retreating glaciers and a reduced snow cover (Section 3.1.1.3) will continue to have a strong impact on the runoff regimes (land surface and rivers) and their variability, both on an annual average and seasonally. Average runoff volumes will increase worldwide as global warming continues, albeit with regional differences (Fig. 3.1-5; Douville et al., 2021: 1119). Increasing runoff volumes are predicted in particular for the northern high latitudes and regions in Central and East Africa, while decreases in the Mediterranean region and parts of Central and South America will lead to considerable shortages of blue water, especially in the summer months (Douville et al., 2021: 1119).

At the same time, the seasonal fluctuations in runoff volumes will increase regionally (Douville et al., 2021: 1058). The runoff peaks associated with the snowmelt in spring will also occur earlier in the year, and the runoff caused by the snowmelt will decrease as the snow recedes. Overall, once the maximum runoff volumes have been exceeded, including from glacier melt (Section 3.1.1.3), the average annual runoff in one third of the glaciated catchment areas will decrease by at least 10 % under the RCP4.5 scenario by 2100. The sharpest declines are expected in Central Asia and the Andes (Caretta et al., 2022: 556; Huss and Hock, 2018). Glacial melting can have a negative effect on the supply of drinking water (Section 4.4).

3.1.1.5
Increase in combined extreme water events

The frequency and severity of floods and droughts will continue to increase (IPCC, 2019a). Agricultural and hydrological droughts are "expected to become more frequent, longer and more severe in a warmer future" (Yuan et al., 2023). Regions such as the Mediterranean area, South Africa, Central America and the Amazon basin, as well as parts of North and South America and Australia, are expected to become drier, due both to lower precipitation and to an increase in evaporation (Fig. 3.1-6). Droughts will therefore become more pronounced and last longer, depending on the emission scenario for greenhouse gases (wCaretta et al., 2022: 610). Lightning droughts will also occur more frequently and more intensively, as dry conditions are more frequently accompanied by higher temperatures, and relative humidity continues to fall in many regions (Yuan et al., 2023).

Flooding will also occur more frequently in many regions, e.g. in Asia, Central Africa, Western Europe, Central and South America, parts of North and South America, the Mediterranean and Eastern Europe. Depending on the region and type of flooding, they represent a growing socio-economic risk (Caretta et al., 2022: 608). A larger proportion of land areas is also likely to be affected by river flooding in the future, although the regional projections vary greatly due to human influences such as water management or changes in land cover, e.g. as a result of development or agriculture (Caretta et al., 2022: 605 f.; Seneviratne et al., 2021).

The modelled effects increase with accelerating warming, although the variability of the results also increases at the same time (Dottori et al., 2018). The effects of future floods are also unevenly distributed regionally, with the greatest losses expected on the Asian and African continents (Dottori et al., 2018; Merz et al., 2021). More frequent and heavier heavy rainfall – together with other factors such as increasing urbanization – will also lead to an increased and more intense occurrence of flash floods (Fowler et al., 2021; Yin et al., 2023). For dry regions, this means a simultaneous increase in extreme precipitation, even though there will be a decline in overall precipitation (Tabari, 2020).

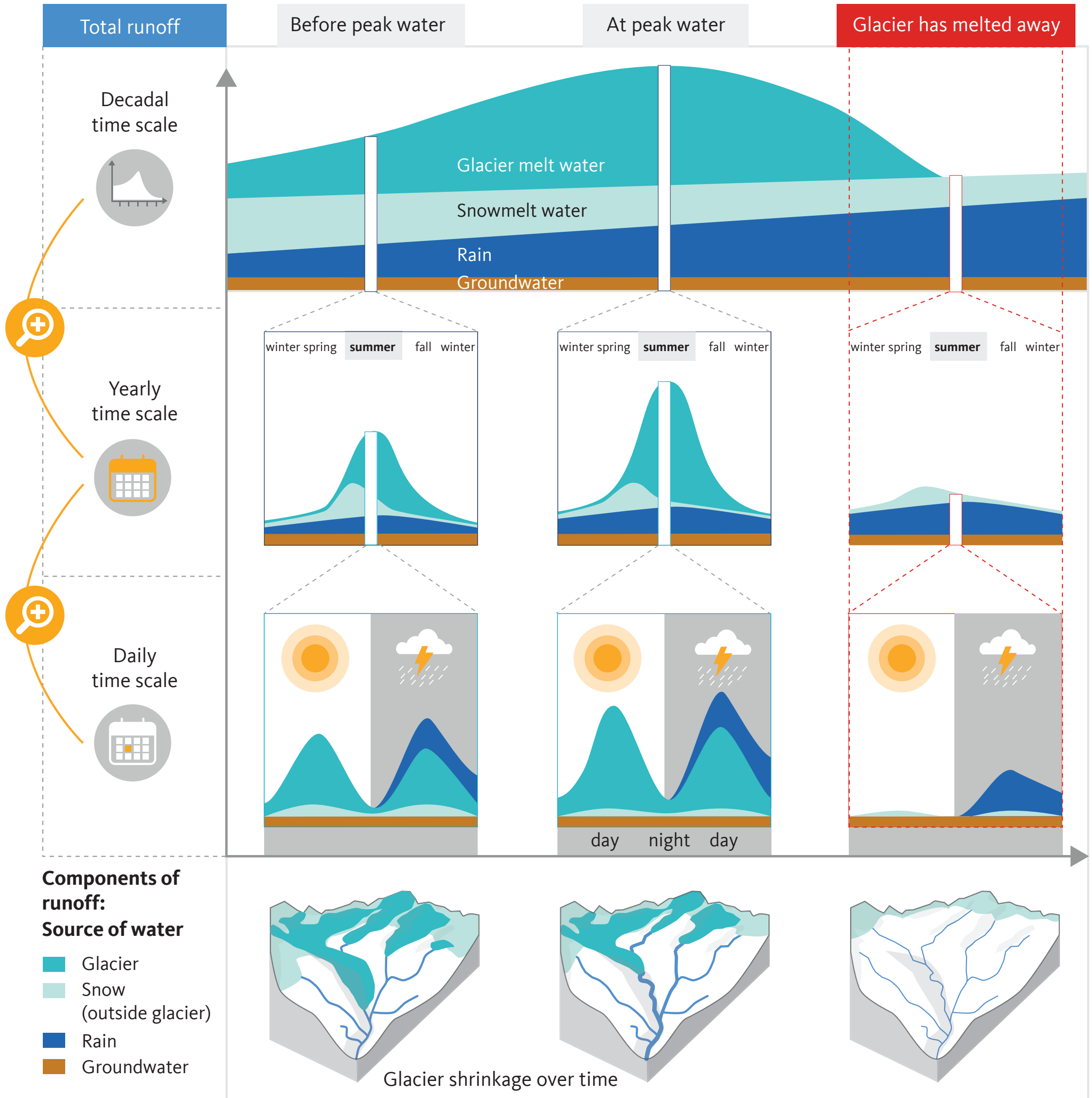


Figure 3.1-4
Effects of glacier melt. The diagram shows a simplified overview of the relative amounts of water from different sources when glaciers shrink in a river catchment with large glacier cover (e.g. >50 %) that lead to changes in runoff. The sources are glaciers, snow (outside the glacier), rain and groundwater.
Source: Hock et al., 2019

3.1.1.6
Sea-level rise, variable salinities and weakening ocean currents

Sea-level rise is caused by warming and the associated expansion of seawater, as well as by melting glaciers and ice shelves. The resulting successive desalinization of the ocean's surface layers slows the formation of deep water off Greenland and with it the driving force behind the large-scale ocean currents that stabilize the Earth's heat balance and supply the deep sea with oxygen. The Gulf Stream, which shapes Europe's mild climate and precipitation and balances out seasonal extremes, is also affected. However, as climate change advances, the Gulf Stream will progressively decline, so that, according to recent findings, at least a partial collapse is possible before the end of this century (Ditlevsen and Ditlevsen, 2023; van Westen et al., 2024). In Europe, this would trigger severe cooling (with average temperatures 5°–15 °C lower than today in many European cities), the effects of which are hardly predictable to date (van Westen et al., 2024).

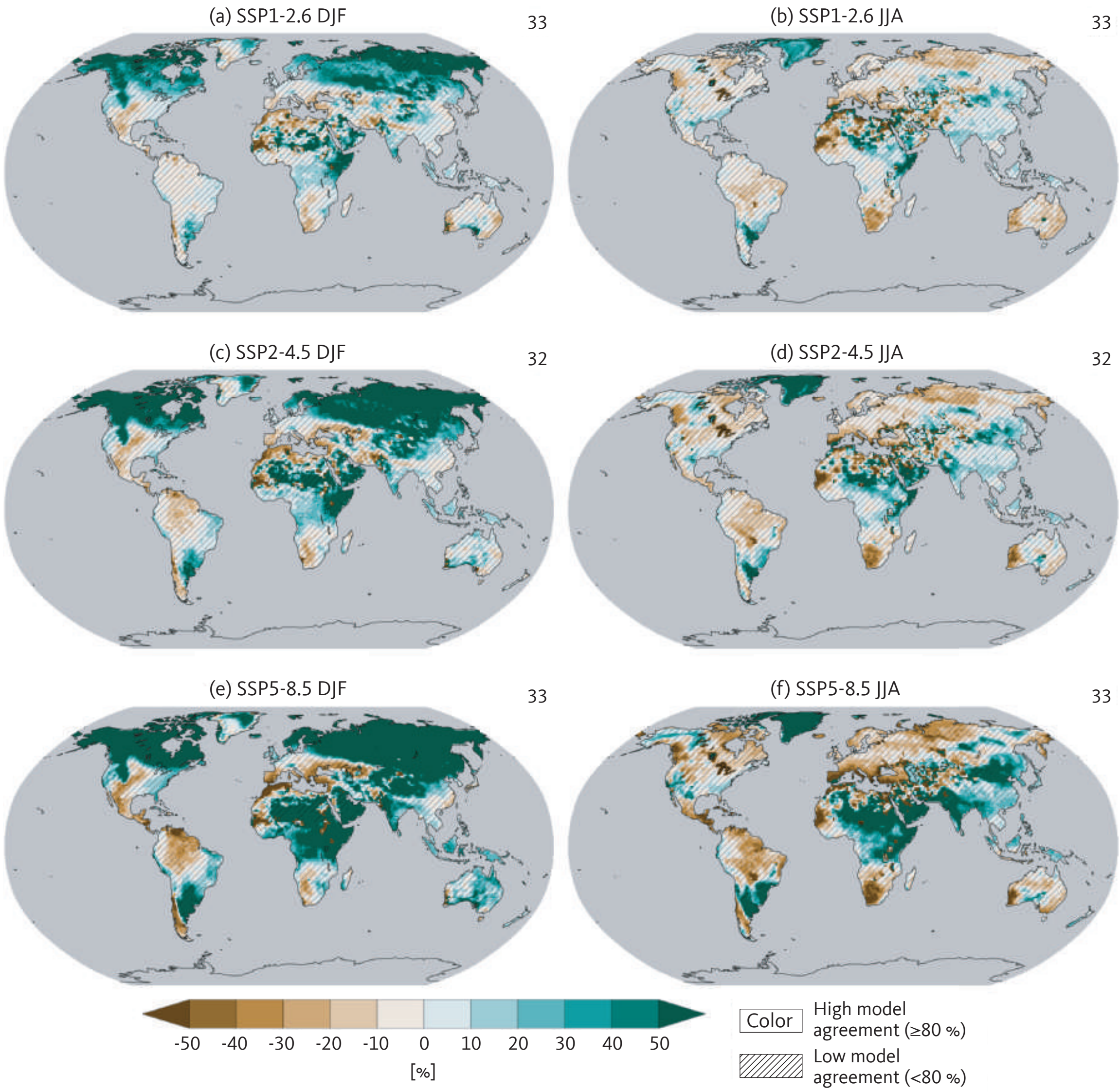


Figure 3.1-5
Future changes in runoffs. The diagram shows projected long-term relative changes in the seasonal mean runoffs in the period from 2081–2100 compared to 1995–2014. The global maps show the projected relative (%) changes in seasonal mean run-off for December, January, February (DJF; left-hand side) and June, July, August (JJA; right-hand side), averaged over the available CMIP6 models (which is indicated by the number on the top right in each panel) SSP1.2-6 (a, b), SSP2-4.5 (c, d) and SSP5-8.5 (e, f).
Source: Douville et al. 2021: 1118

One billion people currently live near a coast and are increasingly directly affected by rising sea levels and correspondingly higher storm surges (IPCC, 2019a). The Intergovernmental Panel on Climate Change's Special Report on the Oceans and Cryosphere (IPCC, 2019a) assumed that future rises in the sea level could perhaps be stabilized below one metre for a long period if global warming were limited to 1.5 °C. If warming is stronger, however, the oceans can rise further by 2100 and eventually reach several metres (IPCC, 2019a, 2021c). Correctly estimating the stability of the (West) Antarctic and Greenland ice shelves is a major uncertainty factor – the total amount of water currently stored in the Antarctic and Greenland glaciers corresponds to a sea-level rise of 65 metres (Fox-Kemper et al., 2021: 1316).

In late October 2023, British polar researchers published a study according to which, over the next 80 years, the glaciers of the West Antarctic Ice Sheet will inexorably slide into the sea faster than previously assumed – even if the world succeeds in limiting global warming to 1.5 °C (Naughten et al., 2023). Another aspect is the accelerated melting of Greenland's ice masses (IPCC, 2019a). This means that, according to the latest findings, rising glacier runoffs into the warming ocean by the year 2300 can no longer be prevented even at 1.5 °C global warming, with a projected rise in the sea level of up to 3 m (IPCC, 2021c). Taking into account the uncertainties and the latest findings, a sea-level rise of even as much as seven metres in the same period seems possible – a rise similar to that experienced by the Earth in the last interglacial around 125,000 years ago at a comparable average temperature (Rohling et al., 2019). Population genetic data of Antarctic octopods indicate that this sea-level rise was probably accompanied by the collapse of the West Antarctic Ice Sheet. This conclusion is supported by gene exchange between populations otherwise separated by ice (Lau et al., 2023). Even beyond the 7 m level, sea-level rise will continue for centuries, depending on the extent of climate change. This challenge would be beyond the capacity of current coastal defences on low-lying coasts (Oppenheimer et al., 2019). Climate change has thus long-since triggered processes that can no longer be stopped or reversed in the short term, signalling a loss of control for humanity. Low-lying coasts and small islands are particularly at risk of flooding in the future. Steric effects (the expansion of water masses due to changes in density caused by changes in salinity or water temperature), ocean currents, land uplift and subsidence, and changes in fields of gravity due to the melting of the large ice masses in Greenland and Antarctica or as a result of vertical land movements, cause sea levels to rise by different amounts in different regions. Locally, the sinking of the seabed as a result of groundwater extraction and the production of oil and gas are also factors.

As the sea level rises, ever higher and more intense storm surges will occur (IPCC, 2019a), which may penetrate far inland and reach the freshwater systems there. Freshwater reserves will also become salinized via the groundwater on many coasts or small islands as sea levels rise. For example, rising seawater penetrates the freshwater lenses of islands and leads to an increase in salinity (Cantelon et al., 2022; Mazhar et al., 2022). However, the salinization of freshwater reserves and soils will also increase in arid regions. As aridity increases or agriculture expands, irrigation will increase (Section 3.2.1.1), evaporation will lead to a progressive concentration of the minerals dissolved in the water and thus to salinization.

3.1.1.7 Conclusions

Deteriorating living conditions caused by increasing climate change are already putting the adaptability of nature and humans to the test. Human adaptation to the current extent of change is already necessary. Nature, too, is already undergoing large-scale changes that can be understood as adaptations or evasive reactions (IPCC, 2022a). As climate change progresses, the capacity of both humans and nature to adapt is continuously decreasing (IPCC, 2022a). In order to maintain as much adaptability as possible and considering the precautionary principle, there is no alternative to limiting climate change to 1.5 °C of global warming and, if possible, even reversing it in the long term. This requires an end to anthropogenic CO_2 emissions and a sharp reduction in emissions of other greenhouse gases, as well as the removal of CO_2 from the atmosphere.

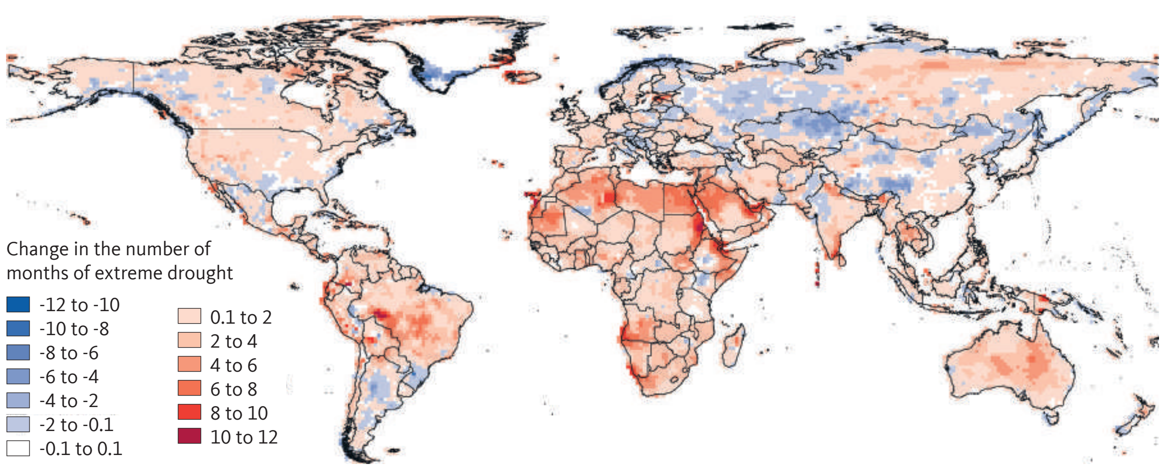


Figure 3.1-6
Changes in extreme droughts. The diagram shows the change in the number of months with extreme drought per year (in the period 2013–22 compared to 1951–60). Regions with an increase in droughts are shown in red; regions with a decrease in the annual number of months with extreme drought are shown in blue. Regions without changes are highlighted in white.
Source: Romanello et al., 2023

The findings on rising sea levels alone show that the limits of adaptability could be exceeded. The risks to humans and nature are becoming increasingly uncontrollable in many regions, particularly in view of the ever-more-frequent and intense extreme events such as heatwaves, floods and droughts (Chapter 4).

3.1.2
Extreme events challenge and overwhelm the infrastructure

The more frequent occurrence of extreme weather events has an impact on the flood-protection infrastructure and the provision of a safe supply of drinking water. These burdens will increase in the future.

Engineering structures such as dykes, dams and sewerage networks are dimensioned for a maximum load case, i.e. a maximum flow rate that the structure can discharge without damage. In Germany, for example, a flood with a statistical probability of recurrence of 100 years (HQ_{100}) is used as the basis for calculation in dyke construction; for dams it is 1,000 or 10,000 years, depending on their size (DIN 19 700). In addition, areas in which a 100-year flood event is to be expected are designated as floodplains in accordance with the Federal Water Act (WHG section 76). The designation of building areas and the authorization of building projects is generally prohibited in these areas, and permitted only in exceptional cases. The hydraulic dimensioning of sewer networks in settlements is also based on historical precipitation data in order to minimize the frequency of flooding, i.e. a condition in which untreated wastewater unintentionally escapes to the surface (DIN EN 752). With climate change, however, these calculation bases for how much stress the infrastructure is expected to withstand are shifting, with regard both to the frequency of flood events and to the need for floodplains and sewer network capacities.

The increase in the frequency and intensity of extreme precipitation is now leading to higher peak discharge values and higher probabilities of recurrence worldwide. The currently customary dimensioning of water-management installations and the designation of areas at risk of flooding based on historical data series is therefore no longer appropriate for minimizing the increasing risks to human health and economic flood damage. In other words, the risk of infrastructure failure – as was last observed during the flood disaster in Libya in 2023, when two dams burst following an extreme rainfall event (Henson and Masters, 2023) – will continue to increase. In Germany, the water industry has accordingly moved away from talking about flood protection. Instead, it has adopted a form of risk characterization in which increased risks of extreme events can be reduced by various measures, but can no longer be completely or largely excluded.

The same applies to the hydraulic design of water-management systems to ensure a reliable water supply in the face of increasing droughts and heatwaves. Major heatwaves lead to higher daily peak consumption levels for which neither the capacity of the treatment plants nor the distribution grids are designed. There may therefore be temporary supply bottlenecks and restrictions on use. Prolonged periods of drought change the soil-moisture regime and lead to the drying up of near-surface spring-water deposits and to a widespread drop in groundwater levels and surface-water levels. This jeopardizes the adequate supply of drinking water.

A lack of runoff in watercourses during long periods of drought can lead to a further deterioration in raw-water quality due to increased contamination with pathogens and organic trace substances (Section 3.1.3; Karakurt et al., 2019), so that existing treatment processes are no longer able to guarantee perfect drinking-water quality. An additional challenge is that drinking-water-supply systems are often not redundant; rather, a settlement area is often supplied by only one water resource (e.g. groundwater, surface water, bank filtration). Loss of this water resource due to drought or heat, which cannot be compensated for by diversifying the supply via other water sources, can therefore pose an existential threat. In addition to food production (through agricultural irrigation) and drinking-water supply, human health would also be directly affected by the lack of water supply for wastewater disposal and hygiene. The water crisis in Cape Town from 2015 to 2018 came very close to such a failure of the drinking-water supply (Section 4.2.). As a result of the extreme drought in western South Africa from 2015, the levels of the reservoirs used to supply Cape Town with drinking water fell (Burls et al., 2019; Section 4.2). As a cost-saving measure, water consumption was temporarily limited to 50 litres per person per day. However, a shutdown of the drinking-water supply and the rationed supply of the population via water-distribution points was averted due to the onset of rainfall (Burls et al., 2019). A modelling study shows that the risk of another multi-year drought in western South Africa could increase by up to 80 % by 2100, depending on the greenhouse-gas emission pathway (Pascale et al., 2020). Similar challenges for the drinking-water supply of cities can be observed worldwide, most recently in Montevideo in 2022–2023 (Section 4.2).

3.1.3 Impacts of droughts and extreme weather events on food security

For humans, the exacerbated challenges under discussion culminate in increasing insecurity regarding their way of life, particularly as a result of increasing droughts and poor water quality. Droughts also have a wide range of health impacts caused by reduced food security and associated malnutrition (Fig. 3.1-7; Section 3.3.2). In view of the significance of droughts for agriculture and thus for global nutrition and the multiple impacts of droughts on the economy and society (Fig. 3.1-7), trends that are already foreseeable or observable today – and their impacts – will continue to intensify. Accordingly, the near-global drought in 2022 had an impact on water supply and water security, food security, access to electricity and economic activities due to low water levels in rivers (Romanello et al., 2023).

The IPCC identifies droughts and the interplay between different aridity types and their culminative effects as the most cost-intensive natural disasters (Fig. 3.1-7; Mirzabaev et al., 2019) and points out that they have significant effects not only in rural regions but also in cities. The Food and Agriculture Organization (FAO) emphasizes that one in five cities with at least a million inhabitants is located in an area with a high to very high drought-risk rating. So far, this affects a total of 370 million people worldwide (FAO, 2019).

Droughts and prolonged, repeated or particularly hot periods during droughts have a direct impact on the productivity of food systems (crop cultivation, livestock farming, aquaculture and fisheries), leading to yield losses and, potentially, to the complete loss of an agricultural cycle (Brás et al., 2021; Zampieri et al., 2017). At the same time, they lead to greater fluctuations in the production and availability of food throughout the year. In times of food shortages – caused, for example, by the COVID-19 pandemic, the war of aggression on Ukraine or crop failures due to droughts or heavy rainfall – food prices have recently been rising sharply or fluctuating

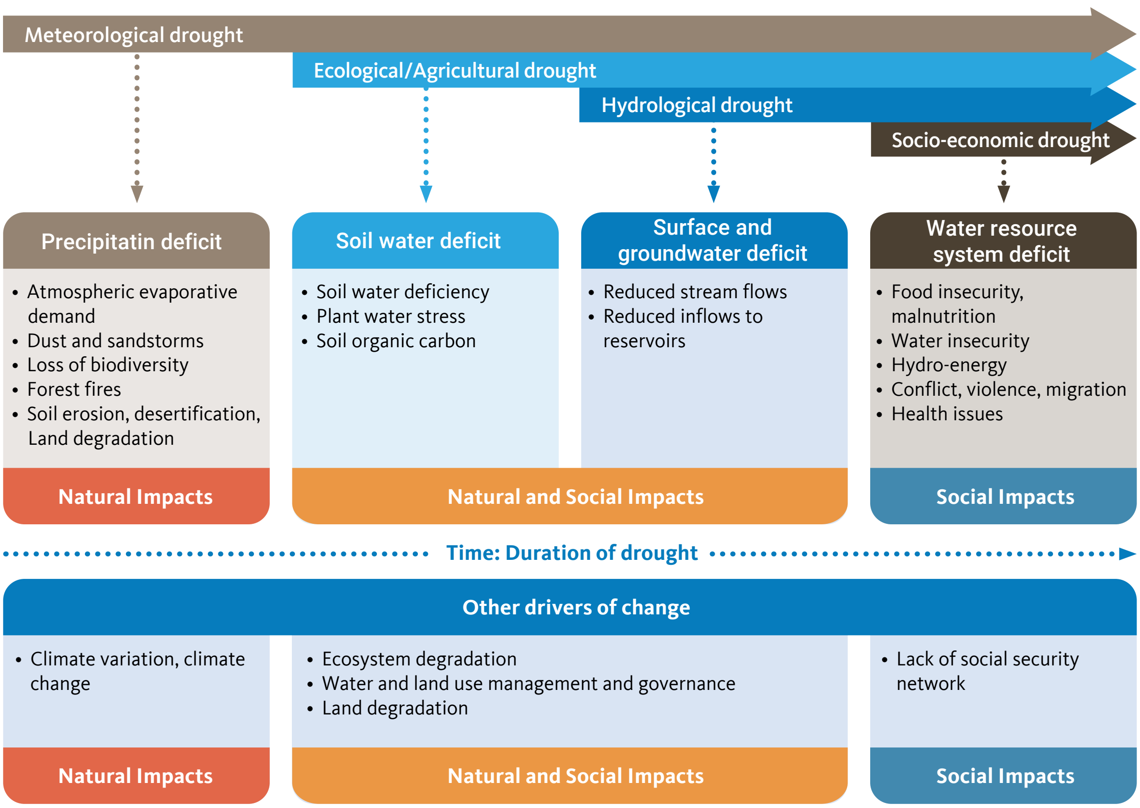


Figure 3.1-7
Types of drought and their impacts. The diagram shows a schematic overview of the effects of different types of droughts on water-related processes and the social consequences. Water scarcity exacerbated by climate change and other human activities affects all levels, from the ecosystem to society, triggering crises that weaken social cohesion and its functions and resilience to environmental crises.
Source: Reichhuber et al., 2022

again worldwide since 2021. These developments are recorded by the FAO's Food Price Index (FFPI), a measure of the monthly change in the international prices of a basket of food products. Brás et al. (2021) point out that crop failures in Europe have already tripled in the last five decades due to droughts and heatwaves. Various factors come together here that will lead to even more unfavourable developments as climate change intensifies.

Inappropriate land management is characterized by monocultures, over-fertilization, salinization and soil compaction. This can lead to a reduction in soil quality and a loss of habitat for the natural vegetation. This greatly increases the risk of destructive floods, which often follow longer periods of drought. The overexploited and dried-out soils cannot absorb the suddenly available water quickly enough and torrents form, eroding the soil and jeopardizing agricultural land, livestock farms and human settlements with their destructive force (Hornidge and Scholtes, 2009; Section 4.3). The United Nations Convention to Combat Desertification (UNCCD) draws attention to these negative chain effects, which give rise to exacerbated challenges in the WBGU sense, but also emphasizes the positive, potentially mutually reinforcing effects of resilient land management (Fig. 3.1-8; Reichhuber et al., 2022).

The agricultural yields that do not materialize in regions that are repeatedly hit by droughts, heatwaves and floods are lacking on local and regional markets, and this has a negative impact on food security (Reichhuber et al., 2022). Poverty is thus reinforced in multiple dimensions, which also makes it more difficult to maintain local options for the future. The danger of mutually

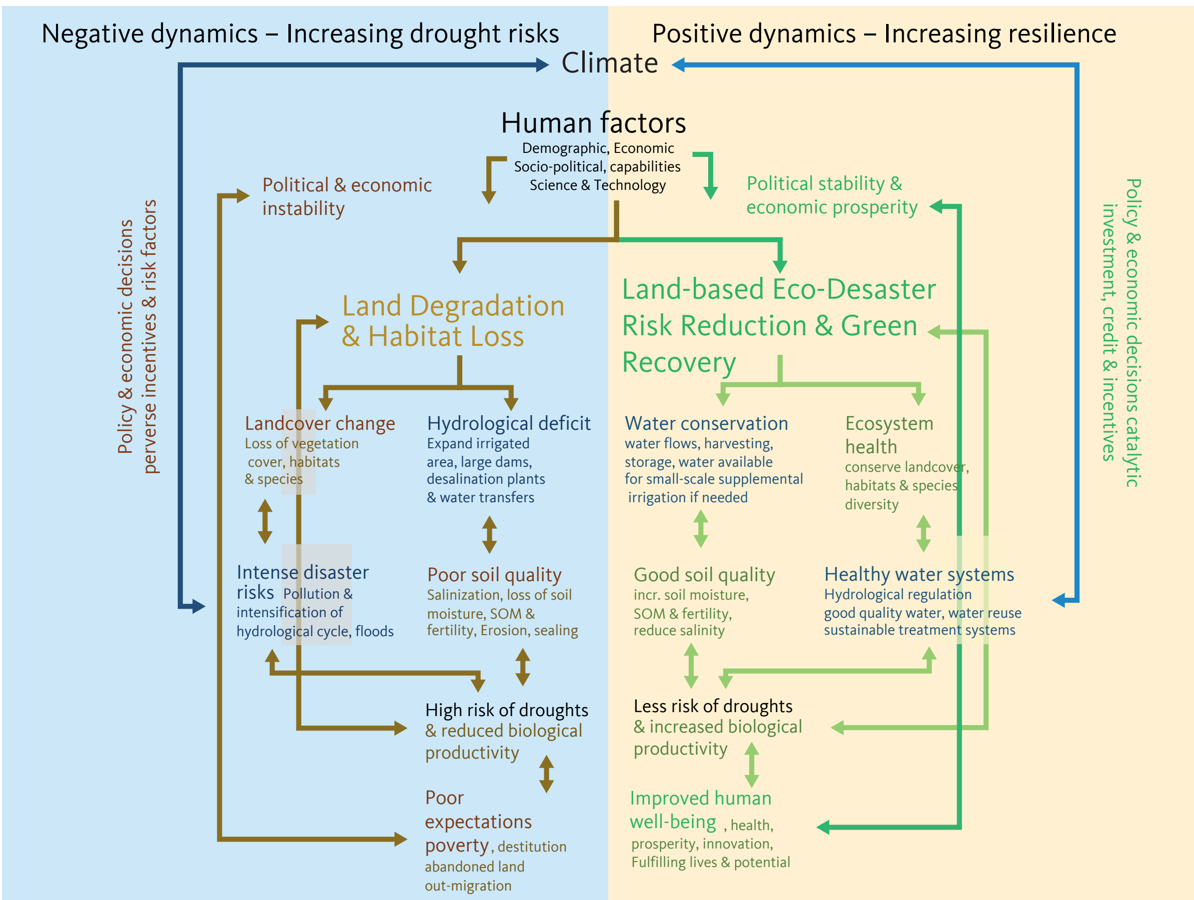


Figure 3.1-8
Dynamics of drought events. Schematic representation of the dynamics that lead to the increased occurrence of drought events (left) and dynamics that can increase resilience (right). One factor that promotes resilience, for example, is the use of sustainable land-management methods, but only in the case of successful climate-change mitigation.
Source: Reichhuber et al., 2022; King-Okumu, 2021; Niemeijer et al., 2005

reinforcing risks is particularly high in regions that are especially badly affected and are confronted with the additional challenges of climate change and species extinction, high poverty rates, low levels of social cohesion for ethnic, religious or other reasons, and unstable political regimes – up to and including armed unrest or forced changes of government through armed coups, such as those that were increasingly observed in the Sahel region last year (Bergmann, 2022; Unfried et al., 2022).

Climate change is exacerbating humanitarian crises because of the water factor. This can currently be observed in Sub-Saharan African countries such as Mali and Burkina Faso, but also in Ethiopia and Sudan, as well as in countries of the Middle East, including Gaza, where war-related water shortages are exacerbated by persistent drought. Particularly affected are population groups whose income security is characterized by a high dependency on nature and thus a high vulnerability to water shortages. In some of these regions, this leads to an increase in seasonal or longer-term labour migration, with small island states being disproportionately affected by migratory pressure (IPCC, 2022a).

3.1.4 Exacerbated challenges due to environmental pollution

At least three billion people are dependent on water of uncertain quality due to a lack of monitoring (UN, 2022). How water quality develops in the future will not depend solely on contamination with pollutants. Changes in water abstraction and local hydrological conditions, which are driven by both climate change and socio-economic developments, also play a role (Jones et al., 2023).

3.1.4.1 Trends in water pollution

Water pollution is characterized by a constant increase in concentrations and by changes in the composition of the substances involved. Substance inputs from agriculture and industry play a key role here. The processes involved in creating new materials, new infrastructure and innovative technologies are energy-, resource- and water-intensive. The complexity of pollution is increased by modern, newly developed substances and by mixtures of substances and possible interactions, for example with microorganisms (Persson et al., 2022; Posthuma et al., 2019; Gomes et al., 2020; EEA, 2022). Most of the long-term risks are unknown and are the subject of ongoing research.

The following trends in water pollution are emerging worldwide (Jones et al., 2023): pollution from organic pollutants – measured in terms of biochemical oxygen demand (BOD) – and pathogenic pollutants – measured as the concentration of coliform bacteria (faecal coliforms, FC) – will decline in some regions of the world, especially in Europe and parts of North America and Asia, irrespective of the future scenario. On the other hand, pollution will increase sharply elsewhere, especially in Sub-Saharan Africa. The reason for this is high population growth coupled with weak economic growth and the associated increase in water abstraction and pollutant emissions into water bodies (Jones et al., 2023).

Another indicator of water pollution is inorganic pollution, which consists mainly of salts. It is measured as the amount of solids dissolved in water (total dissolved solids, TDS) and will increase in many regions by 2100, especially in the future scenario SSP3-RCP7.0 'regional rivalry' (Section 4.5; Jones et al., 2023). Fig. 3.1-9 shows the projected global changes in water pollution up to the year 2100.

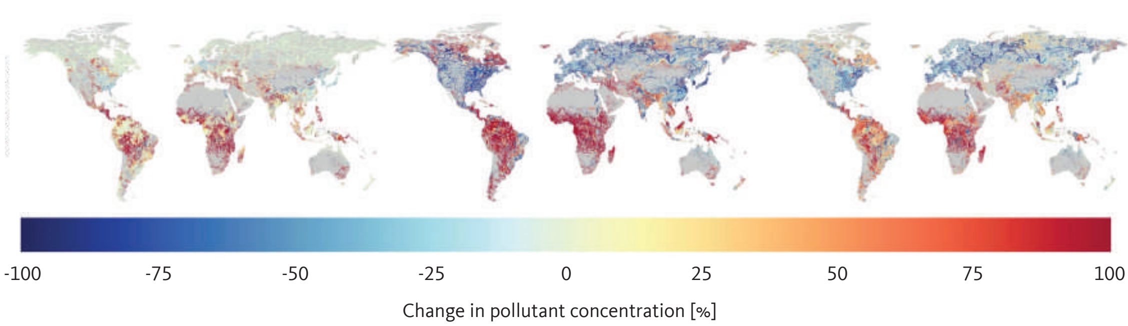


Figure 3.1-9
Water pollution. The diagram shows changes in surface-water quality under climatic and socio-economic changes in the SSP3-RCP7.0 scenario with high greenhouse-gas emissions (red: increase, blue: decrease in the concentration of pollutants). The changes in the pollutant concentrations of dissolved solids (TDS, left), biochemical oxygen demand (BOD, centre) and coliform bacteria (FC, right) are shown as indicators of salinization and the accumulation of organic and pathogenic pollutants.
Source: Jones et al., 2023

3.1.4.2
Influence of climate change on water pollution

Climate change exacerbates the existing situation via changes in precipitation patterns (Konapala et al., 2020), snowmelt-runoff regimes (Kraaijenbrink et al., 2021) and in the frequency and intensity of extreme events such as droughts or floods (Caretta et al., 2022; Sections 3.1.1, 3.1.2). During periods of drought, the concentration of pollutants in surface waters can no longer be sufficiently diluted (Karakurt et al., 2019). Flooding and melting snow and ice mobilize pollutants, making them bioavailable (van Vliet et al., 2023). In addition, rising water temperatures during heatwaves influence the physical, chemical and biological processes in surface waters, which can affect the concentration and chemical properties of transported substances (Jones et al., 2023; Bosmans et al., 2022; Bonet et al., 2023; Capon et al., 2021). Warming lowers the concentration of dissolved oxygen, which can lead inter alia to fish mortality, particularly if there is additional oxygen depletion due to the heavy organic pollution of water bodies (van Vliet et al., 2023). Furthermore, higher temperatures and reduced or absent precipitation can lead to the concentration of pollutants through evaporation and accelerate chemical weathering (Kaushal et al., 2021). Together with uncontrolled climate change, the overall result is an extreme, barely controllable stress situation for water resources and thus for humans and nature. This shows how insufficiently contained climate change intensifies the effects of further environmental pollution and vice versa.

3.1.4.3
Water pollution by microplastics

Microplastics are an example of substance inputs into water bodies and possible interactions between substances and organisms. Micro- and nanoplastics act as a vector for additional harmful contaminants with potentially serious consequences for the environment and health. For example, there are already indications of an increased mortality rate in zebrafish and respiratory diseases in humans (Section 2.3.4.4; Barreto et al., 2023; Kumar et al., 2023b). Exposure to micro- and nanoplastics is likely to increase: in a future scenario without countermeasures, the amount of plastic – and therefore also micro- and nanoplastics – released into the environment is expected to double globally to 44 million tonnes per year by 2060 (OECD, 2022b).

3.1.4.4
Chemical pollution due to increasing demand for raw materials

The rising demand for materials for technologies and renewable energies is leading to a growing extraction of raw materials such as copper and lithium (Europäische Kommission, 2020b; Bogardi et al., 2021; Raabe, 2023). Mining of raw materials has a negative impact on local water bodies, e.g. through the input of process chemicals and hydrological changes that have consequences for humans and the environment (Section 2.3.4.6; WBGU, 2023). In Chile, for example, around 80 % of copper-production sites are located in areas that are exposed to extremely high water stress. By 2040, 100 % of production facilities are expected to be located in such areas (Delevingne et al., 2020). The water problem in regions which, in some cases, are already water-scarce is exacerbated by the increase in mining and, as described above, by the consequences of climate change (Bogardi et al., 2021; see also Chapter 7 on the consequences of the extraction and use of fossil fuels and raw materials for the energy transition). The negative consequences of raw-materials mining can be reduced by recovering metals and other substances from industrial wastewater and end-of-life products using circular, water-conserving processes (Chapter 7).

3.1.4.5
Nutrients and harmful algal blooms

The eutrophication of water bodies due to excessive concentrations of nitrogen and phosphorus compounds is already at a critical level (Rockström et al., 2023a). Because of pollution from nitrogen compounds, primarily from agriculture, the shortage of freshwater in rivers could triple worldwide by 2050 and lead to a shortage of drinking water for the population. This is shown by a scenario which, in addition to water quantity, also considers quality in relation to water scarcity (Wang et al., 2024).

Emissions of nitrogen compounds will continue to rise, largely due to the expected increase in the use of fertilizers in agriculture (Glibert, 2020; Wang et al., 2024). This could exacerbate the water problems caused by harmful algal blooms, which produce toxins and consume the oxygen in the water that is important for other organisms (Griffith and Gobler, 2020; CDC, 2024). If an algal bloom becomes too dense, it prevents phytoplankton from absorbing solar radiation (CDC, 2024), which is essential for their survival. Harmful algal blooms will become more frequent because of rising phosphorus and nitrogen concentrations or changes in their ratios to each other; it will also be increased by rising temperatures and long periods of heat. This is particularly likely in Southeast Asia and some countries in South America and Africa (Glibert, 2020). Due to the algal bloom and its harmful consequences for freshwater ecosystems, the water can only be processed for drinking water at considerable expense (CDC, 2024; Glibert, 2020; Cressey, 2017). Projects such as the installation of over-canal solarphotovoltaic arrays and similar concepts for lakes can reduce algae growth and evaporation by creating shade.

3.2 Exacerbated challenges caused by socio-economic and geopolitical developments

While the water supply will become more variable and scarcer in many places in the future as a result of the effects of climate change and increasing pollution (Section 3.1), studies also indicate that the overall global demand for water will increase and contribute to an increase in water stress in many regions (Section 3.2.1). A lack of water supply can be a limiting factor for growth, development and poverty reduction (Section 3.2.1). Multidimensional poverty and social inequalities, as well as autocratization and polarization processes and geopolitical interests, weaken societal cohesion, promote the fragmentation of governance systems and reduce societal resilience to water-related crises like droughts and floods (Section 3.2.2). In this way, they further encourage the development of water-related emergencies (Chapter 4).

3.2.1 Overexploitation of water resources and the impact of exacerbated water-related challenges on economic development

Exacerbated challenges arise particularly in those regions of the world where rising demand for water for economic or societal purposes comes up against a declining or greatly fluctuating supply of water. This drastically reduces the scope for action to achieve goals such as access to safe drinking water, sanitation for all and food security. Advancing climate change will lead to increased fluctuations and, in some regions, to a reduction in the water supply (Graham et al., 2020a; Koutroulis et al., 2019; Section 3.1.1). Unless action is taken, increasing pollution will further restrict the water supply (Section 3.1.4).

The other side of the equation is the development of the demand for water. Forecasting future trends in demand is difficult and fraught with uncertainty, as it depends on the development of technological, socio-economic and ecological conditions in the countries and regions under consideration. Humans also influence these framework conditions and thus the development of demand, both directly and indirectly via climate change. Which scenarios come closest to reality will depend on our actions and how the natural systems react. Studies on the development of demand for water indicate that it will increase globally and contribute to an increase in water stress in many regions (Section 3.2.1.1).

Trading in virtual water can contribute to increasing water stress (Section 3.2.1.2). A lack of water supply, increasing variability and extreme events influence the potential for economic development (Section 3.2.1.3) and thus also affect social inequalities and geopolitical developments (Section 3.2.2) as well as the health of humans and ecosystems (Section 3.3). Only consistent action by politicians, business and society can keep enough room for manoeuvre open, reduce negative impacts and give humans and ecosystems an opportunity to adapt to the limited availability of natural resources. However, there are also natural limits to such action (Chapter 5).

3.2.1.1 Rising water demand and consumption

UNESCO (2023) estimates that the global demand for water will increase by about 1 % per year and thus by 20–30 % by 2050 (see also Caretta et al., 2022). However, the margin of error for this assessment is more than 50 % (UNESCO, 2023). There can also be significant regional differences in the development of water demand. A large proportion of the expected increase in demand will happen in low- and middle-income countries, especially in emerging economies. Regional differences in the development of water demand reflect changing use patterns in the three areas of municipalities, industry and agriculture (UNESCO, 2023).

In many regions, increases in demand from municipalities are only made possible by an expansion of the water supply and, to a lesser extent, water disposal. They are therefore more prevalent in regions where water supply and disposal are being expanded (UNESCO, 2023).

Industrial demand for water comes primarily from water-intensive processes, e.g. in production or energy generation. Increases in industrial demand for water therefore generally go hand in hand with advancing industrialization. Improved efficiency in water use can, in turn, reduce the demand for water over time (UNESCO, 2023).

The demand for water in agriculture is primarily driven by irrigation and depends on various factors, e.g. the nature of the soil, the effects of climate change, the crops grown and the cultivation methods used (UNESCO, 2023; Caretta et al., 2022). Competing uses, restrictions on water supplies, food consumption patterns and trade also play a role (UNESCO, 2023), as does the growing demand for biomass for energy production (Caretta et al., 2022). Projections on the development of water demand vary considerably, depending on the underlying assumptions, e.g. on the socio-economic, technical and climatic development.

The IPCC estimates that the demand for water for irrigation could double or even triple by the end of the century (Caretta et al., 2022). The Food and Agriculture Organization (FAO) assumes that, taking climate change into account, the water requirement for irrigating arable crops will increase by at least 30 % by 2050 compared to 2012 (FAO, 2022b). In addition to higher evapotranspiration as a result of climate change, according to projections rising irrigation requirements will contribute to the increasing depletion of groundwater resources by the end of the century (Caretta et al., 2022; Section 3.1.1.3).

According to studies, increasing water demand and, as a result, increasing water abstraction and consumption will be a major cause of growing water stress globally, especially in the first half of the 21st century, and this can significantly exacerbate water-related problems (Graham et al., 2020a; Wada and Bierkens, 2014; Distefano and Kelly, 2017; Fig. 3.2-1). Particularly in urban areas, the increasing demand for water due to industrialization processes and demographic and income development (and the associated expansion in water supply and disposal) will contribute to increasing water stress and increasing water scarcity (Caretta et al., 2022; He et al., 2021; World Bank, 2016a). India and Northeast China will be particularly affected (Section 4.2), as will be many low- and middle-income countries, especially in Africa, parts of Asia and Central and South America (Graham et al., 2020a; Wada and Bierkens, 2014).

Despite major uncertainties regarding regional climate change, a reduction in the water supply is also likely in many river catchment areas. This may be the case even if the average forecast for the river basin indicates an increase in the water supply as a result of climate change. The decreasing water supply exacerbates the effect of rising water demand (Caretta et al., 2022).

In order to prevent existing imbalances between water demand and supply from escalating further, it is not enough to rely solely on technological change. Most of the Shared Socioeconomic Pathways (SSPs) assume growth rates that many countries will only achieve without exhausting their water resources and without complete dependence on water imports if they drive technological progress at a historically unprecedented and possibly unrealistic speed (Distefano and Kelly, 2017). A transformation of global water management through precautionary and forward-looking adaptation measures is therefore necessary (Chapter 5).

3.2.1.2
Future trade in water-intensive goods (virtual water): the example of agricultural goods

In view of the increasing demand for water and the simultaneously decreasing supply of water in many places, the trade in virtual water can be expected to intensify.

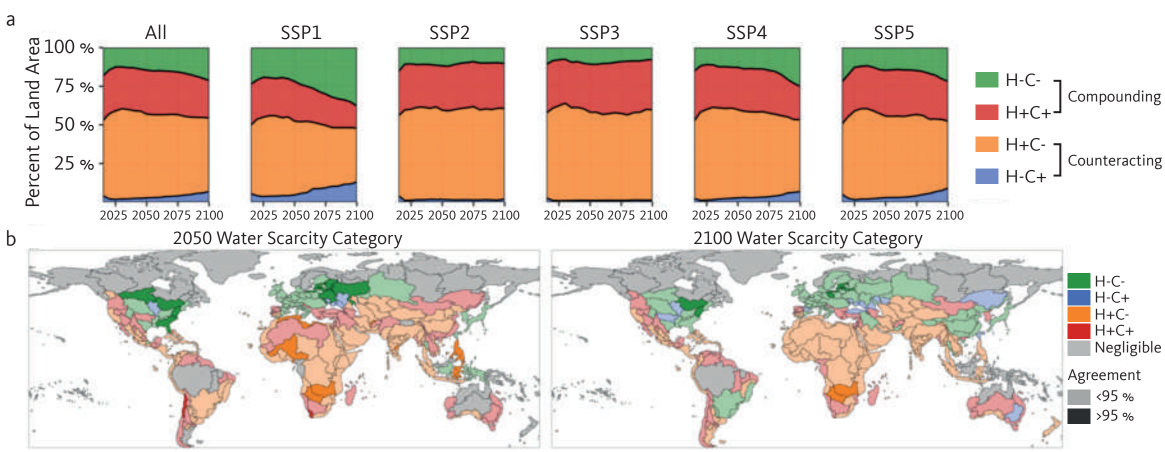


Figure 3.2-1
Spatial and temporal visualization of the factors influencing changing water scarcity. (a) Temporal changes in the proportion of the land area that shows the simultaneous effects of human and climatic systems on changes in water scarcity by component and sign of change, for different Shared Socioeconomic Pathways (SSPs). Water scarcity is measured by the Water Scarcity Index, i.e. the ratio of water abstraction from all sources (renewable surface runoff, non-renewable groundwater, desalination) to the total accessible surface runoff determined by the General Circulation Model (GCM). The 'All' scenario represents the totality of all land areas across all 75 scenario combinations of SSP, Representative Concentration Pathway (RCP) and GCM that are considered. (b) Water scarcity category in 2050 (left) and 2100 (right). (+) stands for rising water scarcity, either due to human influence (H) or climate change (C), and (–) for decreasing water scarcity (e.g. H+ C+: human influence and climate change both lead to an increase in water scarcity in a particular catchment area). The robustness of the results is indicated by the degree of shading: a darker colour indicates more than, a lighter colour less than 95 % agreement across all 75 SSP-RCP-GCM scenarios. Catchments where negligible changes in water scarcity have been observed are shaded as such if at least 95 % of the scenarios for that particular basin match. All basins in which this is not the case are shaded according to their scarcity category in the non-negligible scenarios.
Source: Graham et al., 2020a

However, there are only a few projections, such as Graham et al. (2020a), that comprehensively map developments at the global, regional and river-basin levels – for blue and green water, surface water, groundwater and non-renewable groundwater, taking climate change and socio-economic development into account.

Graham et al. (2020b), like much of the literature on virtual water flows (Section 2.3.1), analyse trade in agricultural products. Assuming a business-as-usual scenario (Shared Socioeconomic Pathway 2, combined with Representative Concentration Pathway (RCP) 6.0), they show that exports of green and blue water contained in agricultural products could triple globally by 2100 compared to 2010 (from 905 billion m^3 and 56 billion m^3 to 3,200 billion m^3 and 170 billion m^3). While Graham et al. attribute this primarily to rising demand as a result of population growth, it would be necessary to consider further socio-economic and climate scenarios in order to make robust statements on the influence of socio-economic development and climate change on future exports of virtual water. The authors expect a shift in virtual water flows that will follow a shift in global food production: in regions with significant agricultural production, the projections by Graham et al. (2020b) show a significant intensification of blue and green water exports between 2050 and 2100. There is no assessment of the potential environmental impacts of this expected intensification and shift in the virtual water trade, since Graham et al. only record virtual water flows volumetrically.

Many countries already increasingly meet their irrigation needs from groundwater, some of which is non-renewable (Section 2.2.3.1). As the supply of surface water is becoming more variable and, in many places, scarcer, this trend is expected to continue unless countermeasures are taken, or unless increasing water shortages limit further groundwater abstraction (Bierkens and Wada, 2019; Section 3.1.1.3). According to Graham et al. (2020b), trade in non-renewable groundwater (sum of imports and exports) could increase fivefold by the middle of the century. The main exporting regions are the USA, Mexico, South America and North Africa as well as, on the river-basin level, the Nile, the Rio de la Plata and the Murray-Darling Basin (Fig. 3.2-2 e and f). Non-renewable groundwater is used, for example, along the above-mentioned river courses for agricultural irrigation to produce staple foods such as rice and maize for export (Graham et al., 2020b). According to the projection by Graham et al. (2020b), trade in virtual water is expected to decline in the second half of the century following the increase in the first half, since exports from water-scarce regions will decline as their resources become increasingly depleted.

Countries whose imports largely originate from countries and regions that do not use their water resources sustainably run the risk of being indirectly affected by increasing water stress in the exporting regions (Sartori et al., 2017). Particularly countries that are dependent on food imports are potentially vulnerable (Section 2.2.3), as increasingly variable and diminishing water resources in exporting countries can jeopardize food security in importing countries and put them in an emergency situation. According to Graham et al., by the end of the century East and West Africa and India in particular will be unable to meet their food requirements from their own production and will import agricultural products and the (predominantly green) water they contain. India – together with Pakistan and the Middle East – could also become one of the largest net importers of blue water and non-renewable groundwater (Graham et al., 2020b).

On the other hand, simulations by Gouel and Laborde (2021) show that trade can help mitigate welfare losses from climate-change-induced changes in agricultural yields by enabling countries whose productivity declines as a result of climate change to import more agricultural products and to switch their production to more productive alternatives.

3.2.1.3
Impact of exacerbated water-related challenges on economic development and poverty reduction

Growth and development are impaired by a lack of – or increasingly variable – water supply, as well as by extreme events such as droughts, heavy rainfall and floods. Losses caused by inadequate water supplies and sanitation systems, flooding in urban areas and insecurity in the irrigation sector already amount to around US$470 billion per year (Khemka et al., 2023). According to the World Bank (2016a), water-related impacts of climate change could reduce global gross domestic product by between 0.37 % (assuming a sustainable development pathway, SSP1) and 0.49 % (in a scenario without adaptation and assuming resurgent nationalism and regional rivalries, SSP3) by 2050. Regional losses could be much greater, for example in the Middle East (–14 %), the Sahel (–12 %), Central Asia (–11 %), and East Asia and Central Africa (–7 %). However, the amount of damage expected varies greatly from one projection to another, depending on the sectors included, types of damage, scenario and modelling assumptions (Caretta et al., 2022; Takakura et al., 2019).

The effects of water on economic development arise on the one hand because water is an important production factor, and water scarcity therefore hinders economic activity. Particularly against the backdrop of climate change, water as a locally and seasonally limited resource is a potential obstacle to growth and development – in low- and middle-income countries (LMIC), but also in high-income countries (HIC; Distefano and Kelly, 2017).

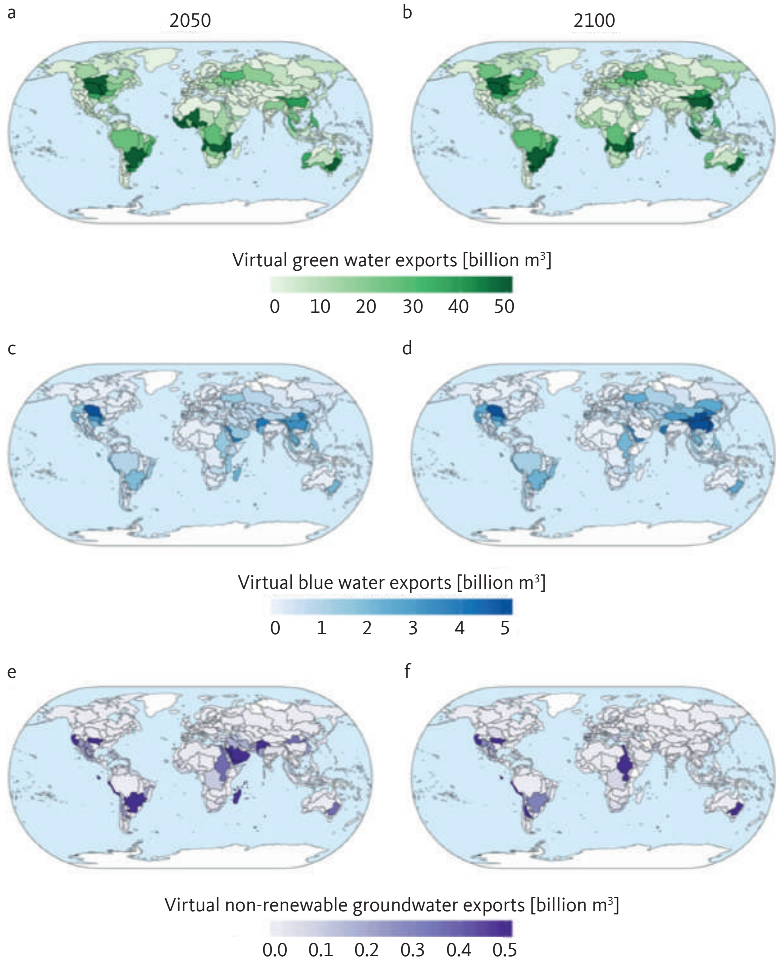


Figure 3.2-2
Forecast of virtual water exports at the river-basin level in 2050 and 2100. Virtual exports of green water in (a) 2050 and (b) 2100, virtual exports of blue water in (c) 2050 and (d) 2100, and virtual exports of non-renewable groundwater in (e) 2050 and (f) 2100, each in billions of cubic metres. The figures show the average of five model runs for the combination of Shared Socioeconomic Pathway 2 (SSP2) and Representative Concentration Pathway (RCP) 6.0. All the figures only include exports of agricultural crops. Additional, possibly necessary virtual water imports are not included.
Source: based on Graham et al., 2020b

Regions that are already suffering from water stress, such as the Middle East, the Sahel and Central and East Asia (World Bank, 2016a), are particularly affected.

On the other hand, extreme events such as floods destroy human lives and assets. Studies show that gross domestic products fall after water-related disasters and do not recover in the 20 subsequent years. This applies equally to low- and high-income countries (World Bank, 2016a). Damage caused by heavy rain or flooding leads to a partial or complete loss of existing assets. The consequences are high costs for citizens and companies that rely on the infrastructure, as well as for private and public investors and capital providers with a financial stake in the infrastructure.

According to the European Environment Agency (EEA, 2023), extreme weather and climate-related events caused economic losses totalling an estimated €560 billion in the EU Member States between 1980 and 2021, including €56.6 billion in 2021. If the trend remains unchanged, the annual damage caused by flooding in Europe alone could double by 2080 compared to around US$7 billion per year between 1960 and 1990 (World Bank, 2016a). It is estimated that the Dutch financial sector's investment portfolios contain a total risk of €83 billion in potential losses from water-related natural disasters. Such risks jeopardize the stability of financial institutions and thus, in addition, urgently needed investments in the water sector (Schellekens and van Toor, 2019).

Multidimensionally poor households are disproportionately affected by the impact of water-related disasters. They are already disadvantaged in the distribution of water resources (Section 2.3.2). Their homes and assets are more vulnerable and are often located in regions with a higher risk of water-related disasters. This reduces incentives to invest in physical assets such as infrastructure, which could be destroyed.

Exposure to extreme events and increasing water scarcity and variability, especially in the womb and in early childhood, can also result in water-related diseases (Section 3.3.2), loss of income and malnutrition (Cooper et al., 2019; Shively, 2017). These can lead to less investment in people's skills, especially in the skills of children, and negatively impact growth in the long term (World Bank, 2016a).

Studies have shown that water-related shocks and extreme events such as droughts or floods can have a negative impact on the health, education and income of affected groups of people even decades later, particularly for populations dependent on agriculture, especially rainfed agriculture, e.g. in rural Vietnam, India, Indonesia or Mexico, but also for people in urban areas, e.g. in Latin American countries (World Bank, 2016a; Caruso, 2017; Randell and Gray, 2019).

Socio-economic trends such as rising food requirements resulting from population growth or geopolitical developments can further aggravate the impact of exacerbated water-related challenges on growth and development, especially for vulnerable population groups, increase the risk of water-related and humanitarian emergencies and jeopardize the achievement of SDG 1 'no poverty'. By contrast, other factors such as better institutions and infrastructure, access to markets and greater openness to trade and international capital flows can mitigate the impact of extreme events and variability in water supply (World Bank, 2016a; Shively, 2017; Cooper et al., 2019). This impact can be explained, among other things, by the following reasons: because emergency aid is provided more quickly and effectively, because the necessary funds for the reconstruction of destroyed infrastructure can be made available more quickly, or because shortfalls in food production can be cushioned by markets and imports.

And finally, there is evidence, e.g. from Sub-Saharan Africa, Brazil and India, that water-related extreme events fuel conflicts within a country and thus inhibit growth and development (World Bank, 2016a). However, water is rarely the sole cause of disputes between countries, although it can exacerbate them (World Bank, 2016a). The Pacific Institute (2023) estimates that water has been a cause, weapon or victim of conflict worldwide in almost 1,300 conflicts. Section 4.3.2.2 illustrates the connection between water and conflicts using the MENA region as an example.

World Bank estimates show that the expected losses can be drastically reduced, possibly even avoided, if governments respond to water scarcity by improving efficiency and redistributing water to where it has the most benefits. However, in regions with very severe water scarcity, such as Central and East Asia, losses of more than 5 % of gross domestic product can be expected even with better water management. In these regions, more far-reaching political measures and reforms are needed to counter the projected effects of climate change (World Bank, 2016a).

3.2.2 Social inequalities and geopolitical power shifts

Water supply and quality also depend on forms of use, settlement structures and distribution infrastructures. The management of the resource, embedded in a larger governance framework for political and social control, determines its sustainable use; at the same time, however, it is dependent on the climatic, geological and topographical conditions (Huggins et al., 2022).

Social polarization processes weaken social cohesion, promote the fragmentation of governance systems – in the area of water management, particularly with regard to formal and informal, non-state water governance – and weaken social resilience: on the one hand to sudden disasters such as floods, and on the other to 'creeping disasters' such as prolonged periods of drought or the gradual collapse of irrigation infrastructures (Fig. 3.2-3; Huggins et al., 2022; Section 2.3.2).

The following sections take a closer look at the social dimensions of the worsening water crisis, in particular at the escalating effects of autocratization and polarization processes, geopolitical interests, multidimensional poverty and social inequalities.

3.2.2.1 Geopolitical exacerbated challenges

Polarization and autocratization make international cooperation on water more difficult

Since water circulates in cycles, the management of water and biological resources is often a task that transcends political boundaries (Huitema and Meijerink, 2017). This is particularly relevant in times of increasing geo- and security-political tensions. An increase in social polarization processes has been observed for years in countries on all continents and in all income groups (low-, middle- and high-income countries). In many countries, these are also accompanied by political autocratization processes (Nord et al., 2024; Nowack and Leininger, 2022). At the level of multilateral policy-making, this also leads to an autocratization of international negotiations, for example within the UN Security Council or the UN General Assembly (Kloke-Lesch and Hornidge, 2023; Lührmann and Lindberg, 2019; Emmons, 2020). Current examples include the disputes surrounding Israel's war in Gaza following the terrorist attacks by Hamas on 7 October 2023, or the Russian war of aggression against Ukraine.

In the areas of transboundary water management or water-related multilateral negotiations, the increasing geopolitical tensions represent an additional exacerbation of the situation. Examples can be found in cross-border water management along the borders of China and India or in parts of Central Asia, as well as in the Middle East

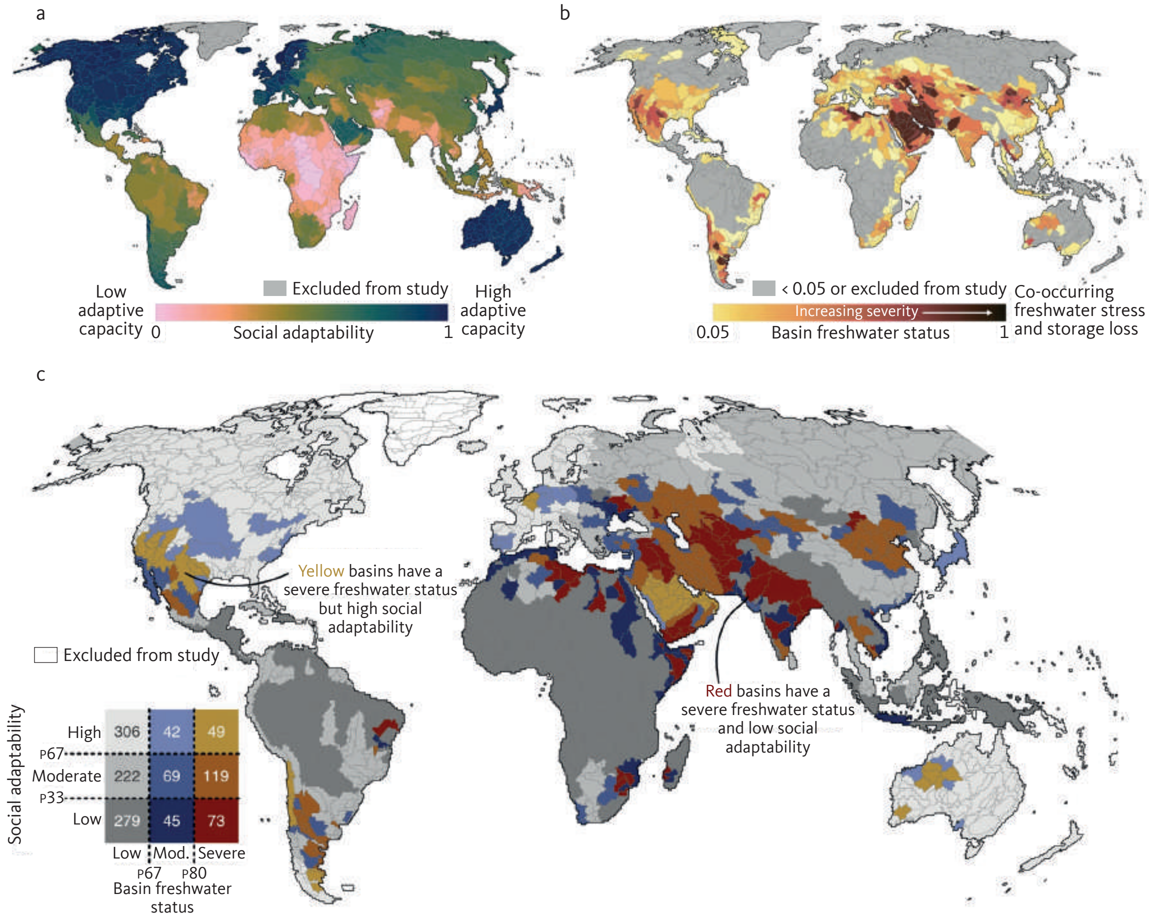


Figure 3.2-3
The relationship between the freshwater status (combination of freshwater stress and storage trend per catchment area) of a catchment area and social adaptive capacity. a) Social adaptability in the catchment area. b) Freshwater status in the catchment area. c) Combination of freshwater status in the catchment area and social adaptability.
Source: Huggins et al., 2022

or along the border between the USA and Mexico. At the level of multilateral water governance, the fact that some countries, such as South Africa or Mongolia, regard the agreement of global standards and rules for a common water policy as an unacceptable infringement of their national sovereignty makes it more difficult to develop such a policy further (Dombrowsky et al., 2022b).

This prevents the development of common global or even regional approaches and solutions to eliminate water scarcity and pollution, which are necessary in view of the impact of global environmental changes on the local and regional dimension of these problems.

An increase in political autocratization can make it more difficult to implement participatory approaches to water management that are geared towards balancing interests and distributive justice, as well as sustainable resource management. The competition for groundwater between farmers and the central government in Azraq, Jordan, is an example of unsustainable resource management by a moderately autocratic regime, and points to possible limits of autocratic systems for a socio-ecological transformation (Dombrowsky et al., 2022a; Hornidge et al., 2013). Similarly, a strongly hierarchical water-management system does not appear conducive to sustainable water use in many cases, as it makes it difficult to coordinate different sectors and actors (Lukat et al., 2023; Hornidge et al., 2013).

3.2.2.2
Social inequalities, poverty and power imbalances exacerbate the unequal distribution and overexploitation of water

Clean water is not only a scarce and sought-after commodity but also a very unequally distributed one. Consequently, water governance is characterized by very different constellations of actors and interests between different social contexts, countries, regions and different levels of governance. Especially in some subtropical countries and areas with high water scarcity, unequal water distribution often exacerbates water emergencies.

Calow and Mason (2014) point out that water crises are often caused not by a lack of supply but rather by unequal distribution. In addition to inequality, poverty and a highly unequal distribution of political and economic power are also seen as key factors in the global water crisis (Calow and Mason, 2014). The unequal distribution of water and the overexploitation of water resources can be seen, among other things, in the higher water consumption of higher-income population groups in urban areas. In Cape Town, for example, the richest 14 % of residents consume 51 % of the city's water, while low-income households and those in informal settlements, which make up 62 % of the urban population, consume only 27 % of water (Fig. 3.2-4; Savelli et al., 2023). At the same time, it is the socially disadvantaged groups and informal settlements that often do not have the infrastructure needed to collect or drain heavy rainfall, for example, or to ensure access to water over longer dry periods. As a result, the impact of the increasing interdependence of climate change and socio-political circumstances is steadily growing. Groups that are already vulnerable and characterized by inequalities, such as girls and women, multidimensionally poor people (multidimensional poverty goes beyond the measurement of income and includes education, health and standard of living; see Chapter 2) and children, are further disadvantaged by the unequal distribution of water, and existing water problems are increasing (Schleifer and Otto, 2019). Climatically and ecologically induced problems with the water supply and distribution deficits reinforce each other.

3.3
Consequences and challenges caused by damage to the health of species, ecosystems and humans

The increasing climate crisis and pollution, and the associated effects on hydrological processes, environmental conditions and, not least, on biodiversity will have direct and indirect consequences for human health (Section 3.3.2), also impacting on the health of other organisms and – associated with this – on the functionality and species composition of ecosystems (Section 3.3.1). The threat ranges from restrictions on the performance of individuals, including humans, due to physiological effects and infections, to the loss of habitats and negative impacts on the cohesion and functioning of ecosystems and societies, and on the stabilization of the water balance used (Capon et al., 2021; Caretta et al., 2022; Scherer et al., 2023; Albert et al., 2021).

3.3.1
Impacts on freshwater ecosystems, organisms and biodiversity

Freshwater ecosystems worldwide are already severely and irreversibly damaged and increasingly restricted in their functionality and provision of ecosystem services (WBGU, 2023; IPCC, 2022, 2023a; Section 2.2.1). A number of these ecosystems have already been largely lost because of drainage; the remaining systems are still at risk due to the combination of the various exacerbated challenges (Sections 3.1, 3.2). These negative changes – such as the restrictions on the water supply and quality, reductions in the resilience of aquatic ecosystems or even their complete loss – will continue without effective countermeasures (Fig. 3.3-1).

All ecosystems, both aquatic and terrestrial, contribute to the global hydrological cycle (Section 2.1). Freshwater ecosystems in particular are increasingly under threat; they are already becoming degraded, and this process will continue faster than that of terrestrial ecosystems in the future unless the trend is reversed (Fig. 3.3-1; Albert et al., 2021; Vari et al., 2022). Bodies of fresh water around the world are particularly affected by rising global temperatures, as both water quality and water quantity are greatly influenced by atmospheric temperature conditions. This is further exacerbated by the disproportionately high degree of alteration and destruction compared to other ecosystem types, including drainage by humans. Human intervention increases the vulnerability of freshwater ecosystems to the effects of climate change and limits their adaptability (Capon et al., 2013; Reid et al., 2019; Capon et al., 2021). As global warming continues, the increasing intensity and duration of heatwaves, and the reduced mixing of the water column due to the formation and separation of water layers based on their different temperatures (Section 2.2.1.2), will also aggravate oxygen depletion; this will be exacerbated by the growing release and accumulation of CO_2 (Woolway et al., 2021; Polazzo et al., 2022, Parmesan et al., 2022: 200; Capon et al., 2021). This further impairs the water quality for organisms and their communities, while

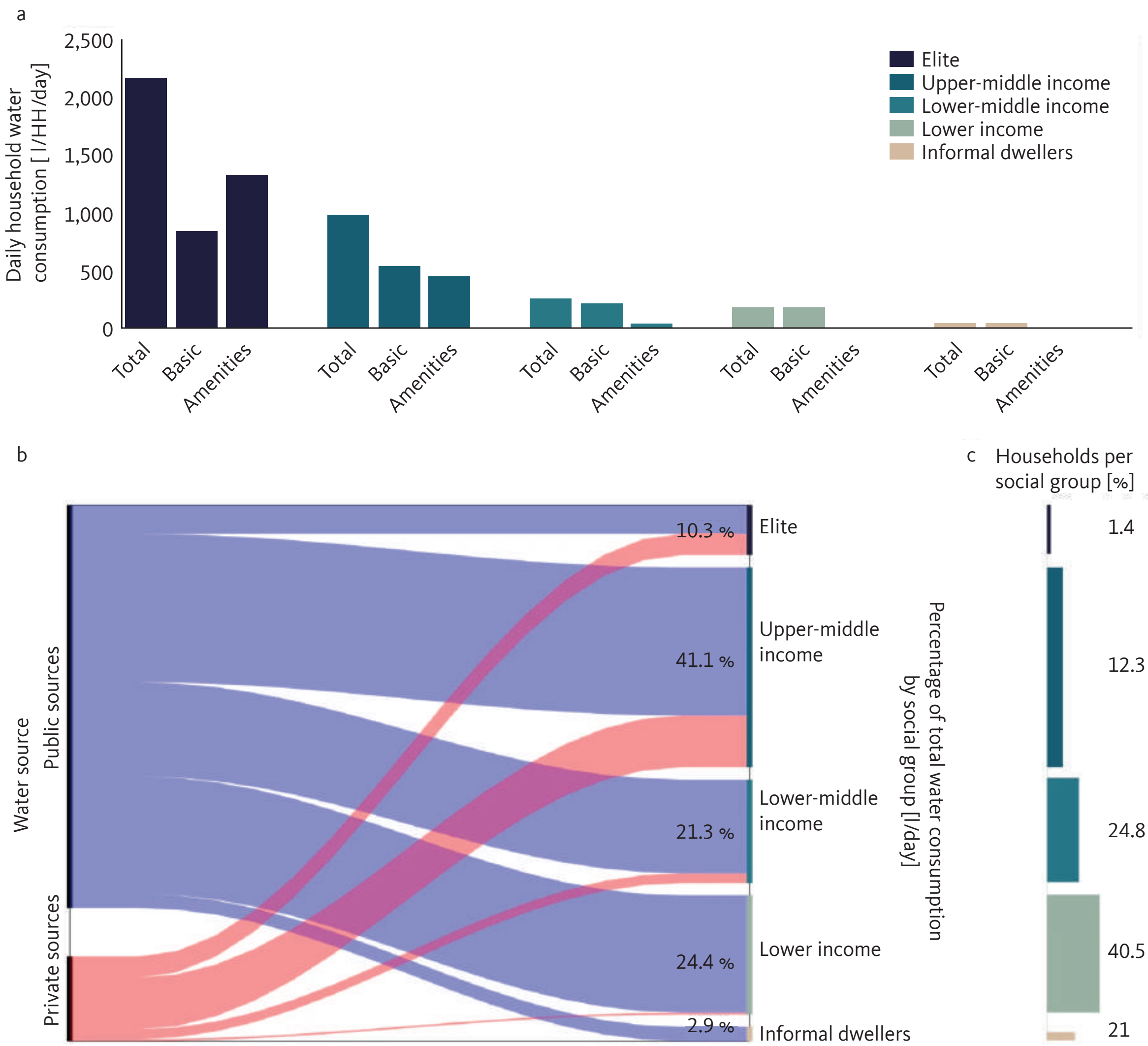


Figure 3.2-4
Modelled water consumption in Cape Town by social group. a) Daily water consumption by social group. b) Water consumption by social group as a percentage of total water consumption. c) The respective social groups as a percentage of total households. Source: Savelli et al., 2023: 931

at the same time increasing demand for oxygen (Capon et al., 2021), e.g. in rivers in the Mediterranean region (da Silva et al., 2023).

Climate change is also altering the water levels in lakes and the seasonal water volumes of rivers (Section 3.1.1.3). This influences connectivity, i.e. the interconnectedness of the water bodies (Parmesan et al., 2022: 200), or leads to changes in nutrient content and water quality with corresponding consequences, e.g. for the food web (Caretta et al., 2022: 618). At the same time, the (seasonal) ice cover of lakes and rivers will decrease (Parmesan et al., 2022). In extreme cases, more frequent and more intense extreme events can lead to the loss of the entire freshwater ecosystem. The negative effects of droughts in particular are also occurring more frequently in our latitudes, as was the case in large areas of Europe in the summers of 2018, 2019, 2020 and 2022 (Buras et al., 2020; Blauhut et al., 2022). The increasing (seasonal) variability and extreme fluctuations in the water supply, together with increasing physical and chemical changes, can have drastic consequences for all freshwater and terrestrial ecosystems worldwide.

The stressors described lead to ongoing changes in species composition and to the disruption of interactions between species, e.g. changes in predator-prey or dominance relationships, and new types of biological communities are formed. This leads to changes, often simplifications of ecological processes and functions involving a reduction in their resilience (Pecl et al., 2017; Caretta et al., 2022; Parmesan et al., 2022; Seebacher

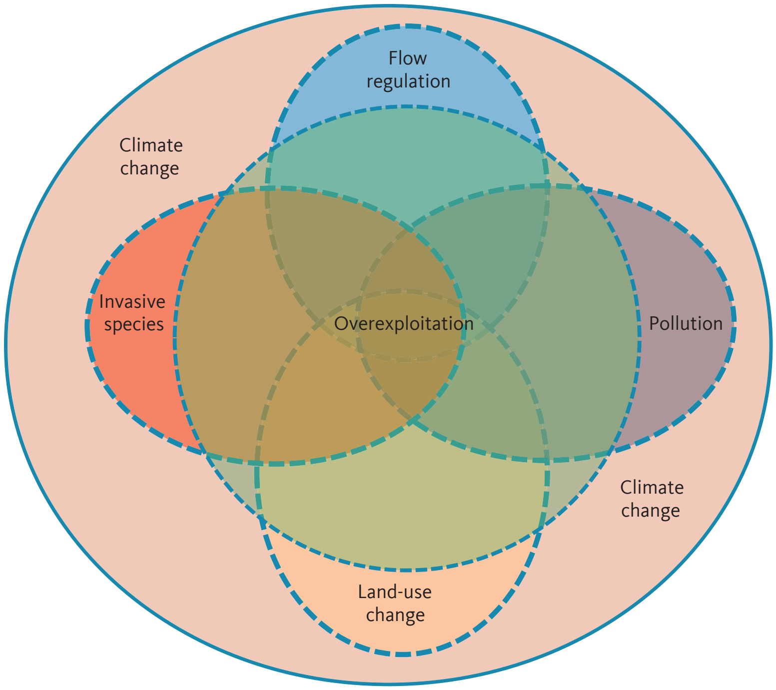


Figure 3.3-1
Conceptualization of global threats to freshwater ecosystems. The entire planetary action space is shown by the ellipse of climate change (pink). The individual freshwater bodies can be positioned within this action area according to the combination of threat categories to which they are exposed. Overexploitation occupies the centre of the space because it is the earliest and sometimes only threat to freshwater biodiversity in remote or sparsely populated areas. Most bodies of freshwater are located in areas where three or more threat categories overlap.
Source: Dudgeon, 2019

et al., 2023). At the same time, the distribution areas of freshwater species are increasingly shifting polewards and to higher altitudes as a result of temperature changes. Although these changes are smaller in scale, their mechanisms are comparable to those already observed in the ocean (or in some cases on land) and are predicted to have increasingly drastic effects in the future (Pörtner et al., 2014). Changes in the time indicators ('zeitgebers', i.e. external influences that affect the internal clock of an organism, e.g. light or temperature) on land and in water – e.g. a temporal change in the ambient temperature in spring – lead to an ever earlier onset of spring flowering, spawning or to an extension of the growing season (Parmesan et al., 2022: 200). Similar phenomena are effective on land and also lead to earlier water consumption by the vegetation (Parmesan et al., 2022: 225). As a result, the temporal consistency of different ecological processes is lost. The time windows for activities and growth between and within species and life stages no longer overlap, which will affect their customary interactions in the future, for example in food intake, competition or reproduction. These processes not only change and threaten existing ecosystems (Section 2.2.1), but also create new ones with unforeseeable compositions and unknown properties. For example, the increasing melting of glaciers is creating post-glacial ecosystems whose future ecological conditions and characteristics may vary from region to region and are generally still poorly researched (Bosson et al., 2023).

Specialist (especially cold-dependent) species and species that are found only on glaciers or in glacier-dominated habitats (endemics) will lose their habitats (Bosson et al., 2023: 566). Individual refugia may persist (Wilkes et al., 2023), but the spread of different post-glacial ecosystems will "locally enlarge the habitats, ecological connectivity and adaptability of generalist species" and lead to a homogenization of habitats (Bosson et al., 2023: 566).

Seasonal changes in the water volumes of rivers, for example, as well as droughts and floods, are leading to an increasingly limited supply of water for flora and fauna. Terrestrial animals have adapted to fluctuations in water supply in different ways. Some mammals, such as camels and some rodents, can use water extremely economically and even manage with the water gained from the oxidation of dry food; accordingly, they will also be more resilient to fluctuations in the water supply in the future. Others, not least humans (Section 2.1; Section 3.2.2), react very quickly to a lack of water with health problems, especially if they are exposed to heat. In combination with heat, increasing water scarcity and droughts will lead more and more to mass extinctions of wildlife in terrestrial and freshwater ecosystems as well as the marine coastal zone (intertidal zone, shallow lagoons and rock pools). In addition, the composition of the vegetation will change (Parmesan et al., 2022; WBGU, 2023).

For example, the vegetation's water requirement increases with rising temperatures and will eventually no longer be met as soil moisture decreases, even if precipitation remains constant or even increases. The result will be vegetation shifts and transitions towards dry forests, steppe formation and, finally, desertification, if the plants dry out or the lethal heat-tolerance limit is exceeded and the vegetation dies off. Due to rising temperatures, increasing drought and falling groundwater levels, the percentage of native trees that are damaged will also rise from year to year, the productivity of the vegetation will fall and the adaptation limits of some species will be exceeded (Teskey et al., 2015; Hammond et al., 2022). Especially in monocultures, pests like the bark beetle can then spread more easily. Increasing pest infestations and the subsequent use of biocides in forestry could also damage water quality. In particular, the application of pesticides close to the ground to damaged wood stored in the forest (i.e. trees damaged by storms, ice or insect pests, for example) can lead to leaching from the adjacent soil surfaces into surface waters and deeper soil layers and possibly entry into the groundwater (Kahle and Nöh, 2009; Rivera-Dávila et al., 2021). Due to the poor biodegradability and the disruptive effect on the hormone balance (endocrine disruptors), this can be associated with negative effects for insects, aquatic organisms and, not least, for humans (Section 3.3.2; UBA, 2017; UBA and BMU, 2017; Tang et al., 2021). Examples of toxic substances include cypermethrin products, which have only been banned in the EU since 2021, and lambda cyhalothrin in forestry. Both substances are now characterized by the EU as environmentally harmful biocides (new priority or priority hazardous substances under Directive 2013/39/EU of the European Parliament and the Council).

The increasing dryness of forests due to water shortages and a lack of precipitation also increases the risk of forest and steppe fires worldwide (IPCC, 2021b). Increasing flooding outside the normal regime (Section 3.1.1) is also detrimental to the productivity and health of ecosystems and their inhabitants, fuelling disease and the death of wildlife, not least through drowning but also through habitat destruction (WBGU, 2023). The increasing salinization of freshwater is also a threat to vegetation, wildlife and entire freshwater ecosystems (Grieger et al., 2020; Jeppesen et al., 2023). Not only will the supply of drinkable water continue to decrease in the future but also biodiversity in brackish water. This is confirmed by the observation that freshwater and marine ecosystems achieve a higher biodiversity than brackish-water ecosystems at stably different salinities. Excessive precipitation will also lead to increasing salinization (Section 3.1.1) on coasts or in lagoons and put pressure on marine organisms and communities. This also applies especially in the extensive intertidal zones (mudflats) of shallow seas such as the North Sea.

Rising pollution (Section 3.1.3) also further restricts organismic performance when concentrations that are hazardous to health are reached. Climate change, biodiversity loss and pollution can also harm the purifying microorganisms in the groundwater and thus further reduce water quality. Pollutants, increasing heat stress due to climate change, and possibly also increasing geothermal use interact and endanger the purifying microorganisms (Blum et al., 2021). Overall, a further decline in water quality is predicted worldwide, and there are also fears for Germany that water quality in ecosystems will come under further pressure in the future due to the pollutants introduced (UBA, 2018b)

In total, a loss of habitat or habitat quality is becoming apparent, especially for terrestrial and freshwater ecosystems – a loss which is determined not only by temperature extremes but also by the supply of freshwater. The supply of water is fundamental to plant growth – and therefore to the functioning of ecosystems like forests or grasslands. Conversely, healthy ecosystems such as forests are essential for locally stable freshwater availability. Water is therefore not only important for biodiversity; biodiversity is also important for water. However, biodiversity will continue to decline in the future as warming progresses and precipitation patterns change, except in the scenario with the lowest greenhouse-gas emissions (IPBES, 2019: XLI; Caretta et al., 2022: 617).

This is exacerbated in many aquatic and terrestrial ecosystems by declining water quality, for example due to the input of nutrients and the resulting increase in eutrophication and deoxygenation (IPBES, 2019a: 349, 61). In a scenario by Albert et al. (2021), the projected changes up to 2050 are shown as extrapolations of the changes since 1970 (Fig. 3.3-2). As long as no tipping points are crossed, such a development presupposes that human behaviour does not change ('business as usual', BAU) and that no transformative action is taken. It is becoming clear that this is not an option for a sustainable future. The projected increased loss of biodiversity due to intensification and the associated

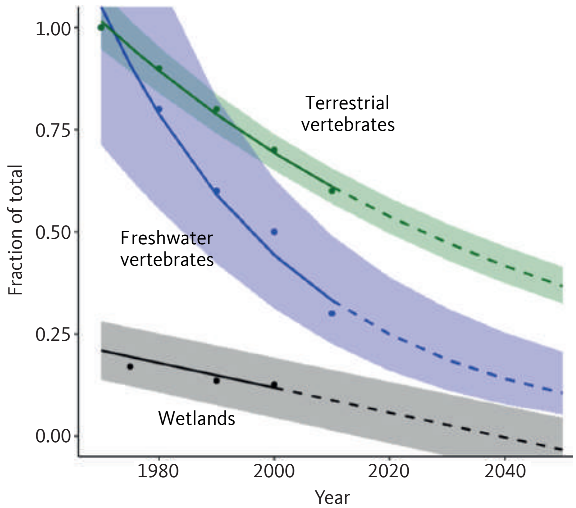


Figure 3.3-2
Trends in global biodiversity from a 1970 baseline. Living Planet Index (biodiversity indicator) for freshwater vertebrate populations (blue), terrestrial vertebrate populations (green) and global wetland loss (grey). The model of global wetland loss was adjusted to the data from 1700 to 2000 and plotted for compatibility with the Living Planet Index datasets from 1970 to 2050. Historical estimates as solid curves with 95 % prediction intervals. Data as cumulative proportions of global totals.
Source: Albert et al., 2021

loss of ecological functions within freshwater and other ecosystems is increasingly jeopardizing the services provided by nature, which also support human life on planet Earth (Lynch et al., 2023).

3.3.2 Increasing impact on human health

Human living conditions can also change so unfavourably that local livelihoods and food supplies are no longer guaranteed. Changes in water quality and quantity and the associated lack of safe water are only part of the threat scenario. Water scarcity, pollution and flooding affect people both directly and indirectly. They can result in the permanent loss of health, healthcare and hygiene facilities, social structures, and even a large number of human lives. Irregular or insufficient water supplies compromise not only the vitality of individual people and their performance in society but ultimately also the performance of society as a whole, with corresponding economic and socio-political consequences. This affects not only the ability to prepare for repeated loss events and limit risks through adaptation, but also to maintain economic performance in the event of increasingly intense loss events (IPCC, 2022a, 2023b).

3.3.2.1 Supply and quality of drinking water

Like other organisms, humans need a stable supply of water in sufficient quantities and of sufficient quality (Section 2.1). Rising ambient temperatures increase the daily basic requirement (Jequier and Constant, 2010), so that the supply of sufficient drinking water is an existential prerequisite for successful heat-protection measures in the climate crisis. In the context of increasing heatwaves, heat-protection measures serve to prevent health problems, in particular to protect vulnerable groups such as people with pre-existing conditions, the elderly, children and pregnant women.

Water shortages could cause drinking-water wells to dry up or become contaminated. There are already examples of this today, and they will become more frequent in the future. The situation has worsened in particular in the Middle East, North Africa, southern Africa, the west coast of Latin America, Central Asia and Indonesia. But Australia, parts of the USA and the Mediterranean region are also facing major challenges (IPCC, 2022a). In low-income countries especially, this could lead to people having to cover even longer distances to obtain drinking water. This task is still performed almost exclusively by women. Differences between rich and poor and between the sexes threaten to become more pronounced, with drastic physical health consequences for disadvantaged individuals (Romanello et al., 2023). Water is not only needed for drinking, but is also irreplaceable for hygiene and sanitation (WASH, clean water and sanitation). Here, the United Nations' successes in the battle for SDG 6 could be cancelled out by advancing climate change (UN, 2018). In addition to drought and drought-related water scarcity, higher water temperatures and more frequent flood events increase the pressure on the continued existence and further development of safe WASH conditions, especially in countries with inadequate wastewater treatment (Mora et al., 2022; UN Water, 2023; Section 3.1.3).

While floods can flush faeces and contaminated soil into surface waters and drinking-water-supply systems, droughts and high temperatures lead to a decrease in water volumes and a concentration of pollutants and germs, creating a preferred breeding ground for vectors of infectious diseases and parasites. The number of associated diseases could rise again worldwide (Mora et al., 2022).

Furthermore, the quality of medical care also depends significantly on the quality of the water supply (e.g. patient care including intravenous fluids or dialysis) or has an influence on it through its own environmental impacts (e.g. hazardous medical waste and chemicals), i.e. it can itself contribute to exacerbation (Sugg et al., 2020; WBGU, 2023). The dangers posed by medical waste such as X-ray contrast media, antiepileptics, antihypertensives, antibiotics and hormonal contraceptives are explained in detail in the WBGU report 'Healthy living on a healthy planet' (WBGU, 2023: 182 ff.). While the increasing use of pharmaceutical products in the EU is being counteracted, e.g. with the fourth purification stage in wastewater treatment plants (Section 7.1), there could be increasing contamination of water bodies in some regions worldwide with residues and metabolized trace substances from municipal wastewater, medical facilities and pharmaceuticals production – with an increased likelihood of exposure and associated health risks for the people in the affected regions if wastewater treatment is inadequate. The increasing relocation of production to low-income countries and the associated water pollution due to a lack of, or less stringent, environmental regulations is a growing problem for the health of aquatic systems and local human health (Ranjan et al., 2022).

The same applies to the administration of growth-promoting hormones in livestock farming, which is banned in the EU but is practised in countries outside the EU. As meat consumption rises, an increase in hormones in water and drinking water is to be expected (Cheng et al., 2020; Yazdan et al., 2022). In the EU states, as in other countries, the use of hormones in livestock farming is regulated but not completely prohibited. The development in targeted animal reproduction is extremely worrying. In pig fattening in particular, hormone preparations are increasingly being used to trigger superovulation (multiple ovulations) in sows, or to achieve mass synchronization and accelerated menstrual cycles. These measures are designed to maximize production yield and minimize costs. In addition to the extremely questionable method of hormone production in horses (pregnant mare serum gonadotropin, PMSG; Manteca Vilanova et al., 2019), the general public may be faced with high costs, as there has been little research into the mass use of PMSG and more expensive, synthetic alternatives and their release into the environment and thus into the water bodies. Yet effects on the endocrine system and the development of aquatic organisms are highly probable.

Another health threat is the uncontrolled release of antibiotics into the water bodies (Larsson and Flach, 2022). Bacteria living in water or hosts can develop antibiotic resistance and, if transmitted to humans, can no longer be combated with reserve antibiotics, or only to a very limited extent. One reason for this is the excessive and inappropriate use of antibiotics in humans and in agriculture (WBGU, 2023). Like the WHO, the WBGU sees this as one of the greatest current threats to global public health (WHO, 2022b).

3.3.2.2
Physical and psychological dangers of increasing extreme events

Floods have direct impacts on people's health, both physically (injuries, possibly fatal) and psychologically (anxiety, depression and post-traumatic stress disorder), as well as through the loss of medical care (staff and infrastructure) or access to it. While, according to the Lancet Countdown Report 2023, the risks of flooding in high-income countries have decreased due to infrastructural flood-protection measures, additional efforts must be made to improve the prediction and assessment of the exacerbating challenges from flood disasters (Romanello et al., 2023).

Floods have both short-term and long-term health consequences (WBGU, 2023). Long-term exposure to water is life-threatening for humans as land-living organisms. In addition to the risk of drowning as a result of (flash) floods, or burial in landslides, there is a growing risk of psychological stress for people who experience evacuation or the loss of their homes or even their entire home regions. "The main causes of morbidity among affected residents and relief workers immediately after floods are injuries and wound infections, inflammatory reactions of the skin, conjunctiva and respiratory tract, as well as a worsening of pre-existing chronic diseases"(WBGU, 2023). Flooding of sewage-treatment plants, agricultural land, industrial areas or contaminated soil can release toxic chemicals. Pathogens can also be flushed from these sources into surface water or groundwater (WBGU, 2023). The rising frequency of flooding will therefore increasingly restrict quality of life and economic success in the future. If the future global temperature were to increase by 1.5 °C, human losses due to flooding would increase worldwide by 70–83 % and direct flood damage by 160–240 % – depending on socio-economic development – compared to the reference period 1976–2005 (Dottori et al., 2018).

Progressive climate change will lead to an expansion of the world's arid regions, in which an estimated 30 % of the world's population already live today (WBGU, 2023). The percentage of land areas affected by (extreme) drought each year has already risen from 18 % in the period 1951–1960 to currently 47 % (2013–2022) and will continue to rise (Romanello et al., 2023). The number and duration of droughts has increased by almost 29 % since 2000, with the highest number of drought-related deaths occurring in Africa (UN Water, 2023). A further intensification of these trends is forecast, as already explained in Section 3.1.3. Areas of the world that already suffer from a lack of precipitation will be particularly affected by extreme droughts (Section 4.3; UNESCO, 2020). This also makes a balanced diet increasingly difficult and can have a corresponding adverse effect on health. The WHO has estimated that 74,000 children under the age of five died from malnutrition in 2019, all of them in low-income countries (WHO, 2023). These children's protein or energy requirements could not be adequately met. The consequences are underweight, underdevelopment, short stature and diarrhoea. In 2019, 148 million children worldwide were underdeveloped and 45 million suffered from malnutrition. Exacerbated challenges due to climate change could reverse the current trend of globally declining malnutrition, with unfavourable prospects for the future.

Further health risks for humans result from unfavourable changes in natural processes. Rising temperatures and periods of drought increase evaporation and reduce the amount of green water. Increasing forest dieback due to a lack of resilience to heat and drought, caused in part by the misguided forestry practices of recent decades, is leading to the loss of forests as living water reservoirs, and thus also increasing the risk of forest fires (Sections 2.2.1, 3.1.1; Romanello et al., 2023).

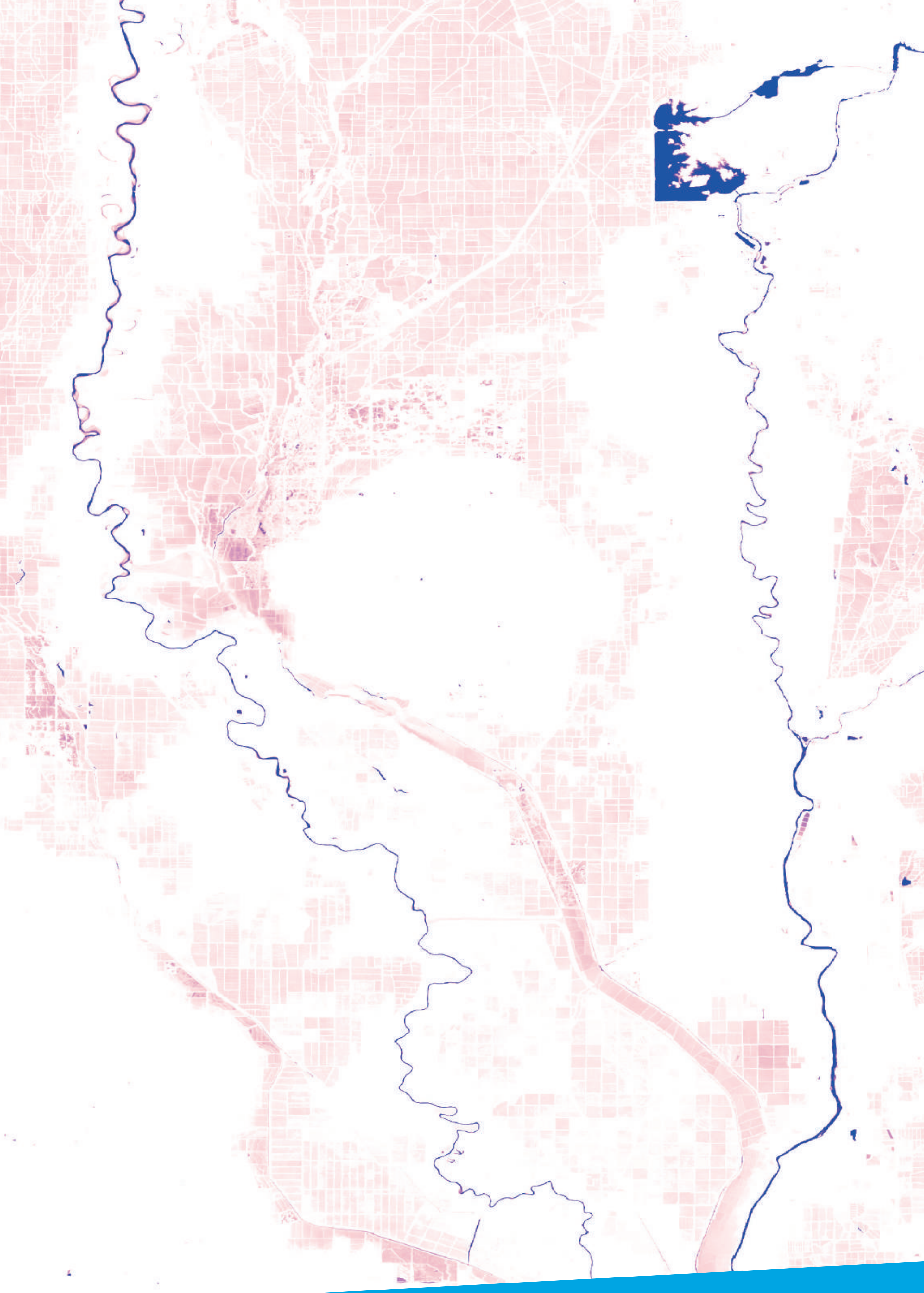
For humans, forest fires pose risks to life and limb, both through direct fatalities from wildfires and through the associated air pollution all over the world. Soot particles and, in some cases, highly carcinogenic compounds from fires will further reduce the quality of life by worsening air quality in the coming years. Successes in air-pollution control could be reversed. Respirable particulate matter (PM) also reduces life expectancy by between several months and several years due, in particular, to diseases of the respiratory and cardiovascular systems (Kirrane et al., 2019; Maximilian et al., 2023). Compared to the period 1995–2014, the number of days on which people are exposed to a (very) high risk of forest fires on a global average is expected to increase by around nine additional days by the middle of the century, which corresponds to an increase of 11 % (Romanello et al., 2023).

3.3.2.3 Increasing spread of infectious diseases

The changed climatic conditions, combined with water shortages, pollution and extreme events such as more flooding favour the spread of infectious diseases. There will be an increase in e.g. gastrointestinal and respiratory diseases, as well as parasite infestations (IPCC, 2022b) – with dynamics that favour the uncontrolled spread of diseases. The global rise in temperature favours the spread of vector-borne infectious diseases, since vectors such as the Aedes mosquito can spread further and further into previously temperate climate zones. At the same time, increasingly frequent flooding is leading to the spread of water-borne and vector-borne diseases such as cholera, diarrhoea, dengue, hepatitis A and E, leptospirosis, parasitic diseases, rotavirus, shigellosis (bacterial dysentery) and typhoid. The Lancet Countdown Report 2023 predicts that the transmission potential of dengue will increase by 36–37 % by the middle of the century. In a 2 °C global warming scenario, malaria could in future spread to 23 % of hitherto malaria-free land areas (Romanello et al., 2023).

3.4 From global exacerbated challenges to regional water emergencies with a planetary dimension

Enormous efforts are already required in order to overcome the challenges involved in dealing with water in systems influenced by humans – as outlined in Chapter 2. Chapter 3 has outlined the emerging global intensification of their influencing factors: these include climate change and pollution, socio-economic and geopolitical developments, and damage to the health of species, ecosystems and humans. They could cause regional emergencies with a planetary dimension that are almost impossible for humans to control. These exacerbated challenges do not exist in isolation, but can produce far more drastic effects in combination with others. These 'compound impacts' demonstrate the urgency of the transformation to sustainability (by changing fundamental system properties) in society, industry, transport, energy, infrastructure, land and space use, and in dealing with natural ecosystems in order to avoid adverse developments and strengthen the resilience of affected systems. Chapter 4 uses five regions as examples (urban agglomerations, MENA region, Hindu Kush, Sub-Saharan Africa, Central Valley) to illustrate where, why and how regional water emergencies have occurred beyond the spectrum of human experience. The emergencies discussed are of the kind that will not remain regionally limited, but will occur worldwide as recurring patterns, i.e. they will develop a global dimension.



Regional water emergencies with a planetary dimension

4

In particularly vulnerable regions, extreme water emergencies can develop that are beyond the scope of human experience. These crises destabilize societies and ecosystems. Examples include water scarcity in cities, droughts and flash floods in the MENA region, melting glaciers in the Hindu Kush-Karakoram-Himalayan mountain range, water pollution in Sub-Saharan Africa or groundwater overexploitation in the Central Valley. These water emergencies can overburden societies regionally and also harbour global risks. Similar patterns occur in many other parts of the world.

The exacerbated water-related challenges described in Chapter 3 can lead to regional water emergencies with a planetary dimension.

4.1
The new scale of regional water emergencies

In recent years, changes have occurred in natural water availability and water supply that are outside the range of variability experienced to date in many regions around the world. This applies to the extent of the changes (from regional to planetary), the frequency and duration of droughts, the scarcity of water resources, and the more frequent occurrence of extreme precipitation and flooding (IPCC, 2022b; Reichhuber et al., 2022; UNESCO, 2023). The WBGU uses the term 'exacerbated water-related challenges' to describe the consequences of climate change for the hydrological cycle, water availability, water quality and the increasing human pressure on water resources (such as rising per-capita water consumption; Chapter 3). Geopolitical upheavals, too, can make sustainable water management and cooperation in transboundary water use more difficult (Kloke-Lesch and Hornidge, 2023).

4.1.1
Changes beyond the scope of human experience

Depending on regional conditions, exacerbated water-related challenges can escalate into regional water emergencies, the extent of which can go beyond the scope of human experience. These water emergencies result from a mutual intensification of the water-related challenges outlined above. These are therefore generally not isolated phenomena but complex cascades of effects or 'compound risks' associated with, among other things, considerable health risks or even death (IPCC, 2022b). The WBGU defines regional water emergencies with a planetary dimension as crises that arise from the interplay of exacerbated water-related challenges (Chapter 3). Water emergencies can be observed worldwide as recurring, typical patterns; they are characterized by a large number of affected people and can damage large natural areas and their biodiversity. The extent and dynamics of these water emergencies can exceed hitherto manageable risks. The increasing changes in the natural hydrological cycle – from melting glaciers in the Himalayas (Section 4.4) to overexploited groundwater in the USA (Section 4.6) – can develop into regional hotspots with their own dynamics. Regional water emergencies can compound existing problems, e.g. in the water, sanitation and hygiene (WASH) sector, and contribute to further societal polarization. They cause humanitarian emergencies either directly or with a time lag. These are

Sacramento River and Feather River, California (USA) characterized by a significant loss of quality of life – the loss of living space and health – and even premature death. Water emergencies can have far-reaching, even transregional consequences and lead humanity into increasingly uncertain spheres of action and a diminishing capacity to act. In their dynamics and interactions with exacerbated water-related challenges, regional water emergencies can cause a planetary emergency (e.g. food crisis).

4.1.2 Examples of regional water emergencies: overview

This section presents examples of regional water emergencies with a planetary dimension which, as patterns occurring worldwide (Table 4.1-1), could become a global challenge in the medium to long term. They have hardly been recognized by the public to date and present risks with a high probability of occurrence and a potentially high level of damage. They should therefore urgently be given greater political attention. Five regional water emergencies are highlighted below which could repeat themselves in a similar way – or are already occurring – in many regions of the world (Fig. 4.1-1):

- water scarcity in cities, e.g. Chennai, India, and São Paulo, Brazil (Section 4.2),
- the increase in droughts and flash floods in the Middle East/North Africa region (MENA; Section 4.3),
- melting glaciers in the Hindu Kush-Karakoram-Himalayan mountain range with risks for the major river basins (Section 4.4),
- increasing water pollution in many places: the example of Sub-Saharan Africa (Section 4.5),
- the depletion of groundwater that can be observed worldwide due to overexploitation and climate change, illustrated here by the example of the Central Valley in the US state of California (Section 4.6).

The examples given outline, among other things, ways of dealing with these emergencies; at the same time, they also address limits of adaptation, health risks and possible limits of controllability (Chapter 5; Fig. 5.1-1). These (regional) limits were almost exceeded, for example, during the Cape Town water crisis in 2015–2018 (Schleifer and Otto, 2019). This water crisis brought Cape Town and its approximately 4.6 million people to the brink of Day Zero, the day when the metropolis would have had no more water (Hill-Lewis, 2023). The local water emergency was just averted (Schleifer and Otto, 2019; Hill-Lewis, 2023; Simpson et al., 2023). Cape Town's water crisis was the result of mismanagement and drought.

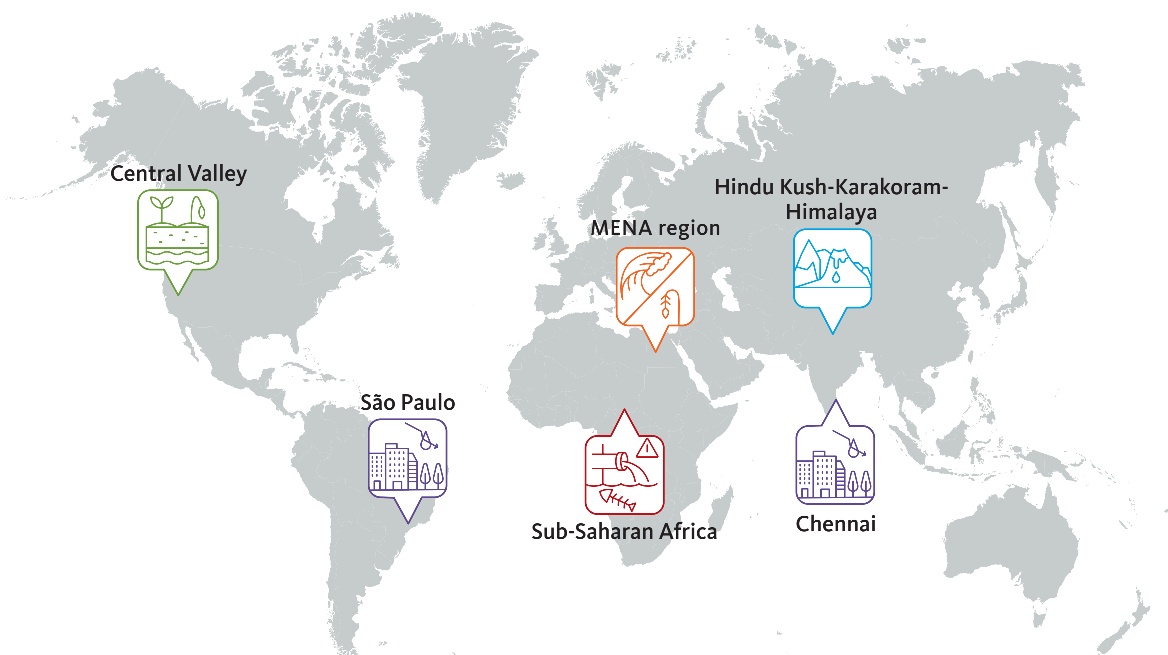


Figure 4.1-1
Geographical location of the examined regional water emergencies with a planetary dimension. Icons mark the cities and regions analysed in this section: the Central Valley in the USA, São Paulo in Brazil, Sub-Saharan Africa, the Middle East and North Africa (MENA) region, the Hindu Kush-Karakoram-Himalayan region and Chennai in India.
Source: WBGU

Table 4.1-1
Selection of regional water emergencies occurring worldwide. The table provides examples of other regions and cities affected by the five crisis patterns shown.
Sources: He et al., 2021; Hugonnet et al., 2021; Hock et al., 2019; UNCCD, 2023; Chaplin-Kramer et al., 2019; Jones et al., 2023; Wen et al., 2017; Scanlon et al., 2023

Crisis patterns	Examples of affected regions and cities
Water scarcity in cities	Megacities affected all year round (2016): › Bangalore, Beijing, Jakarta, Lahore, Lima, Los Angeles, Mexico City, Moscow, New Delhi,
Droughts and flash floods	A drought emergency was declared in 22 countries worldwide in 2022–2023: › South and North America: Canada, Uruguay, USA › Europe: Germany, Greece, Great Britain, Italy, Portugal, Romania, Serbia, Spain › Africa: Djibouti, Mauritania, Niger › Asia: China, India, Indonesia, Kazakhstan, Sri Lanka, › Oceania: Kiribati, Marshall Islands, Tuvalu
Melting glaciers and loss of water reservoirs	› Alaska › Alps › Hindu Kush-Karakoram-Himalaya › Southern Andes › Western Canada and Western USA
Water pollution	› North India › East China › Sub-Saharan Africa › Central and Northwest Mexico
Overexploitation of groundwater	› Arabian Peninsula, Iran (Middle East) › Central Valley (USA) › Central and Southern High Plains (USA) › Don and Dnieper basins (Eastern Europe) › Ganges-Brahmaputra Aquifer (India) › Hai He River Basin and Aquifer of the North China Plain (China) › São Francisco Basin (South America)

The likelihood of lower rainfall and droughts in southern Africa has increased five to sixfold as a result of climate change (Pascale et al., 2020). In June 2023, a water emergency was also declared in Montevideo (Uruguay). In addition to cities, larger regions can also be affected: the regional government of Catalonia (Spain) declared a water emergency and restricted water use from February to the beginning of May 2024 due to water shortages.

Another example is the melting of glaciers in the Hindu Kush-Karakoram-Himalayan mountain range. Depending on the climate scenario, the ice mass and glacierized area in this region is expected to decrease by 20–65 % by the end of the century (Yao et al., 2022). The glaciers are important sources for some river basins in the greater region, e.g. the upper Indus Basin, where 40 % of total runoff comes from glacier melt water (Lutz et al., 2014). The Hindu Kush-Karakoram-Himalayan region is a granary of global importance: 61 % of rice production, 35 % of wheat production and 24 % of maize production come from the region (Hu and Tan, 2018; Section 4.4.2.1). In the lowland plains of the region, e.g. in the Indus Basin lowlands, agriculture is predominantly irrigated (Scott et al., 2019).

Fundamental changes to water regimes are becoming increasingly likely due to insufficient efforts in climate-change mitigation. This makes it all the more important to act early when it comes to adaptation, even if the crisis scenario is still decades away. Otherwise, there is a risk of increasing societal destabilization with growing potential for conflict over ever scarcer water resources and corresponding security-policy consequences.

Mitigating progressive climate change and biodiversity loss, as well as critical changes in water availability, quality and supply, must therefore be given top priority in order to maintain human societies' ability to act. If efforts remain below the required level, humanity will leave its safe sphere of action. The progressive narrowing of the room for manoeuvre in dealing with climate-change-related adversities or intolerable developments means that, at a certain point, the limits of adaptation (depending on resilience) and thus the limits of controllability will be reached (Chapter 5). In extreme cases, the result will be an inability to act, with negative consequences for the well-being and health of humans and nature. The transition from controllability to uncontrollability depends on the respective general adaptive capacities and the ability and willingness of societies to build or restore resilience, for example through the application of capital, technologies and lifestyle changes and the willingness to make corresponding efforts.

4.2
Water scarcity in cities and urban agglomerations

> 933 million
urban dwellers today are affected by water shortages

30–50 %
of the world's population will be affected by 2050

approx. **80 %**

In the last 20 years, over 80 large cities and metropolitan regions worldwide have been affected by severe water shortages (Rusca et al., 2023). The number of reports about cities at risk of running out of water is growing (Cremades et al., 2021; He et al., 2021; Rusca et al., 2023). Montevideo declared a water emergency in June 2023, Barcelona and the Catalonia region in February 2024. Many cities are already overwhelmed by the challenge of adapting their infrastructure to the speed and dynamics of urban growth, especially in low- and middle-income countries. This problem constellation can also be found globally. More frequent or more intense extreme weather events also make undesirable developments in urban development more noticeable, especially the lack of unsealed surfaces and green spaces that can (help) regulate the urban water balance. The following section shows the dimensions of this pattern of urban water scarcity, which occurs repeatedly around the world, illustrated by two examples (Boxes 4.2-1, 4.2-2) and outlines the associated challenges.

4.2.1
Impact patterns, extent and projections

The growth of cities and their populations, the increasing pressure on water resources, exacerbated by the impact of climate change, are the driving co-factors of increasing water scarcity in urban agglomerations worldwide.

4.2.1.1
Impact patterns

In 2016, over 30 % of the urban population lived in areas where water was scarce (He et al., 2021). Lack of surface water, soil sealing, overexploitation of groundwater (abstraction exceeding regeneration) and the increase in the demand for water caused by urbanization and rising per-capita water demand are the main drivers of urban water shortages (He et al., 2021; Flörke et al., 2018; McDonald et al., 2014). Leaks in the water infrastructure are exacerbating the water shortages. Due to the rapid urbanization, two thirds of humanity, i.e. 6.6 billion people, will live in cities by the middle of the century, which means an increase of 2.5 billion people; this will raise the pressure on urban water resources (UN, 2019; WBGU, 2016). 90 % of this growth will take place in Asia and Africa, with the strongest growth expected in cities with a population of up to 1 million people (IPCC, 2022c: 65 f.). According to calculations, urban demand for freshwater is expected to rise by up to 80 % by 2050 (He et al., 2021). Urban regions in Asia and Africa are considered high-risk locations because of the projected climate change (Chapter 3) combined with unplanned, rapid urbanization (IPCC, 2022c). If global warming continues unabated, the contribution of climate change to the worldwide increase in urban water scarcity will rise significantly in the future (IPCC, 2022b). The situation is exacerbated by the competition for use between the water requirements of the growing cities and the agriculture of the surrounding regions, as well as by the influence of climate change (Box 4.2-2).

4.2.1.2
Current extent and projections

The number of people living in cities who are confronted with water scarcity will increase from 933 million people, i.e. one third of the global urban population, in 2016 to 1.6 to 2.4 billion people, i.e. one third to almost half of the global urban population, in 2050 (Fig. 4.2-1; He et al., 2021; UNESCO, 2023). Depending on the scenario, the number of major cities affected by water scarcity will increase from 193 to up to 284, including 10–20 megacities (Box 4.2-1). More and more cities will be dependent on imported water sources, transfers between water catchment areas and freshwater from desalination plants (Sahu and Debsarma, 2023).

According to United Nations data, 42 % of the world's urban population live in cities or urban agglomerations with a total population of fewer than 300,000 people (the UN defines medium-sized cities as those with a population of 1–5 million; WBGU, 2016: 42 f.). As the future global urbanization dynamic will primarily affect small and medium-sized cities, it is not enough to assess global urban water scarcity solely by evaluating

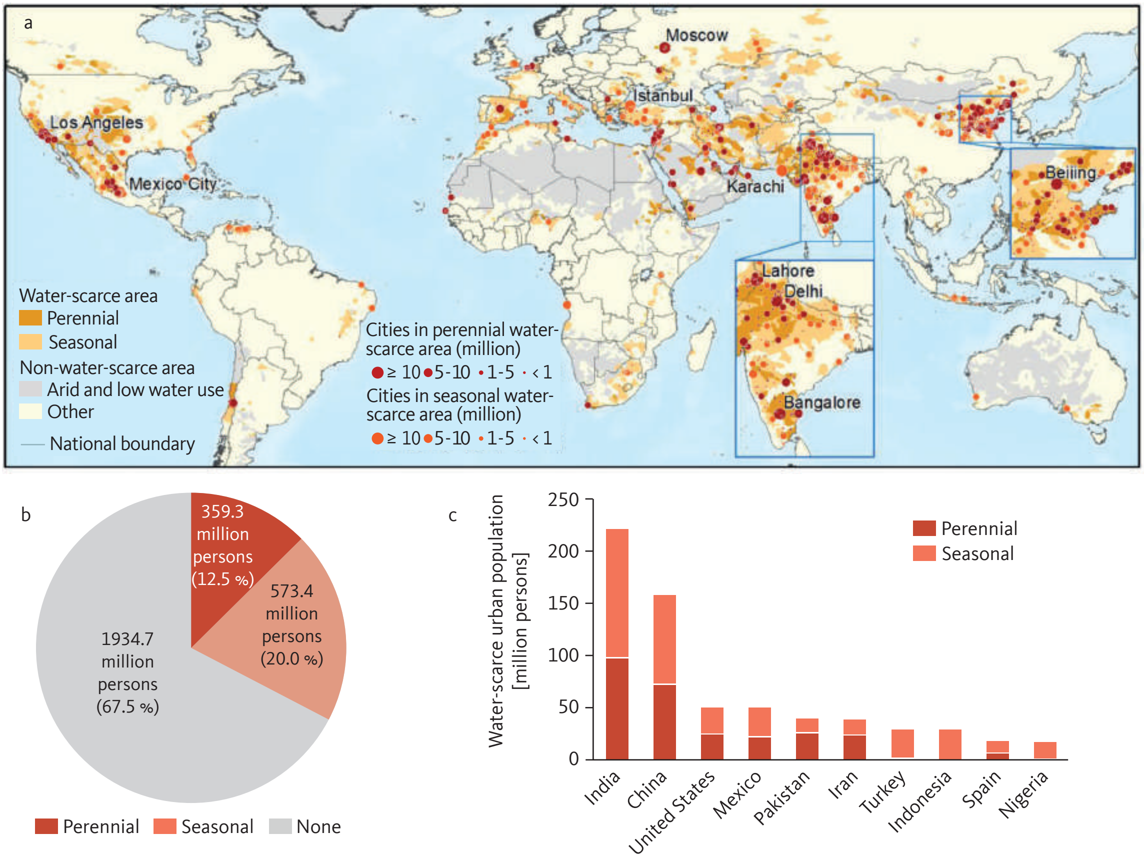


Figure 4.2-1
Global overview of water scarcity in cities. The map shows cities affected by water scarcity worldwide in 2016 according to city-size category, population and geographical location. In a global comparison, cities in India and China are most affected by seasonal and year-round water shortages. Around 20 % of the world's urban population suffers from seasonal water shortages, while about 12 % are exposed to this problem all year round.
Source: He et al., 2021

the exposure of major cities. Yet studies on global urban water scarcity often focus on large cities. Calculations on the urban population affected by water scarcity that take into account all categories of city size and not just major cities are correspondingly higher than the calculations of other studies (He et al., 2021; Fig. 4.2-1). While He et al. (2021) come to the conclusion that the number of people affected by water scarcity will rise from 933 million in 2016 to 1.7–2.3 billion in 2050, the figures from older studies are 150–810 million for the year 2000, 320–650 million for 2010 and 0.5–1.4 billion for 2050 (Flörke et al., 2018; McDonald et al., 2014).

A study of the water situation in the world's 482 largest cities (736 million people or 26 % of the world's population) revealed that 27 % of the cities analysed, i.e. 233 million people, will have a future water demand that exceeds the volume of available surface water. This poses a considerable risk to urban water security, since around 80 % of the world's cities meet their water needs primarily from surface water (Flörke et al., 2018). Rising urban water demand also increases the pressure on groundwater resources. In 238 of the cities analysed, groundwater abstraction exceeded recharge, with an upward trend until 2050. 61 cities were completely dependent on groundwater use.

A study by McDonald et al. (2014) looks at urban agglomerations with populations of more than 750,000 people; globally, there are 150 such urban regions with a total of 1.5 billion inhabitants. The study shows that despite the use of water canals or the transport of water by lorries and trains, a quarter of the cities studied were affected by water shortages because the technical measures taken to date could not fully compensate for the lack of water (McDonald et al., 2014). The study also explicitly considers the possibilities of urban water infrastructures in dealing with water stress (Box 4.2-1).

Box 4.2-1

Water crisis in São Paulo, Brazil, 2014–2016: implementation deficits of urban water legislation

Between 2012 and 2016, Brazil experienced one of the worst droughts in its history, culminating in a serious water crisis in the growing metropolitan region of São Paulo in 2014–2016. Around 20 million people live in this metropolitan region, about a third of them in favelas (informal settlements) or in slum-like conditions (Daniels, 2021). At the beginning of 2015, the water level in the Cantareira system (network of reservoirs supplying the city with water) fell to around 5 % of the total volume (Slater, 2019), triggering the worst water crisis in 80 years (Ozment and Feltran-Barbieri, 2018). The situation improved again in March 2016 after sufficient rainfall. The 2014–2016 drought crisis in São Paulo was caused in particular by management and planning failures, corruption, deficiencies in the maintenance of water-supply infrastructure and the effects of climate change (Slater, 2019).

Management and planning failures: although São Paulo has water regulations, they are often ignored or only implemented in a fragmentary manner (Slater, 2019). In Brazil, the financing of infrastructure projects is also lengthy and prone to corruption (Slater, 2019). In addition, the authorities oriented their water policy towards scenarios based on long-term average precipitation, even though the effects of climate change altering water availability had already been scientifically proven (Soriano et al., 2016). Political failure also played an indirect role. In September 2012, when the drought was already taking its course, the Brazilian government cut electricity prices by 20 % ("the population can consume all the electricity it wants because it is cheap and abundant", Slater, 2019: 14), leading to an increase in electricity consumption. Since about half of Brazil's electricity is generated by hydropower, the pressure on water resources increased further due to the increased storage volume required by the dams of the country's hydropower plants.

Increasing weather extremes: the frequency of droughts in south-east Brazil has increased significantly in recent years (Fearnside, 2021). The first half of 2018 saw another extreme drought, causing winter water levels in the reservoir of the state of São Paulo to fall to their lowest level in 17 years (Gozzo et al., 2022). 2020 and 2021 again saw unusually low rainfall. Deforestation of the Amazon rainforest is regarded as one of the main drivers of increasing droughts in Brazil. The Amazon rainforest transports large amounts of moisture into the atmosphere, which rains down again as precipitation, also in the south and central Brazil – a phenomenon described as 'flying rivers' (Getirana et al., 2021; Fearnside, 2021). In addition to climate change, the El Niño period between 2012–2015 also exacerbated the crises.

Government measures: in anticipation of an acute water crisis, an emergency plan was developed to supply the 500 most important buildings, e.g. hospitals, administration, prisons and police, but this was not made public for fear of unrest. The majority of the water supply would then have had to be provided via distribution points in public places (Watts, 2017). Thanks to timely precipitation, this did not occur.

In 2014, the state of São Paulo introduced financial incentives for more efficient water use with information campaigns and a bonus programme for saving water; this reduced consumption by 17 %. After the crisis was considered to be over in March 2016, this bonus programme was terminated again, a decision that was criticized as short-sighted (Slater, 2019). Reductions in consumption and losses caused by leaking pipes were to be achieved by lowering the water pressure in the pipe systems, which led to a temporary interruption of the water supply and was associated with an increased risk of water pollution (Watts, 2017; Soriano et al., 2016). In the end, the efforts to compensate for the water deficit were unsuccessful, and water availability in São Paulo plummeted by 74 % over the course of 2014. This resulted in protests (Slater, 2019).

The measures taken by the government of the state of São Paulo were often criticized as being too expensive and poorly timed (Soriano et al., 2016; Slater, 2019). The major infrastructure projects decided on at the time, such as the construction of canals and reservoirs or the procurement of water from other federal states, could not be realized ad hoc, and were unsuitable as short-term solutions. Improving the water-storage capacity in the catchment area of the Cantareira system using nature-based solutions has hardly been discussed to date, but offers great potential as an 'invisible reservoir'.

4.2.2
Unequal living conditions and water (in)security

How water scarcity affects the urban population is essentially shaped by the different living conditions and vulnerabilities. This applies in particular to low- and middle-income countries, where a considerable proportion of the urban population lives in informal settlements. Informal settlements and urban neighbourhoods are particularly affected by unsafe water supplies and a lack of wastewater disposal, and the people living there are often subject to risks to their livelihoods and health in the event of a crisis (Simpson et al., 2023). About a billion people currently living in informal settlements are considered especially vulnerable – and the trend is rising (UN-Habitat, 2022). Securing the urban water supply for the entire urban population will be one of the major challenges of the coming decades.

The planning authorities are often particularly hesitant when it comes to building infrastructure in informal settlements to avoid their subsequent legalization. While urban elites in cities with water shortages can often afford a high level of water consumption – e.g. by drilling their own wells, maintaining green spaces, owning

Box 4.2-2

2019 water crisis in Chennai, India: water shortage in one of the world's rainiest megacities

In June 2019, India's fourth-largest city Chennai (11 million people live in the metropolitan region) was affected by the most severe water crisis in 30 years; like the water crisis in Cape Town, it was also referred to as the Day Zero Crisis. Just a few years earlier (2015), the city had experienced the worst flooding in 100 years. Although Chennai's annual rainfall of 1,400 mm is above the Indian average, the city has the lowest per-capita water availability of India's megacities (Kalia, 2020). The groundwater level has been falling for years. After all four of the city's large water reservoirs fell below 1 % of capacity due to insufficient monsoon rainfall (90 % of rainfall occurs during the north-east monsoon in November and December) and thus practically dried up, the city's water supply fell into crisis. The four reservoirs normally provide 60 % of the city's water supply; during the dry season, the water supply is secured by using groundwater, the rest is delivered by tanker lorries. Groundwater supplies were also exhausted in June 2019. The city's groundwater is overexploited and the groundwater level has been sinking for years (Kalia, 2020). During this crisis, the city's water supply could only be guaranteed by procuring additional drinking water by lorry and train, and the price of bottled water quadrupled (Mukherjee, 2022). Droughts also change the dynamics of groundwater contamination, leading to increased health risks when these sources are used for the urban water supply (IPCC, 2022b: 926). For example, periods of drought can lead to an increased accumulation of pollutants in the groundwater. Similarly, the natural runoff into surface waters decreases during prolonged dry periods, so that the proportion of sewage water (sewage treatment plant effluent) and the substances and germs it contains increases accordingly; this has a direct impact on aquatic ecosystems and an indirect impact on drinking-water production (via bank filtrate) (Karakurt et al., 2019). In Chennai, the forced use of less safe water resources and the resulting reduction in personal hygiene led to an increased outbreak of water-borne diseases such as typhoid, cholera and worm infections (Mukherjee, 2022).

The crisis was triggered by insufficient monsoon rainfalls between 2016 and 2018. The 2018 monsoon season was the driest since measurements began, with precipitation reaching only around 60 % of the average level (Mukherjee, 2022). The heatwave from May to June 2019 then led to an acute supply crisis. The deeper historical causes lie in the extensive draining and filling (often with waste) of water bodies in and around the city to make room for the construction of buildings and infrastructure in the rapidly growing metropolis. Traditionally, Chennai had a centuries-old network of rivers, lakes, wetlands, irrigation and drainage systems that formed the basis of irrigated agriculture and provided an important buffer for the dry season. Massive sealing in the course of rapid urbanization drastically reduced the city's water-storage capacity and greatly increased the risk of flooding during heavy rainfall. In addition, the rising number of private wells being drilled deeper and deeper caused the groundwater level to drop sharply; in some cases, saltwater also penetrated the groundwater in Chennai's now densely built-up coastal zone (Mukherjee, 2022). Between 1893 and 2017, the area of surface water in the city fell from 12.6 km^2 to 3.2 km^2 (Bhalla, 2021). Between 2010 and 2020 alone, fast-growing Chennai lost 33 % of its wetlands and 24 % of its agricultural land (Mukherjee, 2022). In future, the climate in the south of India will become drier and hotter, reinforcing this trend.

India has had a National Water Policy since 1987 to guide the planning and development of its water resources (Mukherjee, 2022). The southern Indian state of Tamil Nadu aligned its own water policy with this in 1994, but has not yet adapted it to the updated National Water Policy of 2012, in which, among other things, adaptation to climate change and ecological aspects of the water balance are prominently anchored. Since 2003, all buildings have had to have rainwater-collection systems installed and in 2010, India's largest desalination plant (reverse osmosis) was built in Chennai (UNICEF, 2021).

Government measures: as a short-term measure during the crisis, drinking water was transported over long distances by lorry and train and distributed at public distribution points. As a long-term measure, for example, more desalination plants are planned to improve the water infrastructure. In addition, monitoring of water resources is to be improved, the pipeline infrastructure upgraded and water use made more efficient. The 'City of 100 Tanks' initiative aims to rebuild the water reservoirs that used to exist around temples. Green spaces are to be created to improve the water-storage capacity.

swimming pools and having water delivered by tanker – poor groups have difficulties securing their basic supply of clean drinking and sanitary water (Rusca et al., 2023). For this reason, average values for the water situation in cities often do not show the whole picture. A more differentiated overview is provided by data on access to water and water consumption that is broken down by socio-economic groups and urban neighbourhoods (Savelli et al., 2023). Even political decisions on the urban water supply do not always provide for basic needs or follow justice-based criteria, for example when water from ultra-modern desalination plants is used for industrial purposes instead of ensuring a basic supply for the population. In the event of a crisis, the potential for conflict and protest arises in particular when decisions on prioritizing supplies or rationing are made in a non-transparent manner and are inadequately or belatedly communicated. In many cases, this is a policy failure on the part of the public sector.

4.2.3 Challenges

The following challenges, among others, arise when overcoming water scarcity in cities (Section 6.4):

1. *Identifying suitable measures and speeding up their implementation:* In many low- and middle-income countries, the development and expansion of infrastructure for safe and reliable water supply and wastewater disposal is lagging behind rapid urbanization (Flörke et al., 2018).
2. *Taking the potential and limitations of the entire water catchment area into account:* In order to develop suitable measures, cities affected by water scarcity need an inventory of the current water availability that can be used sustainably in a region. Under the conditions of advancing climate change, this is also essential as a basis for developing early-warning systems. In addition to identifying suitable technical solutions, an assessment of the nature-based potential – i.e. the contributions of nature such as an urban region's water-storage capacity (green and blue water) – can provide orientation for the maximum sustainable size of a city threatened by water scarcity. The services and potential of nature for the urban water balance have often been overlooked in the past and can also play an important role in adapting cities to climate change.
3. *Upgrading the infrastructure of informal settlements and informal urban neighbourhoods:* Informal settlements, which expect strong growth rates in the future, are particularly affected by an insecure water supply and wastewater-disposal system and often at existential risk in the event of a crisis. It is precisely there that planning authorities are often reluctant to build the necessary infrastructure.
4. *Improving data quality on access to water and water consumption:* Average figures on the water situation in cities often do not show the whole picture because access to water and water consumption often vary greatly between neighbourhoods and social groups. Urban data collection should therefore be more spatially and socially differentiated.
5. *Ensuring monitoring of the implementation of regulations and a clear allocation of responsibilities:* In cities or neighbourhoods where a formal water supply has been established and suitable legal regulations on the sustainable use of water are in place, the implementation of these requirements should be monitored. In many cases, the relevant disciplines are also insufficiently integrated. The water levels of the municipal water resources must be continuously monitored. Emergency plans must be drawn up for the event of an acute water crisis (e.g. if a water emergency is declared) – some cities have already started doing this.
6. *Securing funding for adaptation measures:* The need for financing to build sustainable water infrastructures is a constant challenge in view of the high urbanization dynamic and the changing conditions caused by climate change. Improving the efficiency of water use and other measures require better-adapted solutions, combined with a different prioritization of investments and available funds in the given financial room for manoeuvre.
7. *Taking the limits of urban growth into account in planning scenarios:* Finally, there are also some cities that will not be able to effectively solve the problem of water scarcity with infrastructure measures alone (e.g. New Delhi, Lahore, Cape Town or Lima). Such cities often continue to grow rapidly. Here, changing course towards sustainable water use is made difficult by the overexploitation and pollution of ground and surface water, inefficient urban water management (e.g. water losses due to leakages, high water consumption by industry and households, inadequate forward-looking planning, or corruption), the degradation of natural areas, a lack of financial resources and the increasing pressure from diminishing water availability. This can put limitations on adaptation at an early stage and lead to an insufficient water supply. In places where the necessary amounts of water are no longer available, the energy required to extract water is too great and the long-distance transport of water is too costly, further urban growth stands in the way of sustainable development. The high water requirements of thermal power plants in urban centres often exacerbate the situation. This raises the question of the local limits to growth in cities (Cremades et al., 2021; He et al., 2021). If all available means have been exhausted and in-migration restrictions have not been sufficient, a timely organized, orderly withdrawal of parts of the population may be the only sensible option in the event of a foreseeable existential threat to the water supply.
8. *Taking precautions for an emergency and creating resilient healthcare structures:* In the event of an urban water crisis, there may be an increased incidence of water-borne diseases. Healthcare systems can quickly reach their limits or be overwhelmed by extreme events such as flooding. In low- and middle-income countries, informal urban neighbourhoods are particularly affected. The contamination of water with pathogens as a result of inadequate wastewater systems and after flooding, as well as the increased use of contaminated water during water shortages, favours the spread of infectious diseases (e.g. diarrhoeal diseases), accompanied by the risk of epidemics.

In particular, fleeing to other urban neighbourhoods or regions can contribute to the spread. Emergency plans that pay particular attention to vulnerable and informal neighbourhoods and resilient structures in healthcare facilities can effectively curb these dynamics and prevent – or at least contain – the spread of epidemics (Grimm et al., 2022; Kruk et al., 2017; Truppa et al., 2024). Examples include the creation of reserves of drinking water, disinfection facilities and emergency reserves of hygiene products, medicines and medical supplies in safe locations. Appropriate measures must be adapted to local conditions with the involvement of local authorities and organizations – where necessary, with the support of the United Nations and non-governmental aid organizations.

The intensifying water scarcity in cities and urban agglomerations is a growing global problem that could affect many people; if left unresolved, it holds considerable potential for destabilization. This problem therefore deserves greater attention in international sustainability politics, as well as in bilateral and multilateral cooperation, and requires committed, forward-looking action. Transformation research for sustainable urban development is making important contributions here (BMBF, 2023).

4.3
Increase in the number of droughts and flash floods in the MENA region

6%
of the world's population live in the MENA region

only **1%**
of global freshwater resources is available there

24%
decline in per-capita renewable freshwater availability between 2007 and 2018

As a semi-arid or arid region, the MENA region (Middle East and North Africa) has always been characterized by scarce water resources (Fragaszy et al., 2020; Ozturk et al., 2021). The region is currently home to almost 6 % of the world's population, but only around 1 % of the world's renewable freshwater is located in the MENA countries (Fragaszy et al., 2020; Namdar et al., 2021). Between 2007 and 2018, the per-capita availability of renewable freshwater in the region decreased by an average of 24 % (SIWI and UNICEF, 2023). Changing precipitation patterns, increasing aridity and droughts, heavy rainfall events and flash floods, and above all overexploitation, accompanied by major governance challenges in the equitable distribution of the few available freshwater resources are already leading to water shortages and unequal water availability for both humans and the environment in the region today. Today's challenges are primarily political in nature, but in the future water scarcity in the region is likely to increase further due to projected climate change and increasing pressure of use, exacerbating the situation for humans and nature (Chapter 3).

4.3.1
Impact patterns, extent and projections

The last few decades have been among the driest of the last millennium in the MENA region, accompanied by increasing periods of drought (Fragaszy et al., 2020). In addition to the increasingly noticeable impacts of climate change, particular problems are the years of severe overexploitation of surface waters and, above all, aquifers, the insufficient quality of water reuse and the lack of regulation of water abstraction and pollution due to inadequate governance (Hall, 2024; Oberhauser et al., 2023). At the same time, the region has experienced a shift in precipitation patterns over the last two decades (Loudyi and Kantoush, 2020). Heavy rainfall events and flash floods are a growing threat in some of the world's driest regions (Yin et al., 2023). A current example for the MENA region is the heavy rainfall and flooding caused by Storm Daniel in autumn 2023. The floods in Libya, caused by the bursting of the Mansour and Derna dams, claimed more than 4,000 lives; more than 8,000 people are still missing and more than 40,000 have become internally displaced (OCHA, 2023). The MENA region is not 'accustomed' to heavy rainfall events. The soils, some of which are overused and have been desiccated by drought, cannot absorb the water volumes in the short term (Yin et al., 2023), and the infrastructure and drainage systems are often inadequate or non-existent (Loudyi and Kantoush, 2020). In addition, most settlements are located near rivers or in floodplains (Yin et al., 2023). The risk of flooding and drought continues to increase and is likely to disproportionately affect socially disadvantaged and poor population groups in particular (World Bank, 2018).

The MENA region will simultaneously be one of the areas hardest hit by the negative effects of climate change, with many MENA countries likely to experience significantly hotter and drier conditions (Lange, 2019; Namdar et al., 2021; Hajat et al., 2023). In addition to more aridity and longer-lasting droughts, more heavy rainfall events, floods and flash floods are also forecast (Seneviratne et al., 2021; Ozturk et al., 2021; Yin et al., 2023; Section 3.1.1). Heat extremes will become more intense and more frequent and exceed tolerable conditions for humans, leading, among other things, to higher mortality

(IPCC, 2021, 2022a; Hajat et al., 2023). At the same time, the risk of flooding and salinization in coastal regions and low-lying deltas is increasing due to rising sea levels. A large proportion of the population lives on the coasts, particularly in the North African countries of the MENA region (Lange, 2019; World Bank, 2018). Many capital cities and administrative centres are located in coastal regions; their infrastructures are therefore highly vulnerable. Many cities in the region also do not have the appropriate infrastructure to deal with flash floods like those of recent years (Loudyi and Kantoush, 2020).

4.3.2
Increasing water scarcity: negative consequences for humans and nature

As climate change progresses, water scarcity in the MENA region will continue to increase (Namdar et al., 2021). The more frequent and more intense droughts will lead to considerable water shortages and negative socio-economic consequences. The simultaneous increase in pressure from human use will further exacerbate this situation. From a global perspective, the region expects the worst economic losses as a result of climate-related water scarcity (6–14 % of gross domestic product by 2050; World Bank, 2018). Droughts are among the most 'costly' natural hazards in economic and social terms (Fragaszy et al., 2020). They have a considerable impact on national budgets, export earnings and import bills in the region, and they contribute to social inequality, rural flight and political unrest (Fragaszy et al., 2020) and also have a negative impact on health (Section 3.3.2). Dust and sandstorms, which are intensified by droughts and degraded land, also lead to losses in prosperity in the region amounting to around US$150 billion per year (Keynoush, 2022). At the same time, the likelihood of increased flooding and flash floods in this region is growing, with corresponding effects on human health. In addition, the effects of progressive sea-level rise increase the number of fatalities, the economic damage, further costs and the risk of having to retreat (Lange, 2019; Sections 3.1.1.6, 3.3.2).

4.3.2.1
Dwindling water resources due to unsustainable use

Increasing water scarcity is a major challenge for food security in the MENA region – both now and in the future (Keulertz, 2019; Tull, 2020). This is influenced, among other things, by the way in which the remaining water resources are used. In the MENA region, more than half of water consumption (mainly from groundwater use) is unsustainable, i.e. more water is consumed than is available on a renewable basis (Global Blue Water Sustainability Index for Surface and Ground Water; World Bank, 2018: 12 f.). It is therefore a "global hotspot of unsustainable water use" (World Bank, 2018: 38). Unsustainable water use and water pollution also threaten freshwater and marine ecosystems in the region. According to estimates, 17 % of freshwater species are currently threatened with extinction in the Arabian Peninsula alone (World Bank, 2018).

A large proportion of regional water consumption is attributable to agriculture. This also includes losses in agriculture, in processing, distribution and consumption (World Bank, 2018). Agricultural irrigation practices in particular pose an enormous threat to many aquifers in the region (Fig. 4.3-1; Gaub and Lienard, 2021). Fluctuations in the surface-water availability are balanced out by using groundwater to secure the water supply and income for agriculture (World Bank, 2018). However, these groundwater resources are finite. Increasing water pollution from wastewater and saltwater intrusion are also affecting the availability of water for agricultural irrigation. The pollution of freshwater and marine water bodies results in damage to health due to water-borne diseases and even the loss of ecosystem services, e.g. the supply of food from fishing (World Bank, 2018).

Over the past decades, policies in the MENA region have not promoted a sustainable demand for water, and water wastage has not been reduced. Irrigated agriculture expanded from the 1950s; governments built hundreds of dams, the population grew and their standard of living rose (1950–2000: the population quadrupled to approx. 380 million people; Hall, 2024). As early as the 1980s and 1990s, groundwater in Syria, Jordan and Yemen was no longer being used sustainably. Many states subsidized diesel, which meant, among other things, that farmers were able to pump groundwater from ever greater depths. The combination of population growth and an unsustainable, 'ambitious' agricultural policy has led to the loss of freshwater resources. Oases and waterways such as the Tigris, Euphrates and Jordan are now no more than trickles due to agricultural policies and the construction of dams. In addition to other untreated wastewater, agricultural runoff also pollutes freshwater resources and further depletes them. The irreversible nature of the condition of non-renewable and overexploited freshwater resources, especially finite groundwater resources, is now inevitably having an impact on policies. The Iraqi government used to subsidize diesel, water, seeds, fertilizers and pesticides, for example, or provide them free of charge. In 2022, the Iraqi Ministry of Agriculture cut irrigation for agriculture by 50 %. The Autonomous Administration of North and East Syria has rationed water for agriculture (Hall, 2024).

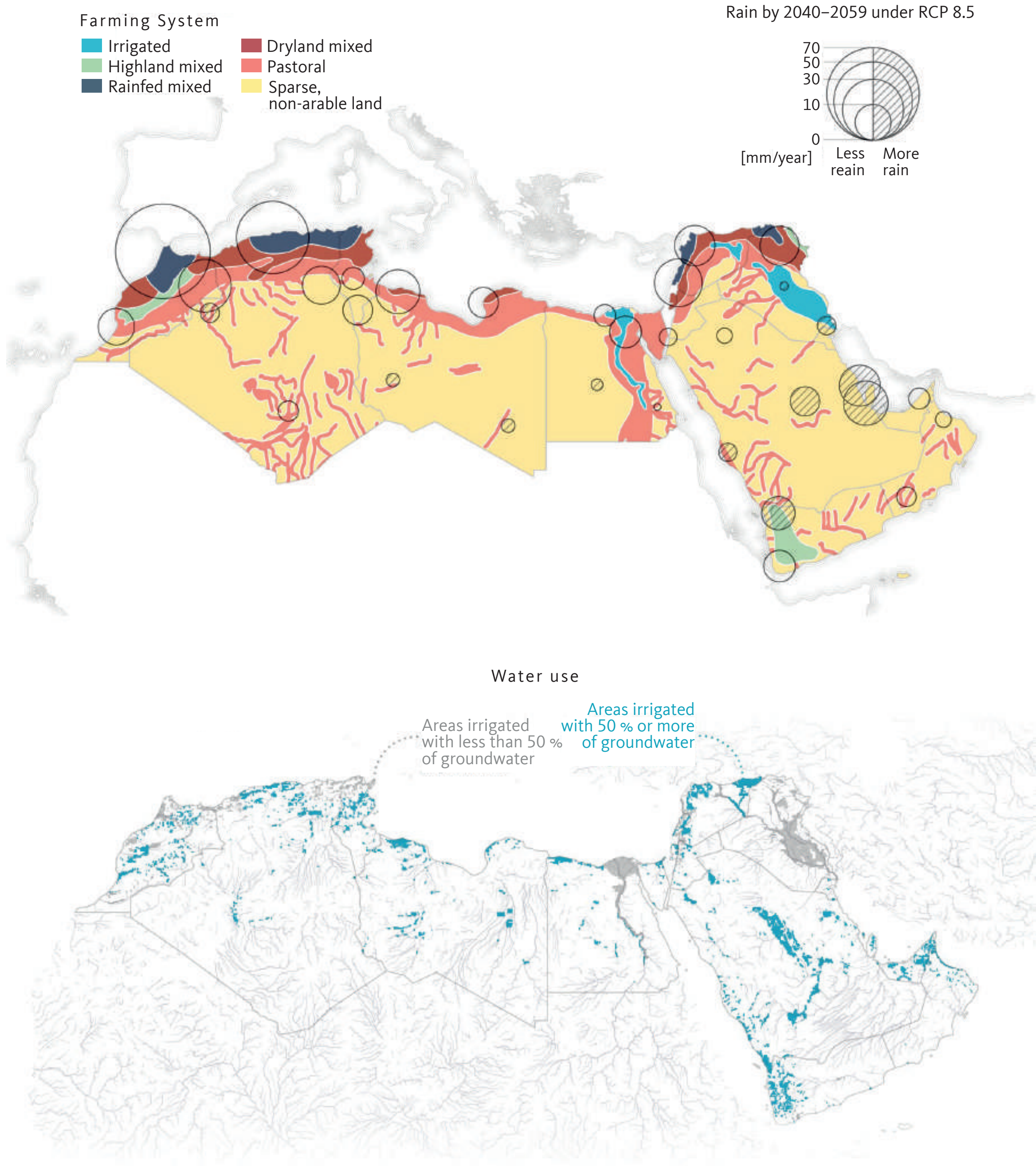


Figure 4.3-1
Projected precipitation changes and agricultural water consumption in the MENA region. The upper map shows projected precipitation changes in the MENA region from 2040–2059 under the RCP8.5 scenario. The changes vary among regions. Areas where surface water and rainwater are the main sources of irrigation will be most affected by reduced precipitation. The lower map shows groundwater as a proportion of total water consumption by agriculture, which is the main consumer in the region at 85 %. In many parts of the region, groundwater accounts for more than half of the water used for agricultural irrigation. Groundwater supply is expected to decrease by a third by 2050.
Source: Gaub and Lienard, 2021: 15

The population of this arid and semi-arid region is dependent on the few river systems, wetlands and groundwater-fed oases, but the effects of climate change and continuing overexploitation are causing lasting damage to these ecosystems. Degraded ecosystems are reinforcing regional megatrends such as migration, while abandoned land in turn accelerates soil degradation in rural areas (Houdret and von Lossow, 2023; Hall, 2024). Due to the increasing loss of soil moisture, changes in precipitation patterns and quantities, and extreme temperature conditions, this negative trend will continue to increase in the future (IPCC, 2023).

The agricultural sector already consumes more freshwater in the region today (85 %; Fig. 4.3-1; IWMI, 2024) than the global average (~70 %), and consumption could be even higher in drought years in the future (World Bank, 2023). Many nations in the region are dependent on agriculture as their source of employment and income; in Morocco, for example, the figure is almost 30 % (World Bank, 2023). However, the foundations for maintaining this sector are increasingly dwindling, as can already be observed in northern Syria, southern Iraq and Jordan (Houdret and von Lossow, 2023). Groundwater levels are expected to have fallen by a third by 2050. Areas whose agriculture depends on surface water and rain will be most affected by the decline in precipitation (Fig. 4.3-1). Water-intensive agricultural exports, too, currently consume a lot of water in some countries in the region.

As individual access to groundwater depends on financial, technical and social resources, water resources are available in disproportionately large amounts to locally influential groups or companies (e.g. large agricultural companies). The majority of the population then have less water available for their production and life-support systems (Houdret and Amichi, 2022; Oberhauser et al., 2023; Hall, 2024).

The region is a net importer of virtual water. The largest share of virtual water flows is attributable to the import of food products, with grain and high-quality food being the most important agricultural products associated with the import of virtual water (Antonelli et al., 2017). For example, the world's nine largest wheat importers are MENA countries (Abouelnaga, 2019). The MENA region imports virtual water from every region of the world. The USA is the largest single exporter, followed by Argentina, Australia and Brazil (Fig. 4.3-2). This involves a high degree of vulnerability to price fluctuations on the global market, particularly for socially disadvantaged or low-income population groups.

4.3.2.2
Effects on political and societal stability and conflicts

In general, the MENA region is characterized by a high degree of political instability and has been suffering from conflicts for decades (Namdar et al., 2021). Some of these tensions have grown historically and are motivated by religious and ethnic differences or those between social classes, but they are also fuelled by geopolitical powers. At the same time, the effects of climate change are leading to further polarization and societal tensions (Section 3.2.2; Gleick, 2014; Falkenmark et al., 2019; Abouelnaga, 2019). Climate change can therefore increase the risk that transboundary water competition between states and countries in the MENA region will lead to direct or proxy conflicts. On the other hand, some analyses show that this can provide an opportunity for bilateral cooperation and diplomacy (Wehrey and Fawal, 2022), because it gives an impetus for less politically sensitive starting points for regional cooperation in the water sector (Houdret and von Lossow, 2023). Two thirds of freshwater resources in the Middle East comes from transnational sources. The dams in Turkey provide an example; they have contributed to a 30 % decline in the volume of water in the Iraqi part of the Euphrates-Tigris Basin over the last four decades (Houdret and von Lossow, 2023). Political stability in the region can also be weakened by internal (civil) conflicts, which can arise, for example, as a result of reduced water availability and the associated higher food prices or migration caused by drought or flooding (World Bank, 2016a). Depending on the extent and severity of future developments and the available resources, there is therefore likely to be more internal migration in the MENA region in the future, particularly from rural areas to cities (Tull, 2020; Wehrey and Fawal, 2022). This will in turn exacerbate the challenges relating to water security and stability in the region (World Bank, 2018; Section 4.2).

4.3.3
Key challenges as starting points for political action

High levels of water consumption and climate change can lead to increased tensions and a heightened potential for conflict in the region (Houdret and von Lossow, 2023). As water is a key factor in the social contract, i.e. the agreements between societal groups and the state on mutual rights and obligations (Loewe et al., 2021), from the perspective of the nation state it has the potential to spark anti-government protests and conflicts between users. In Lebanon, for example, an inadequate water supply has had a negative impact both on trust

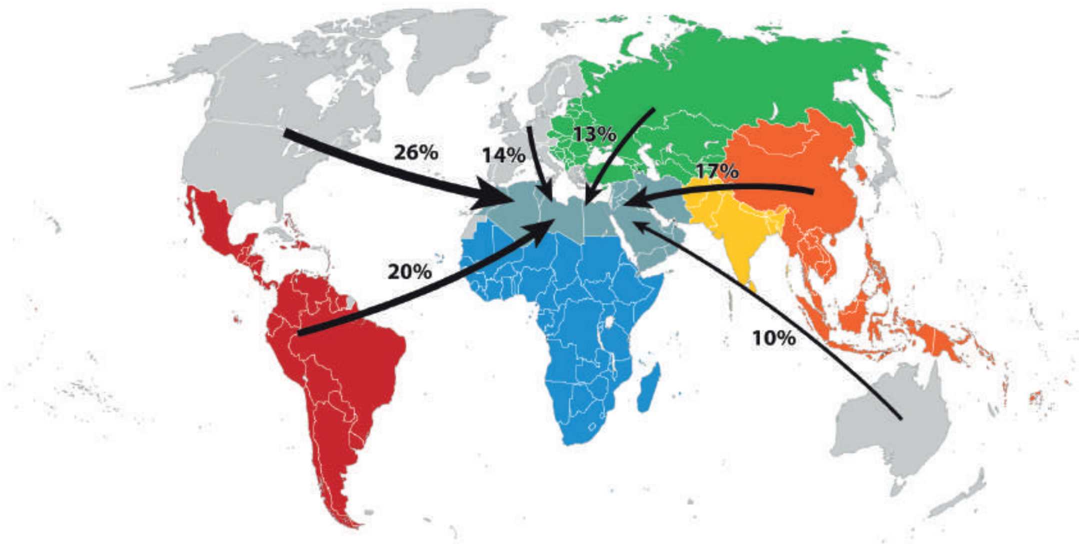


Figure 4.3-2
Virtual water trading in the MENA region in 2015. The map shows the (net) virtual water trade in the MENA region in 2015. The thickness of the arrows represents the relative amounts of imported water. The three most important import sources are North America (26 % of imported water), South America (20 %) and Asia (17 %).
Source: World Bank, 2018

in state institutions and on tensions between individual groups (Houdret and von Lossow, 2023). A reliable water supply, protection against e.g. floods and droughts or participation in water-resource management (e.g. distribution, access, pricing) not only play an important role for state legitimacy but also for the legitimacy of non-state actors. One example are efforts of the so-called Islamic State (IS) to improve the water supply in the areas it occupies (Houdret and von Lossow, 2023). Based on the developments and dynamics in the MENA region described above, two key future challenges are emerging: efficient water management is made more difficult by structural challenges in politics, society and the economy, and transboundary cooperation in the water sector is becoming increasingly difficult.

4.3.3.1 Difficult water management as a result of structural challenges

Despite different country-specific challenges in terms of economic development, poverty reduction and societal cohesion, there are structural challenges in the MENA region that reduce water-related adaptive capacity to climate change. In addition to the lack of capacities among public institutions, these challenges include the high debt ratio, fragility and subsidies that are not compatible with the incentive structure for promoting climate-adaptation measures.

Further problems in many countries in the MENA region make water management even more difficult: armed conflicts make regions partially inaccessible, or collected water-related data are not shared sufficiently, hindering cooperation between sectors and states. Furthermore, fluctuations in the volume and quality of groundwater are invisible and are therefore often neglected (Houdret and von Lossow, 2023). In the worst case, overexploitation can lead to it drying up. The decades-long overexploitation of groundwater resources (World Bank, 2018) has also been linked to a lack of control of illegal wells. For example, politically or economically influential groups (e.g. informal neo-patrimonial networks) often play an important role, using their influence in their own interests. They secure access to water resources, but undermine initiatives to limit water abstraction, which would be urgently needed, for example to protect the environment (Oberhauser et al., 2023; Hall, 2024; Faysse, 2015; Houdret, 2012). Negative impacts on sectors that are relevant for them (e.g. export agriculture) are averted, or implementation of the initiatives is prevented. In addition, water charges are not levied consistently, e.g. for water-intensive consumption by companies (Faysse, 2015).

It is becoming clear that the current overexploitation of groundwater resources in the MENA region is primarily a political problem (Zeitoun et al., 2013; Sowers, 2012). However, this is not just about political stability; it also raises the question of whether the way in which current policy-making is dealing with water scarcity in the region contributes to further societal fragmentation, thus creating, for example, exacerbated challenges that can lead to regional water emergencies with a planetary dimension. The case study of Jordan and groundwater use in Azraq showed that, despite interventions at the operational level aimed at technical aspects such as irrigation efficiency or improvements to the water infrastructure, only small efficiency gains were achieved and general patterns of overuse cannot be changed in this way. Interventions at the constitutional level, e.g. the allocation of groundwater, have the potential, at least in theory, to act as a lever to limit the unquestioned access of influential sections of society to groundwater (Oberhauser et al., 2023).

4.3.3.2
Increasingly difficult transboundary cooperation

Some of the reasons why transboundary cooperation is becoming increasingly difficult include geostrategic considerations such as the use of water for one's own interests and water-shortage-related tensions, e.g. between Iran, Saudi Arabia, Russia, Turkey and the USA as well as Kurdish regions (Houdret and von Lossow, 2023). Furthermore, conflicts can also exacerbate water risks, for example when water infrastructure is attacked during conflicts (Borgomeo et al., 2021). Despite numerous initiatives, water diplomacy has largely come to a standstill. Sweden, in co-operation with the United Nations Economic and Social Commission for Western Asia (UN-ESCWA) and the United Nations Economic Commission for Europe (UNECE), has supported transboundary water management in preparation for the adoption of the UNECE Water Convention (Convention on the Protection and Use of Transboundary Watercourses and International Lakes). However, there are still very few agreements regulating regionally sustainable water management in the MENA region (Houdret and von Lossow, 2023). They include, for example, the Water Convention, which was used to prepare an assessment of the North Western Sahara Aquifer System (NWSAS), thus enabling Algeria, Libya and Tunisia to develop joint solution strategies (UNECE, 2024). The 'Blue Peace' initiative pursues transboundary and multi-sectoral investment plans and is thus committed to building trust in the field of water management in the Middle East.

The challenges described here underline the fact that, in view of the different vulnerabilities of the countries in the MENA region (Namdar et al., 2021), it will be important to identify the expected future developments of droughts and flash floods – and the associated potential ecological and socio-economic consequences – on a region-specific basis. This is a prerequisite for effectively designing solutions and specific areas of transformation and recognizing the limits of controllability at an early stage.

4.4
Melting glaciers in the Hindu Kush-Karakoram-Himalayan mountain range: loss of natural water storage

2 billion
people access their water from the region's river basins

200 million
people are already suffering from increased water stress

20 % to 65 %
glacier loss depending on climate scenario

The cryosphere fulfils an important buffer function: up to now, changes in runoff regimes due to climate change and atmospheric circulation patterns have been cushioned by the annually recurring meltwater from the huge reservoirs of water in glaciers, especially during warm, dry periods. However, this buffer function is in danger of being lost worldwide, with far-reaching consequences for ecosystems and humans (Sections 3.1.1.3, 3.1.1.4).

Apart from the poles, the glaciers of the Hindu Kush-Karakoram-Himalayan mountain range (HKH mountain range) are the largest frozen freshwater reservoirs on earth, which is why they are sometimes referred to as the 'Third Pole'. They feed ten large river basins whose courses originate in eight countries (Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal and Pakistan) and flow through eight other countries. The ten river basins supply almost two billion people with water, i.e. a quarter of the world's population (Fig. 4.4-1; Yao et al., 2022; Nie et al., 2021). However, these 'Asian Water Towers' are among the glacier-based water systems most threatened by climate change and human (over-)use worldwide (Fig. 4.4-2; Immerzeel et al., 2020).

The consequences of climate change, especially melting glaciers, changing precipitation patterns and thawing permafrost, are changing the availability and quality of water for ecosystems and people in the HKH region, above all at high altitudes – but also in the lowlands. In addition, pressure of human use and the demand for water are increasing as a result of demographic change, socio-economic development and infrastructure development in the vicinity of glaciers and rivers (e.g. for industry or hydropower). Hydropolitical conflicts and governance challenges make socially balanced and sustainable water management more difficult. This complex interplay makes the river basins in the HKH region particularly susceptible to water stress. The situation is particularly critical in the Indus Basin, where already

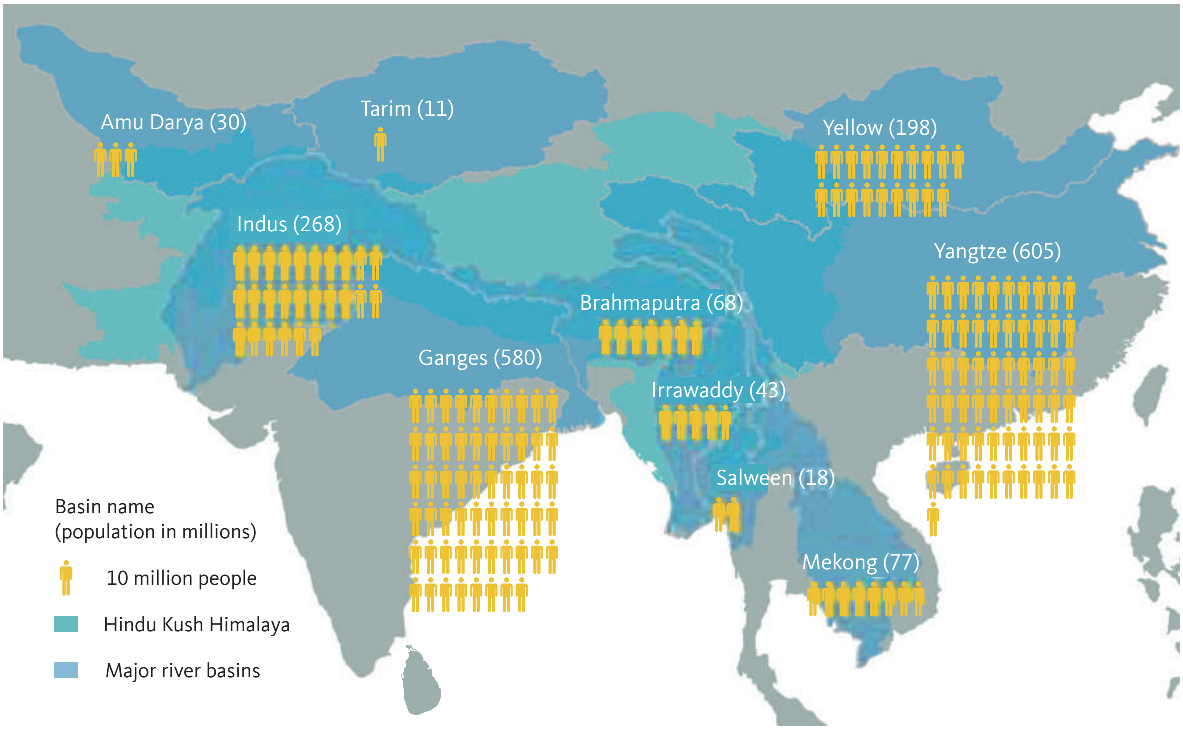


Figure 4.4-1
The river basins and population of the Hindu Kush-Karakoram-Himalayan region. The map shows the number of people living in the region's ten river basins (as of 2019). The most populous areas are the Yangtze Basin (605 million people), the Ganges Basin (580 million people) and the Indus Basin (268 million people). The Tarim Basin is the least populated with 11 million people.
Source: Scott et al., 2019

more than 260 million people live, and the population is expected to grow by about 50 % by 2050 (Fig. 4.4.2; Scott et al., 2019; Immerzeel et al., 2020).

4.4.1 Impact patterns, extent and projections

The causes of the loss of glaciers and their buffer function in the Hindu Kush-Karakoram-Himalayan mountains are outlined below. It is shown that rising water requirements will exacerbate the resulting water scarcity in some regions.

4.4.1.1 Climate-change-induced glacier retreat and changes in runoff volumes

Like glaciers worldwide, the glaciers of the HKH mountain range are also experiencing a steady decline due to climate change, which will continue in the future (Hock et al., 2019; Yao et al., 2022). Even without further warming, a loss of more than 20 % of the ice mass and glaciated area in the HKH mountain range is projected by 2100; this proportion will increase to a third (RCP2.6), a half (RCP4.5) or up to 65 % (RCP8.5), depending on the scenario (Yao et al., 2022; Jackson et al., 2023). The projections differ for the northern and southern basins of the HKH region.

Vulnerability to the consequences of melting glaciers and the associated changes in runoff volumes also depends on the extent to which river basins are fed by glacial meltwater (compared to rainwater). Cryospheric components such as meltwater and permafrost play an important role in supporting baseflows, especially in the late summer months (Fig. 3.1-4; Section 3.1.1.3). In the region, the runoffs from the Indus Basin is particularly dependent on glacier meltwater, which contributes around 40 % of the total runoff in the upper Indus Basin (Lutz et al., 2014; Azam et al., 2021). However, this proportion will decrease with increasing warming (Fig. 4.4-3; Lutz et al., 2014; Scott et al., 2019; Cui et al., 2023). In the upper course of the Indus Basin, 'peak water' – i.e. the time of maximum total annual runoff (Section 3.1.1.3) – will be reached by 2045 (± 17 years; RCP 4.5) or 2064 (± 19 years; RCP 8.5), in most other river basins of the HKH region probably by the middle

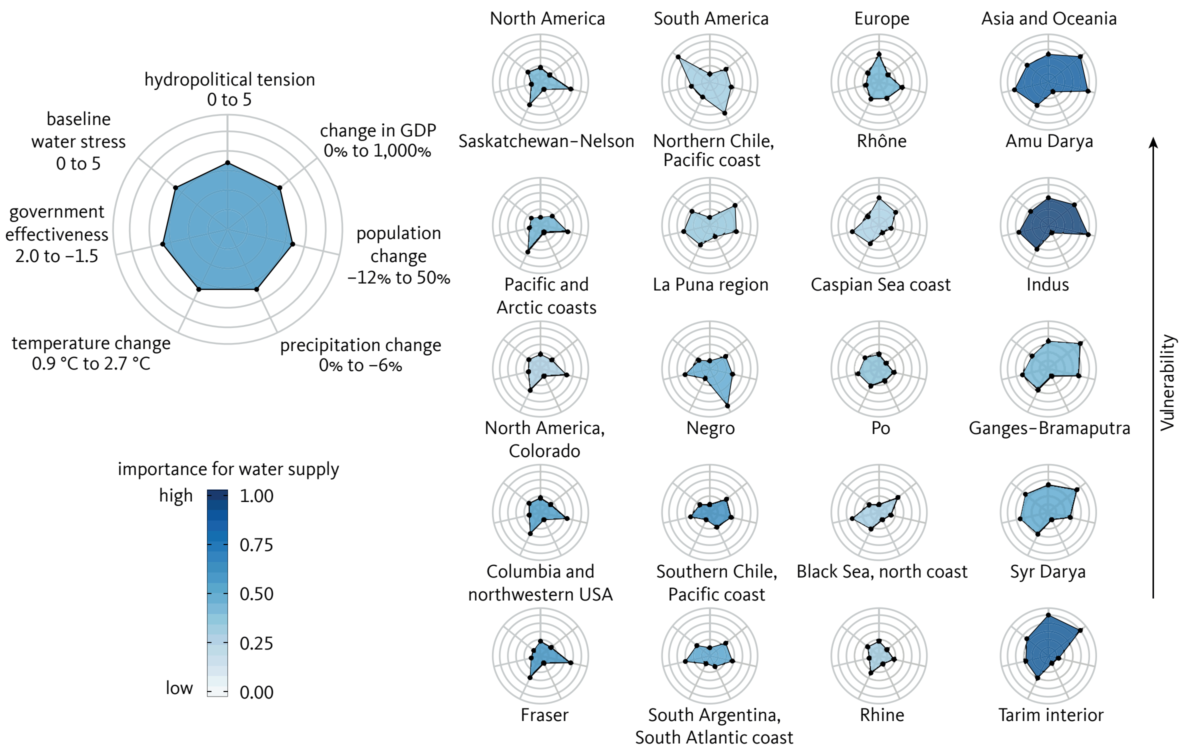


Figure 4.4-2
Vulnerability, importance for the water supply and projected changes in the main cryospheric water towers and associated river basins of each continent. The darker the colour of the polygons, the greater their importance for the water supply of ecosystems and society. The larger the polygon, the higher the vulnerability (decreasing from top to bottom), which was measured using changes in the following indicators: baseline water stress and government effectiveness in the basin; hydropolitical tensions; and projected changes in GDP, population (according to SSP2), precipitation and temperature between 2000 and 2050 (according to CMIP5 RCP4.5). It is evident that the Asian water towers and the river basins connected to them, particularly the Indus Basin, are not only especially vulnerable but also of great importance for the water supply of humans and ecosystems.
Source: modified according to Immerzeel et al., 2020

of the century (Nie et al., 2021; Nepal et al., 2023). The problem is that the decline in total runoff volumes after peak water in the Indus and Tarim basins cannot be fully offset by an increase in precipitation (Nie et al., 2021). In addition, meltwater makes a decisive contribution to groundwater recharge at high altitudes; in the upper reaches of the Indus Basin, for example, meltwater accounts for 83 % of annual groundwater recharge (44 % from glaciers, 39 % from snow; Lone et al., 2021). In the meltwater-fed river basins of the HKH region, the water supply for humans and ecosystems is therefore particularly at risk in warmer and drier phases (June–October), when the snow cover has melted and precipitation does not contribute significantly to runoff. In precisely these phases, up to now glaciers have acted as important buffers for the water supply (Fig. 3.1-4; Kraaijenbrink et al., 2021; Hock et al., 2019).

Not only the quantity but also the quality of the available water is affected: the melting of glaciers and changes in the dynamics of snowmelt, precipitation and evaporation also lead to changing sediment and pollutant loads, e.g. with POPs, PCBs, DDT, arsenic and heavy metals such as mercury, with considerable health consequences for nature and humans (Hock et al., 2019; Nepal et al., 2023; Rasul and Molden, 2019).

Retreating glaciers also have an impact on biodiversity and ecosystems. The HKH mountain range is one of the mountain systems with the highest biodiversity, also due to its topographical and climatic diversity. Four global biodiversity hotspots are located wholly or partly in this region and provide many ecosystem services in the river catchment areas (Xu et al., 2019). Depending on the species and region, changes in water quantity and water quality associated with the melting of glaciers lead i.a. to altered and new habitats, shifts in distribution range, and changes in behaviour, phenology and primary production – with impacts on the functioning and ecosystem services of glacier and mountain ecosystems and their biodiversity (Section 3.3.1; Jacobsen et al., 2012; Cauvy-Fraunie and Dangles, 2019; Rasul and Molden, 2019). The main 'losers' are high mountain species and those that are dependent on glacial conditions (specialists). Species that can live in a wide range of environmental conditions (generalists) and colonize from downstream will be among the 'winners' because they do not inhabit such a specialized niche. The HKH region has a high proportion of endemic species, i.e. species that only occur here (Xu et al., 2019). These are found particularly in the biodiversity hotspots and are threatened by changes to their habitat, both as a result of climate change and direct human intervention such as infrastructure development, urbanization or agriculture. The Indian Himalaya is expected to lose a quarter of its endemic species by 2100 (Xu et al., 2019). Changes in vegetation and its productivity can in turn influence the timing, quality and quantity of water supply in the region.

4.4.1.2
Increasing water scarcity due to rising water demand and infrastructure projects

The reduced future water availability after peak water is reached is accompanied by an increasing demand for water for agriculture, industry and households throughout the region, which is already becoming apparent. It is being driven primarily by demographic change and socio-economic development (Fig. 4.4-4; Maharjan et al., 2023). In some cases there are some major regional differences: in a study from 2022, the highest current demand for water in the region was recorded in the Indus Basin (~299 Gt per year, compared to ~5.1 Gt per year in the Salween Basin; Yao et al., 2022). For the HKH region as a whole, water demand is expected to increase by 11 % up to 2050 and by 18 % by 2090, compared to the 2006–2015 average, with high regional variability (Fig. 4.4-4; Yao et al., 2022).

Irrigated agriculture contributes to the increasing demand for water in some parts of the larger HKH region, e.g. in the Indus Basin (Yao et al., 2022; Fig. 4.4-4). Inefficient irrigation techniques and unsustainable water-use

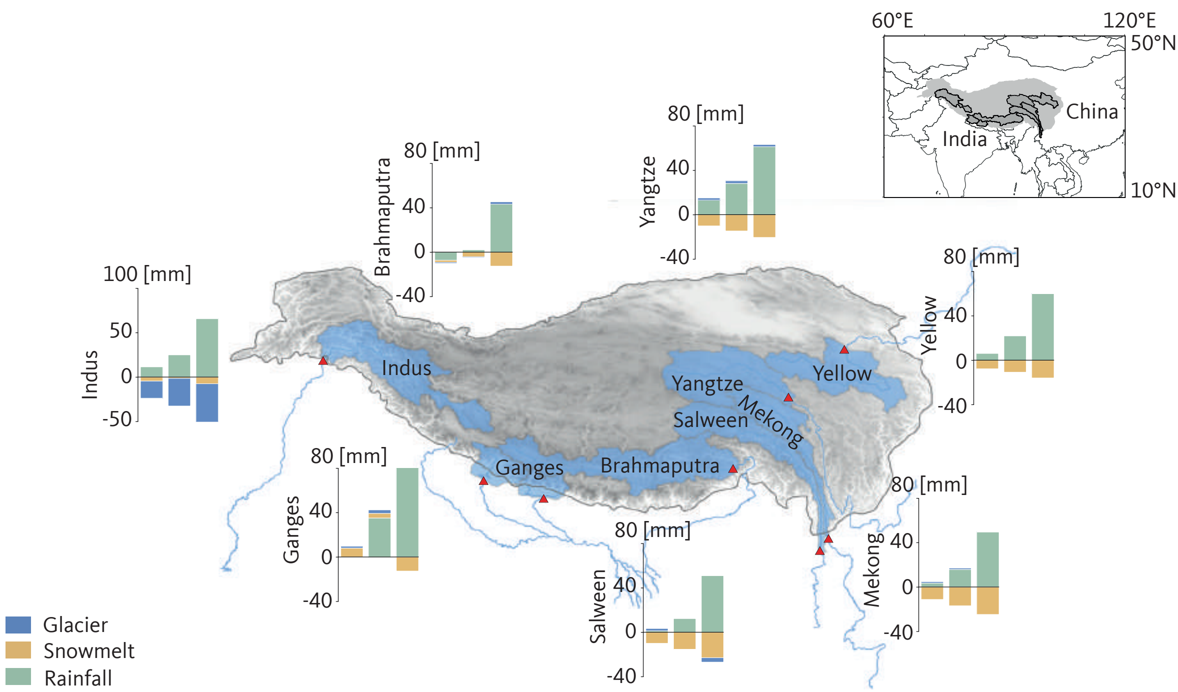


Figure 4.4-3
Relative changes in mean annual runoff in the river basins of the Hindu Kush-Karakoram-Himalayan region under varying degrees of warming. The bar charts show changes in precipitation (green), snowmelt (yellow) and glacier runoff (blue) when warming reaches 1.5 °C, 2.0 °C and 3.0 °C (left, centre and right bars). The changes differ between the river basins, with the share of precipitation in total runoff increasing in most river basins and the shares of snow and glacier melt decreasing. The decline in glacier meltwater is particularly pronounced in the Indus Basin.
Source: Cui et al., 2023

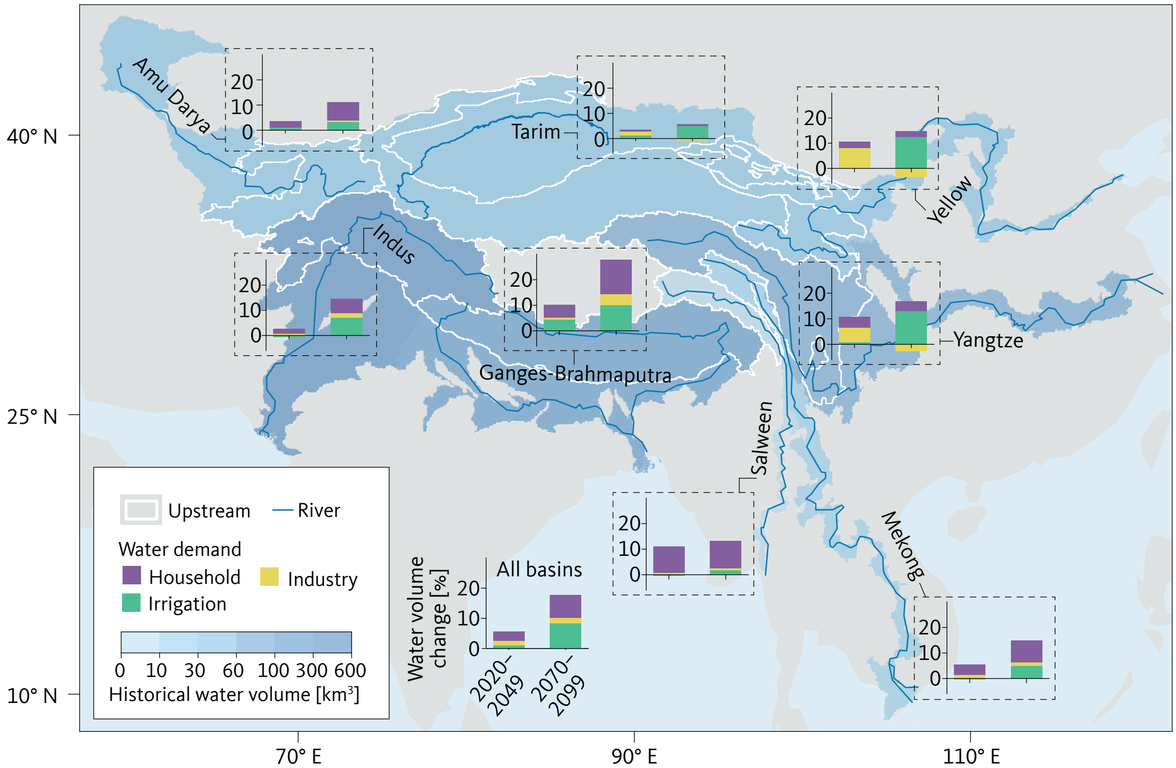


Figure 4.4-4
Future changes in human demand for water in the Hindu Kush-Karakoram-Himalayan region. The map shows projections on changes in water demand in the northern (light blue) and southern (dark blue) river basins of the HKH region for the years 2020–2049 and 2070–2099 compared to 2006–2015. The stacked bars show the relative changes in water abstraction for agricultural (green), domestic (purple) and industrial (yellow) purposes, which, in some cases, vary greatly between the region's river basins. The projections are based on calculations using the global hydrological model H08 under the conditions of the SSP2-RCP6.0 scenario.
Source: Yao et al., 2022

strategies are exacerbating the situation (Rasul and Molden, 2019). Furthermore, overexploitation of groundwater contributes to water stress, particularly in the Indus and Ganges basins (Nie et al., 2021). Increasing pressure on ecosystems is being exerted by energy-supply systems, especially hydropower, as well as by infrastructure projects and mining, which are in turn affected by cryospheric changes (Section 4.4.2). Hydroelectric power plants, for example, are being built ever closer to glacial lakes; mining destabilizes soils and leads to pollution, and water-related infrastructure interferes with natural river courses (Scott et al., 2019; Hock et al., 2019). In the Indus Basin, these interventions have in some cases resulted in reduced sediment transport downstream (Laghari et al., 2015).

The situation in the HKH region at the end of the century is threatening: a reduced water availability will be accompanied by a rising demand for water, which will only increase the water stress that is already being observed in some regions. In the long term, the Asian water towers of the HKH mountain range will no longer be able to maintain their current share of the water supply (Immerzeel et al., 2020). The loss of the glaciers' buffer function can be expected to increase water stress for humans and ecosystems in the region in the future. This could contribute to a destabilization of the region unless suitable and comprehensive adaptation measures are taken. In the HKH region, a variety of innovative measures are already being used to guarantee the water supply, e.g. rationing, constructing so-called ice stupas (artificial glaciers) or installing water tanks. Adaptation can also be observed in individual sectors such as agriculture (e.g. diversification of seeds, changes in sowing times; Maharjan et al., 2023). However, it is still unclear to what extent measures already in use can do justice to the medium to long-term changes – there is a need for research here.

4.4.2
Destabilization potential: water scarcity, natural hazards and geopolitical conflicts

The loss of the glaciers' buffer function, quantitative and seasonal changes in runoff regimes, and increased natural hazards as a result of cryospheric changes involve considerable destabilization potential. There are already signs of impacts on the lifestyles and food security of people both in the high mountains and in the lowlands of the HKH region; these will intensify with increasing climate change, higher water demand and human over-exploitation as well as possible political tensions (Chapter 3). Three major sources of destabilization potential are outlined below as examples.

4.4.2.1
Increasing water scarcity: consequences for food and energy security

Agriculture, households, industry and the energy sector in the HKH region are dependent on an adequate water supply; however, for some river basins increased water stress is already becoming apparent. According to a report by China Water Risk, four of the eight countries in the HKH region are already affected by moderate to severe water stress: Afghanistan, China, India and Pakistan (Hu and Tan, 2018). In addition, four countries (Afghanistan, Bangladesh, Myanmar and Nepal) fall into the category of least developed countries (UNCTAD, 2024), and multidimensional poverty remains high, particularly in the mountainous regions of the HKH mountain range (Gerlitz et al., 2015; Hunzai et al., 2011). Food security also remains a key issue (Maharjan et al., 2023). The melting of glaciers – particularly in the river basins fed to a large extent by glaciers, such as the Indus Basin (from which Afghanistan and Pakistan obtain around a quarter of their water resources) – will lead to increased conflicts of use, which will entail risks for food and energy security and thus also for societal development.

Reduced runoffs in the summer months due to melting glaciers can lead to reduced agricultural yields and lower productivity, with devastating consequences for food security. Meltwater is essential for agricultural irrigation and soil moisture – especially at high altitudes, although the effects can also be felt in the lowlands. The Indus Basin is particularly affected; here, more than 90 % of crops are irrigated and up to 60 % of irrigation outside the monsoon season depends on meltwater (Molden et al., 2022; Biemans et al., 2019). In Ladakh, India, irrigation is completely dependent on meltwater (Nepal et al., 2023). Livelihoods depending on livestock farming are also under threat, e.g. due to changes in pasture landscapes (Maharjan et al., 2023). The livelihoods of 129 million farmers in the Ganges and Indus river basins depend on meltwater (Biemans et al., 2019). Meltwater also plays an important role in the drinking-water supply at many high altitudes in the HKH region (Molden et al., 2022). The effects will also be felt beyond the borders of the region, which acts as an important granary for Asia and is also pivotal to global food production: the eight countries of the HKH region are responsible for

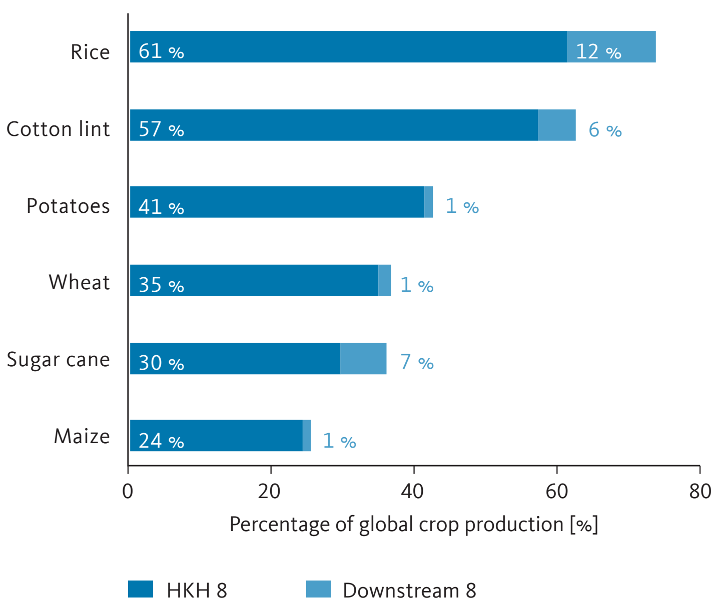


Figure 4.4-5
Food produced in the larger Hindu Kush-Karakoram-Himalayan region as a percentage of global food production. The eight countries of the HKH region, in which the river courses originate (HKH 8: Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Pakistan), for example, account for 61 % of global rice production, 41 % of global potato production and 24 % of global maize production. The rivers flow through eight other countries (Downstream 8: Cambodia, Kyrgyzstan, Laos, Tajikistan, Thailand, Turkmenistan, Uzbekistan, Vietnam).
Source: Hu and Tan, 2018

60 % of global rice production (Fig. 4.4-5), a very water-intensive grain that is also an important staple food (Hu and Tan, 2018).

The energy sector will also be affected by the changes in the cryosphere. Hydropower plays a central role in the region's electricity supply: in Bhutan, almost 100 % and in Nepal almost 93 % of the electricity supply comes from hydropower (Rasul and Molden, 2019). Hydropower is directly affected by changes in flow regimes (seasonality, discharge, sediment load) caused by glacial melting (Hock et al., 2019; Nepal et al., 2023). At the same time, it influences water regimes in uplands and lowlands, for example through river diversions, major construction projects, water storage and evaporation (Boxes 7.4-1, 7.4-2), with consequences for people and ecosystems (Scott et al., 2019; Pandit and Grumbine, 2012). The importance of hydropower in the region will continue to increase: installed hydropower capacity in the HKH region already accounts for a third of the world's installed capacity, and there are initiatives to further increase production capacity in all the countries of the region (Harlan and Hennig, 2022; Hu and Tan, 2018).

The melting of the glaciers in the HKH mountain range is therefore very likely to reduce water availability in the long term for those countries and local communities that are already affected by moderate to severe water stress. Possible consequences are conflicts, (internal) migration and hunger (Molden et al., 2022). Agriculture and the energy sector are both affected by this water emergency and are drivers of the increased pressure of use on glaciers, river basins and ecosystems. Added to this, increasing urbanization also raises the pressure on available water resources and brings with it further challenges for water management (Rasul and Molden, 2019; Section 4.2). Habitat changes, especially in the high mountain regions, mean that traditional and local knowledge can no longer be applied; this jeopardizes traditional agricultural practices in the highland communities, which have a high societal value (Hock et al., 2019; Namgay et al., 2014; Molden et al., 2022).

4.4.2.2
Increasing natural hazards: threat to human life and infrastructure

Natural hazards caused by glacial melting, combined with more frequent extreme weather events, are increasingly threatening human settlements and infrastructure. Changes in the permafrost can heighten these risks, although these have not yet been sufficiently researched (Rasul and Molden, 2019; Maharjan et al., 2023). Natural hazards associated with changes in the cryosphere include glacial lake outbursts, glacier collapses, ice and snow avalanches and landslides. Not only might the frequency of such hazards increase in the future, vulnerability to these hazards will also rise, and individual events will increasingly develop into hazard cascades (Rusk et al., 2022; Nepal et al., 2023). Glacial lake outbursts are among the most serious natural hazards, and people in the HKH region are particularly vulnerable: almost a million people live less than 10 kilometres from glacial lakes (Taylor et al., 2023; Zhang et al., 2024). Glacial lake outbursts are not only a direct threat to human life, they can also have devastating consequences for agriculture, (energy) infrastructure, mining and tourism (Zhang et al., 2023; Nie et al., 2023). The cryospheric changes in the region are making it possible to develop areas in the mountains that were previously inaccessible to humans. This will further increase vulnerability to natural hazards, especially if no adequate risk management or early-warning systems exist. The increasing degradation of permafrost soils exacerbates these dangers and can lead to the further destabilization of the slopes and promote landslides (Bolch et al., 2019; ICIMOD, 2023). Increasing sediment loads in rivers as a result of melting glaciers also pose a threat to humans and ecosystems as slow-onset hazards. The possible medium- to long-term consequences include impairment of hydropower plants and their water-storage function (e.g. due to reservoir sedimentation) or a decline in water quality, with consequences for aquatic ecosystems and human health, since sediment particles are vectors for the transport of heavy metals and other harmful substances (Zhang et al., 2022; Herman et al., 2021; Nepal et al., 2023).

4.4.2.3
Societal and geopolitical conflicts

The projected changes in the cryosphere can lead to major conflicts over use, both at the national level and across national borders. Within the region, for some countries there is a high degree of dependence on renewable water resources that originate outside the respective country's own borders (dependencies between upstream and downstream reaches; Maharjan et al., 2023). For Bangladesh and Pakistan, for example, this applies to 91 % and 78 % of water resources respectively, while for China it is only around 1 % (Hu and Tan, 2018). This creates unequal power and dependency structures. There are already transboundary water conflicts in the region – particularly in the Indus Basin and the Ganges-Brahmaputra Basin – which could intensify due to regional and seasonal shifts in water availability and increasing water stress in the region (Maharjan et al., 2023).

These dependencies complicate water management. In the Indus Basin, for example, changes in runoff volumes and rising conflicts over use could affect already established agreements on water distribution between countries and subnational entities, such as the Indus Water Treaty (Maharjan et al., 2023), which has been successful to date. As recently as 2023 Pakistan took India's interpretation of the treaty on the subject of hydropower to the Permanent Court of Arbitration in The Hague (PCA, 2023). In order to prevent water-related conflicts, solutions must be developed that enable the equitable distribution of water amid reduced availability, including across national borders.

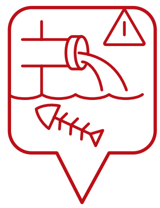
4.4.3 Key challenges

This regional water emergency with a planetary dimension gives rise to key challenges that require solutions at the local, regional and global level:

1. The changes in seasonal and regional water availability and the loss of the glaciers as natural water reservoirs have far-reaching consequences for ecosystems and humans. This concerns, among other things, changes in habitats and traditional ways of life, food security, poverty reduction, energy supply, and societal and political stability. Solutions for dealing with these consequences are still lacking. There is a high degree of planning uncertainty.
2. Rising demand for water from households, industry and agriculture and inefficient water use are exacerbating the pressure of human water use.
3. There are large gaps in data and monitoring. Among other things, this applies to future water availability and water demand (especially upstream-downstream linkages), impacts on ecosystems and biodiversity, and the effectiveness of different mechanisms for adapting to natural hazards (technical, nature-based, institutional). Up to now there has been little research into and quantification of changes in the permafrost, which can exacerbate some of the observed risks. It has also not yet been quantified what the cryospheric changes mean for the livelihoods of the local population, particularly those living at high altitudes, who are largely dependent on nature.
4. Lacking or inadequate disaster risk management or early-warning systems and a high level of societal vulnerability increase the risk of natural hazards for society.
5. Despite rising water-related tensions and conflicts, there is a lack of cooperation between stakeholders and countries in the region.

Melting glaciers also pose water-related dangers in other regions of the world; e.g. the southern Andes, Western Canada, the Western USA (particularly Alaska) and the Alps are particularly affected (Hugonnet et al., 2021; Hock et al., 2019).

4.5 Water pollution in Sub-Saharan Africa



2.7 billion
people are today affected by water pollution

4.2 billion
is their expected number by 2100

38 %
of the world's population affected by organic water pollution will live in Sub-Saharan Africa in 2100

Since the 19th century, economic and population growth and urbanization in high-income countries have been accompanied by rising pollutant emissions into surface waters. The development of a cost- and resource-intensive infrastructure for mechanical and biological wastewater treatment, coupled with the utilization of the dilution effects of surface waters, has reduced the load of organic carbon compounds and nutrients from domestic wastewater in high-income countries. However, persistent organic compounds from industry, households and agriculture continue to be a challenge for wastewater treatment in high-income countries (WBGU, 2023: 174 ff.; Chapter 7).

In low- and middle-income countries, economic and population growth and urbanization are currently driving an increase in the discharge of untreated or inadequately treated wastewater and higher water abstraction. This process is being exacerbated by the effects of climate change. As a result, in parts of Latin America, East, South and Southeast Asia and the MENA region, as well as in Sub-Saharan Africa in particular, there are signs that surface-water pollution will become a major problem by the end of the century, threatening the health of humans and ecosystems. The focus of this section is on Sub-Saharan Africa because this is where the largest relative and absolute increase in the affected population is projected, irrespective of socio-economic development paths and emission scenarios (Jones et al., 2023). The main cause of water pollution is contamination with domestic wastewater and wastewater from livestock farming (Wen et al., 2017), which contains organic carbon compounds such as carbohydrates, fats and proteins, nutrients such as nitrogen and phosphorus, as well as pathogenic microorganisms.

4.5.1
Impact patterns, extent and projections

According to current global projections, surface-water pollution and the number of people affected by it will increase significantly this century. By 2050, 2.5 billion people are expected to be affected by water pollution caused by organic carbon compounds (Wen et al., 2017) and up to 4.5 billion people by water pollution caused by nitrogen (Chaplin-Kramer et al., 2019).

The comparability of the projection studies on global surface-water pollution is limited by the fact that the studies analyse different water-quality parameters (nitrogen, dissolved solids, etc.), as well as different future scenarios and time horizons. For this reason, the focus here is on the projection study by Jones et al. (2023), which developed scenarios for three types of surface-water pollution on the basis of three scenarios (SSP-RCPs) up to 2100. The time horizon and the comparison of development paths and types of pollution are hitherto unique to the study by Jones et al. (2023). For robust forecasts of global surface-water pollution, however, this study must be supplemented by further projection studies that take extensive account of various input sources, dilution effects and degradation processes (Section 4.7).

The SSP1-RCP2.6 'sustainability' scenario – which assumes sustainable, cooperative development within the planetary guard rails – forecasts a reduction in the number of people affected by water pollution from organic compounds from 2.7 billion to 1.5 billion by 2100 (Jones et al., 2023). A decrease to 1.6 billion people is also predicted for the SSP5-RCP8.5 'fossil-fuelled development' scenario, which is characterized by strong economic growth, extensive use of fossil energy sources and resource- and energy-intensive lifestyles. The authors of the study explain this by the strong growth of the global economy, leading to a rapid spread of processes for advanced wastewater treatment (Jones et al., 2023). However, this development path will be dominated by the drastic scale of climate change and its impact on ecosystems and the human population. The SSP3-RCP7.0 'regional rivalry' scenario – which assumes a lack of international cooperation, weak economic growth, a decline in investment in research and education, and massive environmental damage – predicts that up to 4.2 billion people will be affected by water pollution from organic compounds by the end of the century (Jones et al., 2023). Jones et al. (2023) predict similar patterns for the contamination of surface waters by pathogenic microorganisms originating from faecally contaminated wastewater from households or livestock farming, which pose a direct risk to human health, and by dissolved solids (mainly salts originating from irrigated agriculture, industry and, to a lesser extent, from domestic wastewater).

However, these global projections conceal significant regional differences. For most middle- and high-income countries, regardless of the future scenario, the authors predict an improvement in water quality due to lower pollutant inputs achieved as a result of improved wastewater treatment (Jones et al., 2023). In low-income countries, however, the opposite is the case and, regardless of the future scenario, the focus of global surface-water pollution will shift from today's heavily affected regions in East and South Asia to Africa and especially Sub-Saharan Africa (Jones et al., 2023; Wang et al., 2019; Wen et al., 2017). For many areas in Sub-Saharan Africa a substantial increase in the pollution of surface waters by organic compounds, pathogens and dissolved solids is predicted in all future scenarios, leading to several thresholds being exceeded simultaneously (BOD: 8 mg per litre, TDS: 2100 mg per litre, FC: 1000 CFU per 100 ml; Jones et al., 2023; Fig. 4.5-1). As a result, the proportion of the population in Sub-Saharan Africa that is exposed to polluted water (organic compounds, pathogens and dissolved solids) will increase substantially by the end of the century. Jones et al. (2023) project a strong increase for the SSP3-RCP7.0 scenario in particular (dissolved solids: around 800 million people, organic compounds and pathogens: 1.5 billion people). The increase in the affected population corresponds to a factor of two to six compared to today. Sub-Saharan Africa currently accounts for 14 % of the global population and 10 % of the population affected by water pollution. These percentages are expected to increase to up to 25 % and 38 % by the end of the century, meaning that the region will be disproportionately affected by water pollution (Fig. 4.5-2; Jones et al., 2023).

Population and economic growth and the corresponding increase in water abstraction and pollutant inputs into surface waters are particularly concentrated in the rapidly growing urban centres of Sub-Saharan Africa such as Kinshasa, Nairobi and Addis Ababa. As a result, the decline in water quality and the substantial increase in the number of people affected will be much more pronounced here (Jones et al., 2023). This is especially problematic in the context of the numerous other water-supply problems faced by urban areas (Section 4.2).

In addition to water pollution caused by pathogens, organic carbon compounds and dissolved solids, the pollution of surface waters with nutrients (nitrogen and phosphorus) plays a major role worldwide. These nutrients are contained in domestic wastewater and wastewater from livestock farming; however, most of them come from fertilizers used in conventional agriculture (Section 2.3.3.2). For the year 2050, the SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5 scenarios predict that 1.6 billion, 4.5 billion and 1.5 billion people respectively will be affected by nitrogen pollution in surface waters

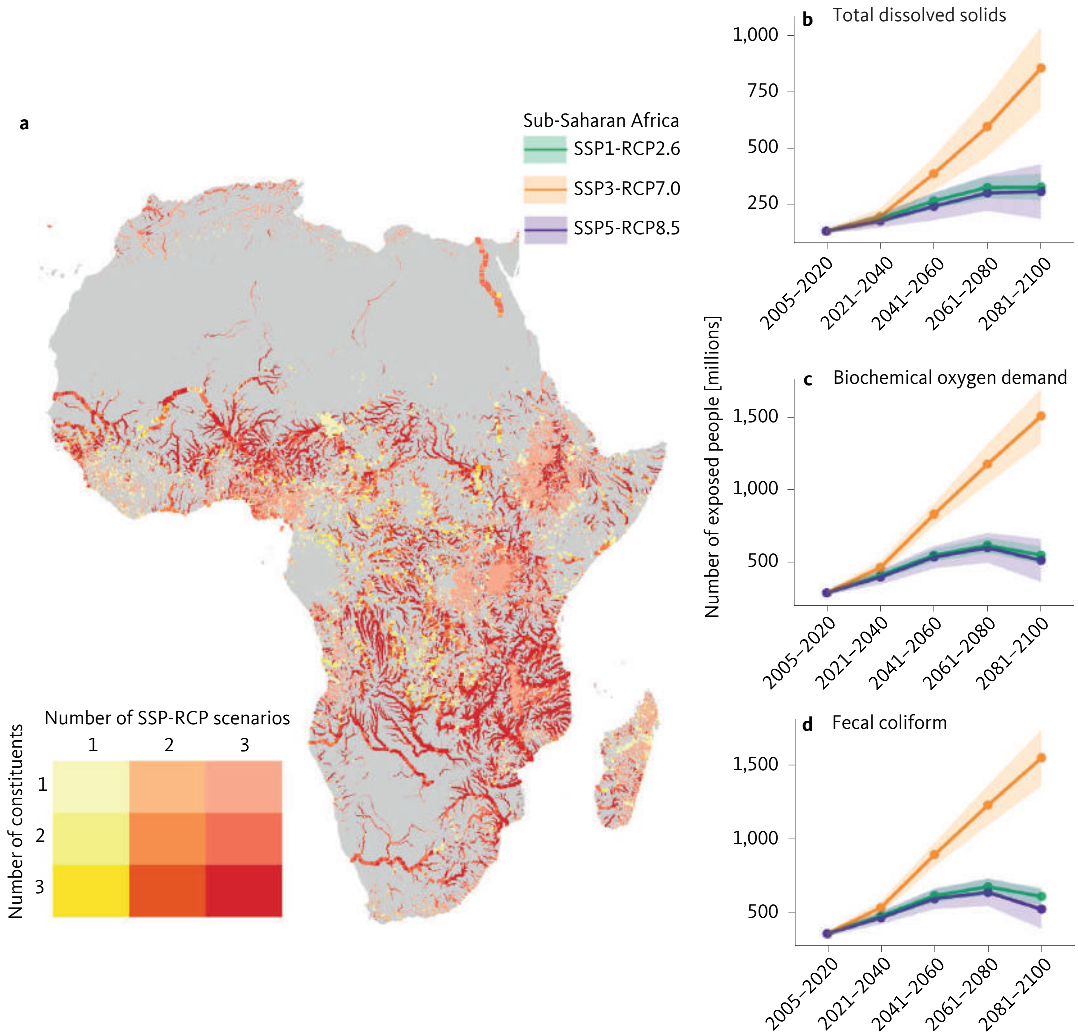


Figure 4.5-1
Future pollution of surface waters in Sub-Saharan Africa and number of people affected. A substantial increase in pollution from total dissolved solids (TDS), organic compounds (biochemical oxygen demand, BOD) and pathogens (coliform bacteria, FC) is predicted for large parts of Sub-Saharan Africa by the end of the century, regardless of the selected future scenario (SSP-RCP).
Source: Jones et al., 2023

worldwide (Chaplin-Kramer et al., 2019). The authors of the study attribute this increase to reduced ecosystem services for preserving water quality due to advancing climate change (Chaplin-Kramer et al., 2019). Compared to other regions, the use of nitrogen and phosphate fertilizers in Sub-Saharan Africa is currently low (FAO, 2018: 23), but the highest annual growth rate in the use of nitrogen fertilizers (4.8 %) of all world regions was recorded there between 2015 and 2020 (FAO, 2018: 57 ff.). A growth rate of 3.6 % was also recorded for phosphate fertilizer in the same period, which was only exceeded in Latin America and the Caribbean (4 %) and West and South Asia (4.4 %) (FAO, 2018: 57 ff.). This is in line with the study by Chaplin-Kramer et al. (2019), which predicts under the SSP3-RCP7.0 scenario that almost 1.2 billion people in Africa will be affected by nitrogen pollution in surface waters by 2050.

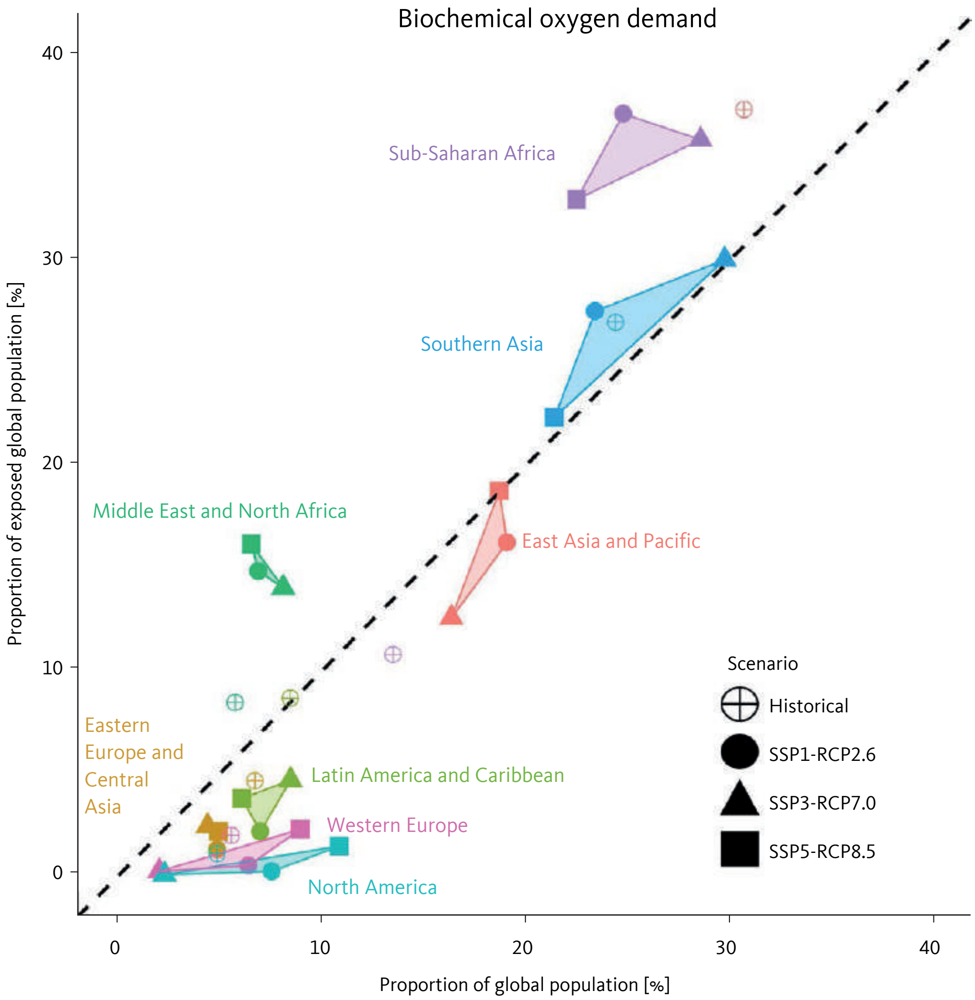


Figure 4.5-2
Proportion of the population in various regions of the world that will be affected by water pollution at the end of the century. Regardless of the future scenario (SSP-RCP), it is expected that Sub-Saharan Africa will be disproportionately affected by water pollution compared to other regions of the world (exemplified here for pollution with organic carbon compounds, expressed as BOD). The results are presented for multiple-year time segments of a historical reference period (2005–2020) and the period 2081–2100, taking into account three future scenarios.
Source: Jones et al., 2023

4.5.2 Consequences of water pollution for humans and nature

Water pollution, especially contamination with pathogens, poses a direct threat to human health, for example through diarrhoeal diseases or parasite infections (Sections 2.3.3, 3.1.4, 3.3.2). Furthermore, malnutrition and cognitive underdevelopment are linked to inadequate water, sanitation and hygiene systems (Sinharoy et al., 2019). The negative effects of inadequate wastewater treatment on health and cognitive development also lead to economic losses due to higher sickness rates and lower productivity. At 3.2 % of GDP, these were significantly higher for Sub-Saharan Africa than for all other regions of the world in 2012 (WHO, 2020: 26 f.). A current model-based study predicts for most countries in Sub-Saharan Africa that positive economic development will help mitigate the higher mortality and economic losses associated with inadequate water, sanitation and hygiene (WASH) by 2050, but will not be able to solve them entirely (Fuente et al., 2020). Accordingly, WASH-related investment will continue to require sustained commitment from international donors and national governments (Fuente et al., 2020).

The pollution of surface waters not only affects humans, it also causes massive damage to aquatic ecosystems. Biodegradable organic carbon compounds from domestic wastewater, livestock farming and agriculture promote microbial growth and oxygen consumption in surface waters (Wen et al., 2017), which can lead to fish mortality (van Vliet et al., 2023). At the microbial level, the input of inadequately treated urban wastewater changes the microbial community and reduces microbial diversity in rivers (Xie et al., 2022). The nutrients nitrogen and phosphorus contained in urban wastewater and wastewater from agriculture and livestock farming lead to eutrophication and algal blooms in surface waters, as well as to the loss of habitats and biodiversity (Section 3.1.4.2).

In addition to the input of nutrients, organic carbon compounds and pathogenic microorganisms from domestic wastewater and wastewater from livestock farming, surface waters are also polluted with mineral-oil hydrocarbons and heavy metals in areas of Sub-Saharan Africa with industrial activity. In the Niger Delta, one of the most important hotspots of aquatic biodiversity in Sub-Saharan Africa (Anyanwu et al., 2023), the impacts of oil production on ecosystems and the local population are clearly noticeable (Box 4.5-1).

4.5.3
Key challenges

Irrespective of the socio-economic development and emission pathway chosen, domestic wastewater is the largest source of water pollution with organic carbon compounds and pathogenic microorganisms (Jones et al., 2023). Accordingly, avoiding the discharge of untreated or inadequately treated domestic wastewater into the environment is the most efficient way of counteracting existing and predicted water pollution. From a global perspective, the status of organized treatment is unsatisfactory: 80 % of global wastewater entering the environment is inadequately treated; in low-income countries, only 8 % of wastewater is treated at all (UNESCO, 2017: 17). The availability of sanitary facilities is an important factor in this context in Sub-Saharan Africa: according to the World Health Organization (WHO) report on sanitation, 51 % of the population of Sub-Saharan Africa use unsafe, unhygienic sanitation systems such as uncovered latrine pits, or practice open defecation (compared to 26 % in Central and South Asia and 1 % in Europe and North America; WHO, 2020: 39).

Settlement areas with higher poverty rates (especially urban informal settlements) have greater infrastructure deficits in terms of water supply and wastewater disposal (Section 4.2.2; Rusca et al., 2023; Sinharoy et al., 2019). There are many reasons for this. On the one hand, the responsible state authorities are sometimes unwilling to extend a centralized wastewater system to informal settlements because they fear that this will imply recognizing these settlements (Sinharoy et al., 2019). Other reasons include a lack of financial resources for construction and operation (WHO, 2020: 86) – especially for the high initial investment required to build a sewage water system – the location of informal settlements on the outskirts of cities or in areas that are at risk during natural disasters, and operators' fears that they will not be able to refinance infrastructure measures by levying charges on the inhabitants of informal settlements (Sinharoy et al., 2019). Apart from these practical barriers to implementation, the system of centralized sewage and wastewater treatment known from high-income countries is not a suitable solution for informal settlements in low- and middle-income countries either, because it cannot respond adequately to strong and dynamic population growth and rapid urbanization (Narayan et al., 2021). Moreover, expanding combined sewage systems, which are widespread in high-income countries, is problematic in areas already suffering from water stress because of the large amounts of water required.

Box 4.5-1

The Niger Delta: a biodiversity hotspot under pressure

The consequences of industrial water pollution in Sub-Saharan Africa are already visible today in the Niger Delta. The estuary delta, which is roughly the size of Ireland at around 70,000 km^2, is situated on the Gulf of Guinea; it is one of the largest wetlands in the world and home to the greatest diversity of aquatic species in Africa (Anyanwu et al., 2023). However, this biodiversity hotspot is under pressure. Due to the strong population growth and rural exodus in Nigeria, urban areas are expanding rapidly; in addition, intensive oil production is taking place (Anyanwu et al., 2023; Edegbene and Akamagwuna, 2022). High concentrations of nutrients, salts, mineral-oil hydrocarbons and heavy metals can be found in many places (Anyanwu et al., 2023; Edegbene and Akamagwuna, 2022). Effects on macroinvertebrates, which play a key role in freshwater ecosystems, have been identified (Edegbene and Akamagwuna, 2022). This pollution of ecosystems also affects the local population, who use the waters of the Niger Delta for fishing, irrigation and their drinking-water supply (Anyanwu et al., 2023). Increased concentrations of oxidative stress markers have been detected in North African catfish from rivers in the Niger Delta, indicating that the consumption of these fish is no longer safe (Arojojoye et al., 2021).

Instead of centralized wastewater collection and treatment, alternative sanitation-system solutions – such as decentralized, non-piped wastewater systems, i.e. the decentralized collection of wastewater in septic tanks or uncovered latrine pits – play an important role in the collection, transport and treatment of wastewater in Sub-Saharan Africa (41 % of the population; WHO, 2020: 39). However, where management is insecure, these systems can also involve increased risks to human health and ecosystems (Section 7.3.2). Latrine pits that are not properly sealed can pollute the groundwater (Hubbard et al., 2020); hygiene protection for workers when emptying septic tanks and latrine pits is often not guaranteed, and a large proportion of the collected wastewater is disposed of untreated in surface waters after collection (AfDB, 2020: 142).

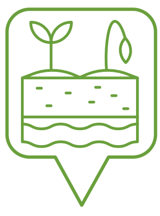
In order to achieve SDG 6.2 'Clean water and sanitation for all' (i.e. comprehensive, safe wastewater disposal), decentralized, non-piped wastewater systems can nevertheless make a significant contribution if health and environmental risks are addressed. The government of Kenya, for example, plans to cover 40 % of wastewater disposal with centralized wastewater systems and 60 % with decentralized systems (World Bank, 2022: 3). In this context, a report by the World Bank (2022) has shown that public-private partnerships can lead to a significant improvement in decentralized, non-piped wastewater systems. In its report on the state of global sanitation, the World Health Organization (WHO) also calls for national decision-makers to recognize the key role that decentralized wastewater systems can play in safe sanitation, and for the informal, existing decentralized wastewater systems to be recognized and integrated into the formal system (WHO, 2020: 71; Section 7.3.1).

Other reasons for the inadequate development of systems for decentralized and centralized wastewater collection and treatment are shortcomings in financing and governance. Although most countries have plans to implement wastewater management, they do not make enough financial and human resources available to achieve the goals they have set themselves (WHO, 2020: 15). Furthermore, national subsidies for water supply and wastewater disposal often do not reach the right areas in low- and middle-income countries. A World Bank study of ten low- and middle-income countries, five of which are in Sub-Saharan Africa, has found that 56 % of funding reaches the richest fifth of the population, but only 6 % reaches the poorest fifth (Andres et al., 2019: 32). Another problem is that international donors tend to prioritize drinking-water supplies over sanitation systems. For example, financial aid for wastewater disposal amounted to only half the sums provided for drinking-water supplies in the years 2010–2018 (WHO, 2020: 15 f.).

The financial decisions of national governments are characterized by political priorities. In this context, the WHO report on the state of sanitation criticizes the lack of political priority and leadership at a high political level on the issue of wastewater collection and treatment (WHO, 2020: 15). Although the proportion of the population who relieved themselves in the open declined globally from 21 % to 9 % between 2000 and 2017, (WHO, 2020: 41), this progress has been achieved in a few countries, while in others progress is too slow or even regressive (WHO, 2020: 34). In particular, the 'Swachh Bharat Mission' or 'Clean India Mission', which was carried out in India between 2014 and 2019, can serve as a positive example of strong leadership from a government that prioritizes sanitation. This is the world's largest sanitation-improvement programme, and it has led to a long-term, marked reduction in open defecation (WHO, 2020: 27).

In addition to domestic wastewater, wastewater from livestock farming is a decisive contributor to the pollution of water bodies with organic carbon compounds and pathogens. A substantial increase in livestock farming and the water pollution it causes is forecast by the end of the century, particularly in the SSP5-RCP8.5 'fossil-fuelled development' scenario (Wen et al., 2017; Jones et al., 2023). The reason for this is the rising global demand for meat and dairy products, the consumption of which is considered desirable in many regions and population groups with rising incomes (WBGU, 2023: 84).

4.6
Overexploitation of groundwater and climate change in the Central Valley, USA



25 %
of fruit and nut production in the USA originates from the Central Valley

10 %
water losses are expected in the region by 2030

75 %
of the wells have suffered a 1.5 metre lowering of the groundwater level 2018–2023

Human intervention in the hydrological cycle to serve societal and economic interests can permanently put the condition of ecosystems and a safe drinking-water supply at risk. One region where the consequences of highly industrialized, irrigation-intensive agriculture and multi-year droughts are particularly evident is the Central Valley in the US state of California. Almost a quarter of the region's catchment areas are now regarded as critically overused. Long-term groundwater depletion exacerbates the risk of irreversible ecosystem damage in the form of land subsidence, salinization or sea-level rise and jeopardizes the maintenance of a safe drinking-water supply. An accumulation of periods of peak withdrawals and losses in times of climate change is forcing policy-makers to act in order to guarantee the security of supply at the state's expense.

4.6.1
Impact patterns, extent and projections

California is the USA's most populous and agriculturally productive state in the west of the country and has a high demand for water. The Central Valley, known as the 'fruit garden of America', stretches through the middle of the state; it is over 600 km long and 80 km wide, and is known for the cultivation of almonds, dates, wine, fruit and vegetables, and other crops. The Central Valley is divided into the Sacramento, San Joaquin and Tulare basins. The 'thirst for water' to supply the population and irrigation-intensive agriculture in the semi-arid climate of the Central Valley is enormous. The Central Valley is a nationally significant agricultural region, supplying 25 % of the United States' fruits and nuts (Love, 2024). The cultivation of water-intensive perennial fruit and nut varieties is attractive for many farmers because of their high economic yields, while the direct withdrawal of groundwater from their own wells remains hardly regulated and inexpensive in most regions (Davenport, 2023). However, water scarcity is a growing problem in California, and it has ecological, economic and therefore societal consequences.

The main drivers of water scarcity in the Central Valley are decades of overexploitation of natural resources and increasing water losses due to evaporation resulting from climate change (Figs. 4.6.1; 4.6.2). Since California was founded in 1850, riparian rights have predominated in the region, granting water-allocation rights to those who own land along watercourses and natural reservoirs. The risk of potential supply bottlenecks as a result of irrigation-intensive agriculture and high temperatures was already recognized in the early 20th century. This was followed in the 1930s by the construction of large-scale water pipeline projects such as the Central Valley Project, the Delta-Mendota Canal and the California Aqueduct to distribute water from the water-rich north and east to the drier south and west (Faunt et al., 2016). Farmers increasingly built their own private wells in order to be able to draw groundwater directly and be independent of supra-regional distribution systems.

Despite the early expansion of infrastructure to diversify supply sources, the risk of local water shortages has increased in recent decades. According to the authorities, about 11 of the 45 sub-catchment areas are considered critically overexploited (CNRA, 2023). In addition to the high demand from highly industrialized agriculture and the needs of a growing population, high temperatures and the consequences of climate change are seen as further drivers of the uncertain supply situation (IPCC, 2022b). The Central Valley has been affected by multi-year droughts since the 1960s. Due to the dense succession of long-lasting drought phases (2006–2011, 2011–2017 and 2019–2021), the period from 2001 to 2021 is considered the driest period in history since the year 800 (Liu et al., 2022). Since the amount of water available from surface waters is less and less sufficient to ensure supplies, the amount of water drawn from the groundwater is increasing. In particularly dry years, the proportion of groundwater in the supply reaches up to 70 %, compared to 30 % in wet years (Faunt et al., 2016). One measure deployed during the 2021–2022 drought emergency, was to completely cut back the water supply to some farms in the Central Valley Project and the State Water Project to secure the basic needs of other consumers (Escriva-Bou et al., 2022a). Farmers compensated for these deficits by increasing the amount of groundwater extracted. The Central Valley accounted for around 90 % of California's total groundwater withdrawals in 2021 (about 18.5 km^3) (DWR, 2023) and the measured groundwater loss reached its highest level at 120 km^3 – it had been around 60 km^3 in 2000 (Liu et al., 2022). The risk of natural groundwater loss is also increasing in other regions of the USA, e.g. around San Francisco, in the alluvial soils of Arizona, on the upper part of the Colorado River and in the Central and Southern High Plains (Scanlon et al., 2023).

The acceleration of climate change is exacerbating an already tense situation in a demographically and economically growing region. Higher temperatures, thinner snow cover in the Sierra Nevada, higher precipitation variability, more intense periods of drought and higher runoff are associated with lower recharge volumes and a declining availability.

Three years of extreme drought came to an end in 2023, largely due to heavy rain and snowfall, which led to flooding but also to the recovery of freshwater reservoirs such as Tulare Lake (DWR, 2023). The largest water gain in two decades (+4.7 km^3) was recorded. However, the long-term trend towards the depletion of freshwater resources has only been slightly mitigated by short-term recovery phases (Liu et al., 2022). According to forecasts, the snow cover of the Sierra Nevada could decrease by 60 % by the end of the century; it is the main source for all freshwater reservoirs in the region (PPIC, 2018). Authorities expect the water supply in California to fall by 10 % by 2040 (CNRA, 2023).

4.6.2 Ecological and socio-economic destabilization potential

Approx. 91 % of the groundwater loss measured in California in 2022 was attributable to the Central Valley (CNRA, 2023). The growing loss of groundwater is having an adverse effect on the environment and ecosystems i.a. via higher risks of land subsidence, earth cracks and earthquakes, hydrological droughts, sea-level rise, groundwater salinization and the loss of plant and animal species (Bierkens and Wada, 2019; Huggins et al., 2022; Jasechko et al., 2024; Figs. 4.6-3, 4.6-4). Geological shifts and damage to groundwater-dependent ecosystems are among the most visible consequences of the years of groundwater depletion in the Central Valley. The Central Valley's hydrological structure consists of a system of overlapping, differently permeable sediment

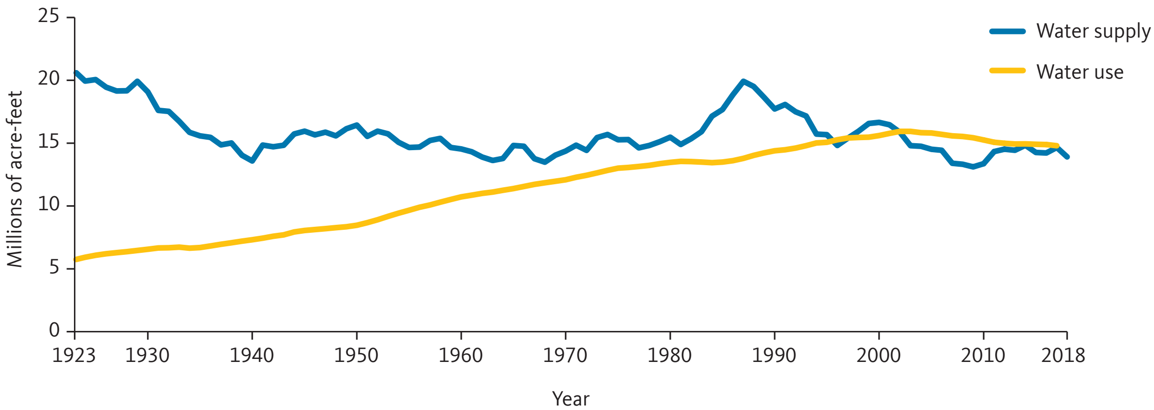


Figure 4.6-1
Development of the water supply and water consumption in California, 1923–2018. Since 1923, the gap between the water supply and consumption has been steadily closing, with consumption exceeding the water supply for the first time in the mid-1990s. Between the early 2000s and 2018, consumption consistently exceeded the water supply. One acre-foot corresponds to about 1.23 km².
Source: PPIC, 2018

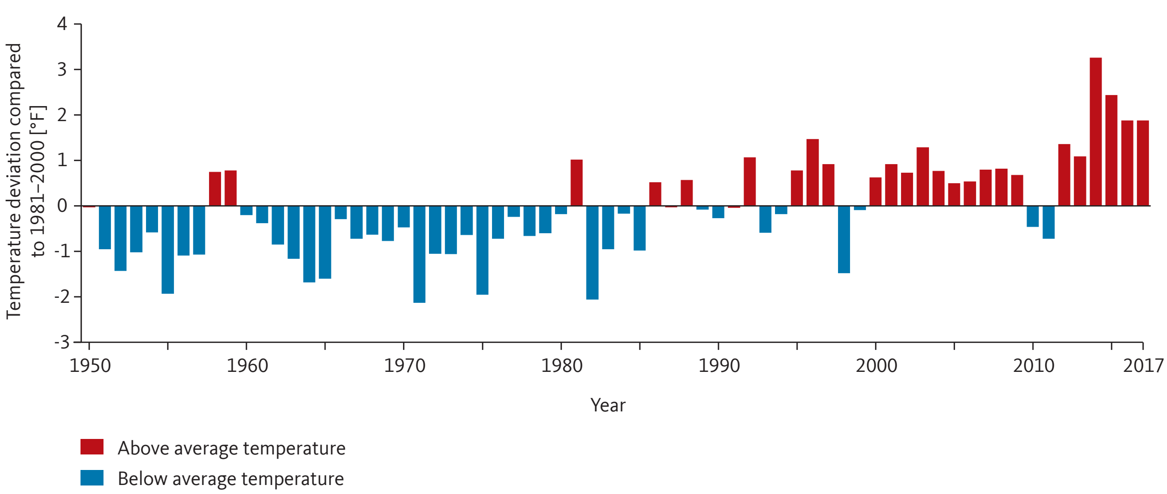


Figure 4.6-2
Annual deviations of air temperatures in California from the mean value of the reference period 1981–2000. Up to 1980, the deviations in air temperatures are lower in most years; from 1990 on, in most years they are higher than the mean value of the reference period. 32°F = 0 °C.
Source: PPIC, 2018

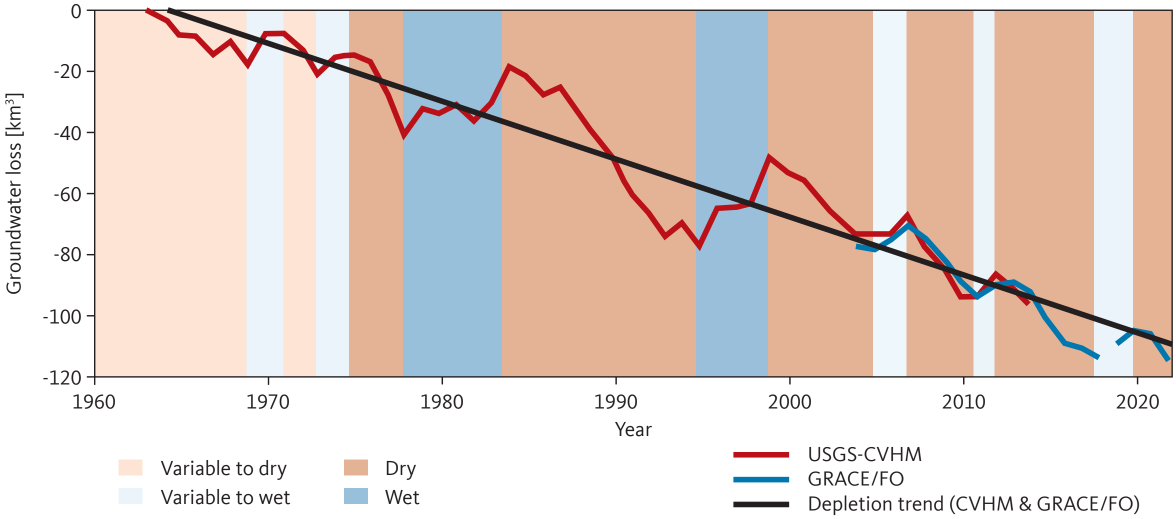


Figure 4.6-3
Groundwater decline in the Central Valley. The results of model-based estimates (USGS-CVHM and GRACE/FO models) show a groundwater loss of 1.86 km³ per year between 1962 and 2021 and a total groundwater loss of 111.5 km³ up until 2021.
Source: Liu et al., 2022

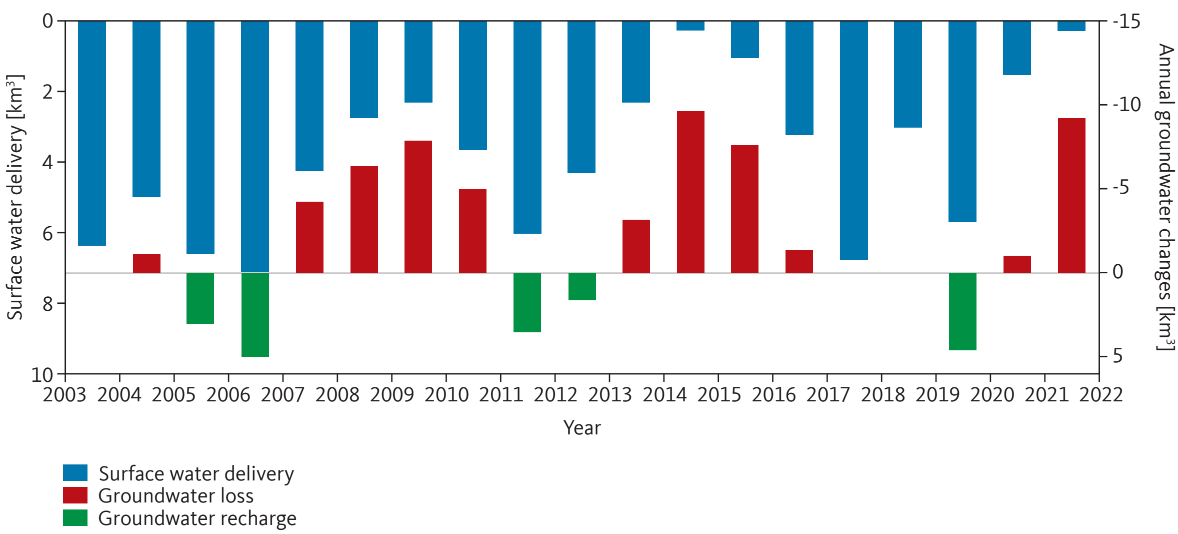


Figure 4.6-4
Water availability from surface waters and recharge or loss of groundwater in the Central Valley 2002–2022. The availability from surface waters has been shrinking since 2002. Despite recovery phases, new peaks in groundwater loss are continuously being reached.
Source: Liu et al., 2022

layers. More than half of the groundwater-bearing layers are fine-grained, containing mainly sand, clay and silt. The water in the coarse-grained layers can be easily extracted and regular recharge leads to comparatively low seasonal level fluctuations. However, most of the Central Valley's wells pump water from the deeper, less permeable aquifers with lower recharge and renewal rates. The drainage of these deeper groundwater-bearing layers by regular pumping leads to soil compaction, increasing the risk of land subsidence and earthquakes (Amos et al., 2014; Galloway et al., 1999).

In the south of the Central Valley around El Nido and Arvin-Maricopa, the land surface subsided by about 1.5 metres between 1962 and 2014, and by up to three metres in the sub-regions of Wasco-Tulare and Los Banos-Kettleman City, which were particularly affected by land subsidence (Faunt et al., 2016). According to Lees et al. (2022), 90 % of subsidence in the San Joaquin Valley is due to groundwater abstraction from the deeper layers of the alluvial groundwater system. Between 1952 and 2017, the water table in the lower water-bearing sediment layers in the south of the Central Valley fell by around 40 metres. Although the aquifers were partially recharged in wet years (e.g. 2016 and 2017), even stopping water abstraction would not reverse the long-term trend of compaction of the predominantly clay-dominated layers, like in the San Joaquin Valley (Lees et al., 2022). Geological shifts that have already been set in motion could have consequences for decades or even centuries.

The depletion of freshwater reservoirs affects not only the environment and ecosystems but also humans. Farms and households with their own groundwater wells are increasingly feeling the effects of these developments. The groundwater level fell by more than 1.5 metres between 2018 and 2023 in more than 75 % of the wells in the Central Valley (CNRA, 2023). The continuing decline will jeopardize up to 53 % of groundwater wells in California and the associated drinking-water supply by 2040 (Bostic et al., 2023). The aggravated supply situation as a result of well-draining or insufficient depth of submersible pumps leads to far-reaching risks to public health. An unsafe drinking-water supply can have direct and indirect negative consequences for people's physical and mental health. Examples include an increased prevalence of diarrhoea, dehydration, changes in the gut microbiome, malnutrition, growth and development disorders, impaired cognitive function, chronic kidney disease and psychosocial stress (Rosinger and Young, 2020).

Ever since the first half of the 20th century, California has relied on measures to diversify sources of supply, e.g. via dams and reservoirs, as well as water imports via pipelines and canals, in order to compensate for bottlenecks and stabilize the supply. However, the contribution of industrial-scale transmission systems to diversify sources is increasingly reaching its limits in times of climate change, among other things due to lower flow rates and technical failures. In the past, the Delta-Mendota Canal and the California Aqueduct, among others, have been affected by operational restrictions.

It is questionable whether the Sustainable Groundwater Management Act passed in 2014 will be enough to ensure a sustainable supply until 2042 as planned. The regulations in the previous implementation plans for the 35 catchment areas are regarded as lacking in ambition. Rather, about 9,000 private and 1,000 public wells are at risk of running dry, resulting in a drop in the groundwater level – with a comparable outcome to a continuation of the status quo (Bostic et al., 2023).

The recourse to groundwater resources increases health and social risks (Chappelle et al., 2021; Cushing et al., 2023). Controlling and eliminating natural and industrial contamination – e.g. arsenic, uranium, nitrate or PFAS – is generally more complex and therefore more cost-intensive for drinking-water treatment from groundwater than for surface water. Furthermore, small water suppliers (for up to 500 people) are frequently responsible for supplying socially disadvantaged groups. The treatment costs for the suppliers and thus the indirect costs for households are often higher for small suppliers than for large municipal utilities. In order to ensure affordability and a water supply for socially disadvantaged groups, some water suppliers subsidize water tariffs by offering so-called 'lifeline rates', which grant particularly low-income households discounts on water tariffs from local suppliers (Chappelle and Hanak, 2021).

Table 4.6-1
Consequences of drought and aridity in California. The 2021–2022 megadrought caused significant economic, societal and environmental damage in the US state of California.
Source: Escriva-Bou et al., 2022a

+ 8 % increase in crop water demands
– 41 % below the 2002–2016 average; total surface water deliveries (for Central Valley and North Coast farms)
+ 184 million in farmers' energy bills due to groundwater pumping
+ 160,000 hectares idle land
– 24 % in revenues (in the Russian River Basin)
– 8,700 full- and part-time jobs
+ 1,000 dry domestic wells
+ 33,5 cm soil subsidence (parts of San Joaquin Valley)

4.6.3 Key challenges

As the supply situation has worsened, the groundwater problem in California has attracted more political attention. Initial successes have been achieved in recent decades thanks to water-saving measures, with household water consumption falling between 2000 and 2020 despite simultaneous population growth. Thanks to drought-emergency measures and appeals to save water, consumption was reduced by 25 % between 2014 and 2016, and long-term water-efficiency measures were put in place. However, once initial measures have been implemented, the challenges and costs of achieving further efficiency gains increase (Ayres et al., 2023): with water savings of just 4 %, the politically set target of 15 % during the 2021–2022 drought period was missed by a wide margin (Escriva-Bou et al., 2022b; Table 4.6-1). In May 2023, Arizona, California and Nevada agreed with the federal government in Washington to reduce their annual withdrawals from the Colorado River – which has been suffering from drought for years – by 13 % in return for a compensation payment of US$1.2 billion (Zeit Online, 2023). Many actors now seem to be realizing the gravity of the situation. However, up to now there has been no comprehensive strategy that not only secures sources of supply but also limits a further increase in water consumption.

For the time being, there are few signs of a comprehensive trend reversal in the Central Valley and California. According to the IPCC's assessment, record temperatures in North America are to be expected more frequently in the future due to global warming (IPCC, 2022b). For years, various approaches have been pursued in California to adapt to the consequences of an uncertain water-supply situation and conserve natural reservoirs. For example, efforts are being made to integrate water scarcity and the consequences of climate change into current plans at the river-basin level. One example of this is the 'One Water One Watershed' (OWOW) approach of the Santa Ana Watershed Project Authority (SAWPA) in southern California. SAWPA is a joint-powers authority consisting of five regional water districts that provides drinking water for more than six million people, as well as industrial and irrigation water. With the OWOW programme, SAWPA aims to identify and promote multiple-benefit strategies and projects for a sustainable hydrological cycle in the river catchment area. Water supply, water quality, rainwater management, water-use efficiency, land use, energy consumption, climate change and living space as well as the interests of disadvantaged communities and indigenous peoples are to be taken into account in planning (SAWPA, 2024). Furthermore, the Central Valley has experience in testing groundwater-recharge and groundwater-storage measures. Recharging groundwater reservoirs is regarded as less susceptible to temperature increases than surface reservoirs because the evaporation rates are lower. Water-retention, -reuse or -supply measures can be used in a targeted manner to make it easier to deal with high water volumes after heavy rainfall events and to prevent damage. However, this requires pumping systems that are expensive to purchase and to make available during periods of non-use (Gerenday et al., 2023). In order to exploit recharge potential, recycled water has been successfully used for artificial groundwater recharge in some districts of California for years (Faunt et al., 2016). Under Californian water law, recycled water meets the highest quality standards (drinking water) and can be used in a variety of ways once authorized. In 2022, the Californian government announced a new strategy to permanently and comprehensively increase the water supply. The plans include increasing retention capacities by around 4,500 million km^3, increasing annual water recycling to 990 million km^3 by 2030, reducing consumption by 616 million km^3 by improving use efficiency, increasing supply through rainwater retention and treatment measures (by around 310 million km^3) and expanding desalination plants (by around 34 million km^3; CNRA, 2022, 2023). By way of comparison, water consumption in the urban catchment area of the largest city, Los Angeles, was just under 620 million km^3 in the 2021–2022 heatwave years (LADWP, 2024). The Californian government also wants to make better provisions for future emergency situations with resilience and drought-emergency measures (CNRA, 2023).

However, as a groundwater-dependent and semi-arid region, the Central Valley is not the only region in the world where there are signs of localized depletion of renewable groundwater resources with far-reaching consequences for humans and nature. The north-east of China (Hai River Basin and aquifer of the North China Plain), the north of India (Ganges-Brahmaputra aquifer), the north-east of South America (São Francisco Basin), the Southwest and South of the USA (Central and Southern High Plains), Eastern Europe (Don and Dnieper basins) and the Middle East (Arabian Peninsula, Iran) are also reaching the limits of their natural capacity as a result of years of intensive crop cultivation and the consequences of global warming (Table 4.6-2; Scanlon et al., 2023). However, the experience of natural groundwater decline in California shows that even with the technical possibilities of high-income countries, the continuation of highly industrialized agriculture can push individual regions to the limits of their carrying capacity (Jasechko et al., 2024).

Table 4.6-2
Change in the total volume of water in the world's major groundwater aquifers. The Central Valley ranks third (after the North China Plain and the Ganges-Brahmaputra), with a trend of -12.1 mm per year and -13.9 km^3 in 19 years. TWS = Total Water Storage.
Source: Scanlon et al., 2023

Basin	Country	Area [km^2]	TWS trend [mm per year]	TWS trend [km^3 in 19 years]
North China Plain	China	437,748	–11.5	–97.1
Ganges-Brahmaputra	India	634,565	–18.9	–231.5
Central Valley	**USA**	**59,425**	**–12.1**	**–13.9**
Arizona Alluvial	USA	225,404	–7.9	–34.5
Upper Colorado	USA	369,857	–3.0	–21.3
C+S High Plains	USA	203,400	–6.8	–26.4
Paris	France	171,968	–3.6	–11.8
Tarim	China	468,333	–2.6	–28.8
Nubian	Sudan, Chad, Libya, Egypt	2,203,920	–1.4	–59.9
Great Artesian	Australia	1,727,400	0,9	30.4
Ogaden-Juba	Ethiopia	1,035,211	2.2	44.8
Guarani	Argentina, Brasil, Paraguay, Uruguay	1,865,481	2.8	100.2
MERAS	USA	202,960	3.8	15.0
Columbia Plateau	Columbia	114,178	4.3	9.5
Iullemeden	Mali, Niger, Nigeria	594,821	5.1	58.8
Upper Kalahari	Namibia, Angola	989,348	5.7	108.6
Northern High Plains	USA	250,965	6.1	29.2

4.7 From regional water emergencies to global patterns

4.7.1 Starting points for improving ways of dealing with water emergencies

Typical characteristics of regional water emergencies of planetary dimension are negative changes in water availability, water supply or water quality. These negative changes can influence each other and form cascades of effects, some of which are self-reinforcing and have transregional reach. The dynamics of regional water emergencies and their interactions with exacerbated water-related challenges (Chapter 3) can lead to a planetary emergency, such as a food crisis.

The WBGU believes that some key starting points for dealing with the associated risks to nature and humans can be derived from an analysis of the regional water emergencies selected here as examples (Chapter 5; Table 4.7-1). In addition to consistent climate-change mitigation and biodiversity protection, these include long-term risk assessment, climate-resilient water management, strengthening societal resilience, restoring ecosystems, securing funding for (adaptation) measures and improving data collection for more reliable long-term projections.

There is an overarching task here for transregional and multilateral cooperation (Section 8.1). The regions selected here exemplify the characteristics of regional water emergencies. These interacting structures and patterns can also be found in many other regions, in most cases spread across all continents and countries of different economic strength and political organization. It is therefore necessary to find global and common answers.

Affected regions are often inadequately prepared for water crises

The examples of regional water emergencies mentioned show that the regions threatened or affected by such crisis patterns are inadequately prepared for the medium and long-term challenges that lie ahead. In many regions, the water infrastructure is dominated by current economic and societal constraints or interests, or by path dependencies. This usually comes at the expense of long-term precautions. One example would be the breakdown of the irrigation infrastructure in post-Soviet Central Asia. The transformation from a centralized planned economy to integration into a globalized market economy posed substantial economic and political challenges for the societies of Central Asia in the 1990s–2010s. Ecological or climatological considerations and corresponding policies for sustainable water management were rarely prioritized.

Social groups and societies are affected very differently

Exacerbated water-related challenges and regional water emergencies have different impacts on social groups and societies. The ability to cope with crises is lowest among vulnerable groups worldwide, above all in low- and middle-income countries, whose livelihood systems are frequently very close to nature and often directly dependent on water (e.g. agriculture). The resilience of social groups and societies to exacerbated water-related challenges and regional water emergencies with a planetary dimension can be improved above all by strengthening their capacity to act. International cooperation for sustainable water management is of particular significance here. It is important in this context to ensure that projects that are sensitive to gender-specific role distributions are developed cooperatively with both large- and small-scale water users. For example, land-intensive agriculture and production for export is male-dominated in many countries, while small-scale vegetable and fruit production relevant for local food security and diversity is in women's hands.

Accordingly, international cooperation as well as scientific cooperation in the field of sustainable water management must be designed in accordance with the societal organization pattern and promote societal cohesion and resilience via water collaborations. This requires a proactive state that follows the principles of the rule of law and the welfare state and supports societal self-organization.

4.7.2 Gaps in understanding of regional water emergencies

There are still gaps in understanding the long-term dynamics and the associated region-specific risks. What is required, therefore, is a better spatially resolved data basis, more reliable projections and regionally specific modelling. Above all, the current projections cannot adequately depict expected future extremes, partly because developments caused by climate change have only recently started taking effect and the variability of climate events cannot be comprehensively depicted. A way should therefore be found to adequately integrate the latest observations and research results into the projections, and to improve their spatial resolution. In this way, projections of extreme events could provide a more reliable picture and help improve regionally specific adaptation measures.

- There are large gaps in data collection in the Hindu Kush-Karakoram-Himalayan region. This applies, among other things, to the future water supply and water demand, especially links between upstream and downstream reaches, impacts on ecosystems and biodiversity, and the effectiveness of different adaptations to natural hazards (technical, nature-based, institutional). Up to now there has been little research into, and quantification of, changes in the permafrost, which in some cases can exacerbate the observed risks. Similarly, it is not yet possible to quantify what the changes in the cryosphere will mean for the life-support systems of the population (particularly at high altitudes), which is largely dependent on nature.
- Average figures for the water situation in cities often do not show the whole picture. A more differentiated overview is provided by data on access to water and water consumption, broken down by socio-economic groups and urban neighbourhoods. It is therefore necessary to differentiate urban data collection more in spatial and social terms.
- In many countries in the MENA region, water management is hampered by a lack of capacities on the part of local authorities. Some regions are inaccessible due to armed conflicts; in others water-related data collected are not shared adequately (Houdret and von Lossow, 2023). This hinders cooperation between sectors and countries; for example, fluctuations in the quantity and quality of groundwater are often invisible.
- There is a need for projections on surface-water pollution up to the end of the century that take all sources of pollution into account (including domestic wastewater, agricultural irrigation, livestock farming, industry) as well as dilution effects and degradation pro-

cesses in water bodies. These projections should include several water-quality parameters (e.g. nitrogen, dissolved solids, pathogenic microorganisms) and different socio-economic development pathways and emission scenarios, in order to capture different types of pollution, cover the range of scenarios and improve the comparability of the studies.

Research on the potential extent, regional distribution and range of regional water emergencies with a planetary dimension and their interactions with each other is still in its infancy in many cases.

Table 4.7-1
Regional water emergencies of planetary dimension: risks, measures and supraregional and global needs for action. The table shows which risks arise from each type of water emergency for humans and nature and which key measures can be derived from this in order to identify the global need for action to meet the challenges that are outlined.
Source: WBGU

<table>
<tr><th>Water emergency</th><th>Significant risks for humans and nature</th><th>Key measures</th><th>Supraregional and global need for action</th></tr>
<tr><td>Water scarcity in cities and urban agglomerations</td><td>› Impairment of the water supply
› Impairment of sanitation system
› Societal and political destabilization</td><td>› Accelerate infrastructure expansion
› Take path dependencies and climate projections into account
› Implement the ‘sponge city’ concept
› Keep an eye on the entire water-catchment area</td><td rowspan="5">Forge ahead with climate-change mitigation and biodiversity conservation

Research: forge ahead with data collection for reliable long-term projections

Risk assessment and avoidance:
› Develop monitoring, early-warning systems and disaster prevention (further)
› Identify the limits of controllability

Accelerate adaptive, innovative and resilient planning and management and make water use more sustainable and efficient

Strengthen societal resilience:
› Political and societal participation
› Supra-regional and global cooperation
› Education

Promote restoration (green and blue water)

Develop innovative financing approaches</td></tr>
<tr><td>Increasing droughts and flash floods</td><td>› Impairment of the water supply
› Direct health risks
› Loss of income or livelihoods
› Societal and political destabilization
› Impacts on food security
› Damage to/destruction of ecosystems</td><td>› Generate region-specific solutions
› Implement disaster prevention and early-warning systems
› Plan and implement long-term sustainable water use
› Integrate measures into political and socio-economic reforms
› Establish water reservoirs that can also absorb flash floods</td></tr>
<tr><td>Glacial melt</td><td>› Impairment of the water supply
› Natural hazards as a threat to human life and infrastructure
› Societal and political destabilization
› Impacts on food security
› Damage to/destruction of ecosystems</td><td>› Strengthen intergovernmental coordination and cooperation
› Expand risk prevention and disaster management and improve lacking data basis
› Make water use more efficient and sustainable in various sectors
› Establish alternative water reservoirs</td></tr>
<tr><td>Water pollution</td><td>› Direct health risks
› Damage to/destruction of ecosystems</td><td>› Domestic wastewater/WASH: Adapt infrastructure solutions
› Increase political priority
› Treat increasing wastewater from agriculture and industry</td></tr>
<tr><td>Overexploitation of groundwater</td><td>› Damage to/destruction of ecosystems
› Impairment of infrastructure and technology
› Impairment of the water supply
› Societal and political destabilization
› Direct health risks
› Loss of income or livelihoods</td><td>› Also consider risks to drinking-water supply in high-income countries
› Dare to try innovative approaches to dealing with increasing risks
› Use water-budgeting approaches and capital-market financing instruments</td></tr>
</table>

Maintain a safe distance from the limits of controllability

5

In a heated world with critical climatic, ecological, socio-economic and geopolitical developments, societies will reach the limits of controllability. Stopping anthropogenic climate change and taking transformative adaptation measures are key to maintaining our distance from these limits. In cases where all adaptation options have been exhausted, retreat options will have to be prepared. Deciding which risks are no longer considered acceptable and which adaptation path is to be pursued will also be the subject of societal negotiation processes.

In many parts of the world, water is often not available in the required quantity and quality (Chapter 2). Climate change and the degradation of ecosystems, together with socio-economic and geopolitical changes, lead to exacerbated water-related challenges (too much – too little – too polluted; Chapter 3). These can result in regional water emergencies of planetary dimension (Chapter 4). In areas that are at risk of such regional water emergencies, negotiation processes must be conducted at an early stage to decide which risks are acceptable and what depth of intervention of adaptation measures is still acceptable – because adaptation can only succeed together with and not against the population (Section 5.2). Public forums should be set up for this purpose. Science also plays an important role in the assessment of risks and uncertainties. Furthermore, precautionary measures that ensure a climate-resilient landscape water balance are an important component in avoiding extreme water emergencies.

There are increasing changes taking place in water availability, quality, supply and demand, and an increasing occurrence of extreme events with impacts beyond the spectrum of human experience. In extreme cases, human societies will be confronted with the limits of controllability. In order to be better equipped in the future, it is necessary to recognize these limits at an early stage (Section 5.1), identify the actions that need to be taken (Section 5.2) and prepare decisions for cases in which all adaptation options have become exhausted (Section 5.3).

5.1 Recognizing limits

In the future, the global hydrological cycle is expected to undergo permanently ongoing and accelerating changes, which will further exacerbate the effects of climate change, the overuse of water resources, the unequal distribution of water, the degradation of ecosystems and loss of ecosystem services and the threats posed by water-related health risks (Chapter 3). The interplay of these factors can lead to regional water emergencies of planetary dimension, where the limits of controllability are reached: humans and ecosystems in the affected regions will be deprived of their natural life-support systems. In view of the predicted climatic, ecological, socio-economic and geopolitical developments, such limit states and regional water emergencies can be expected to become increasingly common worldwide. Without prompt proactive action and transformative policies, the limits of controllability can be exceeded in affected regions (Fig. 5.1-1).

In order to maintain a safe distance from the limits of controllability, measures are required at the global, regional and local level:

First, it is important to limit exacerbated water-related challenges (Chapter 3) which, as global drivers, have a direct impact on the global water balance. The prerequisite for this is an ambitious climate policy, includingcompliance with the goals of the Paris Agreement. This is the only way to limit the changes to the global and local

Yaptik-Sale (Russia)

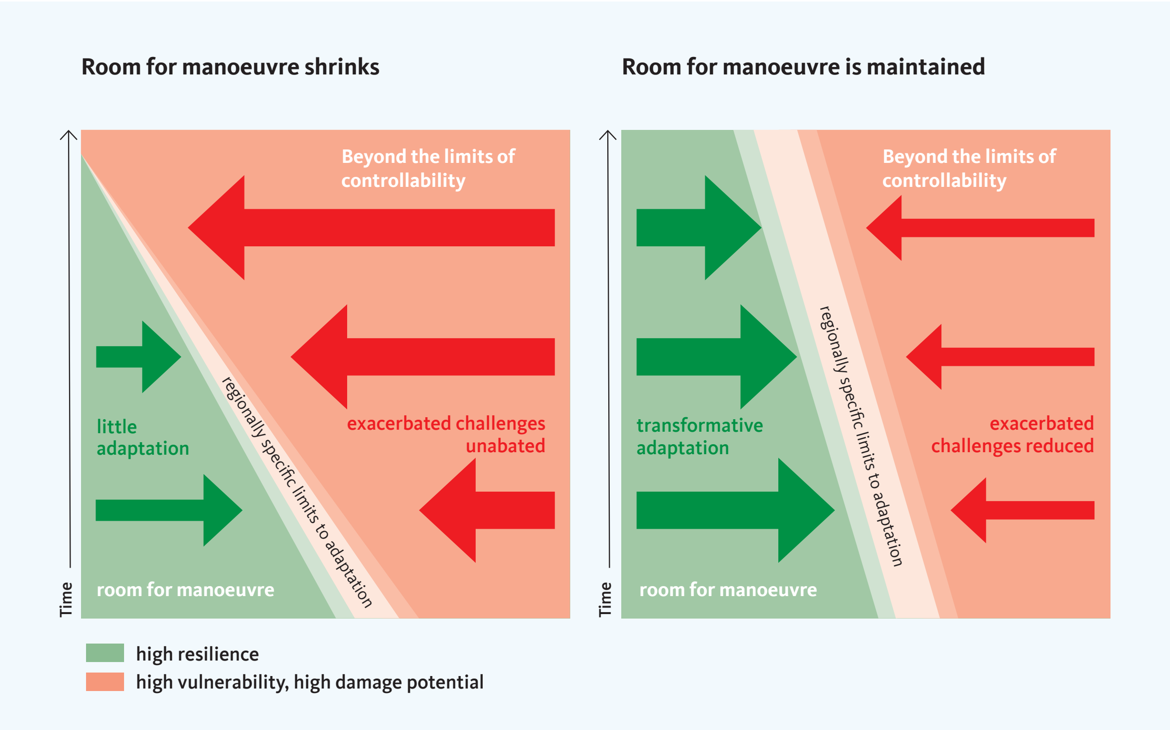


Figure 5.1-1
WBGU's concept on the limits of controllability. Unchecked aggravations of water supply, water distribution and extreme events, coupled with inadequate adaptation can lead to regional water emergencies and to the limits of controllability being exceeded. Beyond these limits, which can vary from one region to another, the risks are intolerably high (red area). Which risks are considered intolerable and which individual adaptation paths should be pursued is also the subject of societal negotiation processes.
Left: If only minor adaptation measures are taken, the room for manoeuvre shrinks (green area). Water-related challenges exacerbated by increasing climate change, ecosystem degradation and pollution, as well as socio-economic and geopolitical developments can unleash their full force. Vulnerability and damage potential increase, and the risk of exceeding the limits of controllability grows over time.
Right: Transformative precautions increase resilience and reduce the impact of exacerbated water-related challenges, while at the same time containing the exacerbated challenges themselves. Room for manoeuvre (green area) is also maintained in the longer term.
Source: WBGU

water balance caused by climate change. Equally important is the implementation of the Kunming-Montreal Global Biodiversity Framework (GBF) in order to protect the fundamental role of nature in the global hydrological balance. The earlier action is taken, the more options there are.

Second, regional water emergencies (Chapter 4) must be avoided as far as possible. If the exacerbated water-related challenges cannot be controlled, existing regional water emergencies will intensify and the likelihood of further water emergencies of planetary dimension will increase. As defence against them, transformative adaptation measures (Box 5.1-1) and climate-resilient water management with a transformative depth of intervention are needed, since previous (incremental) adaptation measures will no longer be sufficient. In concrete terms, this requires a willingness to radically change course, in particular by shaping structural change, for example in land-use, industrial, settlement and infrastructure policy – both nationally and in the context of international cooperation.

As it is not always possible to maintain a safe distance from the limits of controllability, regions at risk must prepare for a plan B at an early stage. If transformative measures no longer help, an orderly and timely retreat may be the only option left. Where the limits of controllability are crossed, the options for action are reduced to reactive crisis and disaster management accompanying the retreat.

A precautionary water policy and forward-looking, transformative adaptation measures are needed to ensure a water-just future and the preservation of natural life-support systems. These necessary transformations are not limited to the water sector and are not aimed solely at emergency response. They require global action such as climate-change mitigation and biodiversity protection, the conservation and restoration of ecosystems, as well as action at regional, water-catchment-area and local level (cities, villages) at the same time, to maintain a sufficient distance from the limits of controllability.

Tipping points can be reached in especially vulnerable regions. It is therefore of the utmost urgency to place and establish the issue of water higher on the international agenda. The current strong momentum created by the UN Water Conferences in 2023, 2026 and 2028 should be used by governments to maintain a sufficient distance from the limits of controllability worldwide by taking comprehensive precautions. In the short term, institutions should immediately begin developing effective strategies that will strengthen global water-related co-operation in the medium term. However, precautionary water policy can only succeed if timely progress is also made in other policy areas. The climate-change mitigation targets of the Paris Agreement are key to this.

Water should be integrated and made more visible as a separate dimension (supply and quality of blue and green water and adaptation to new threats) in its own right and with its own indicators in the national implementation mechanisms of the 2030 Agenda, the Paris Agreement and the Kunming-Montreal Global Biodiversity Framework (GBF). Water targets are already a key component of the 2030 Agenda; however, access to drinking water, sanitation and the implementation of the IWRM remain a challenge (Section 8.3).

The German Sustainable Development Strategy for the national implementation of the 2030 Agenda, which is currently being further developed, addresses the need to improve water quality and adapt to the impacts of climate change. It should recognize the great challenges posed by exacerbated water-related challenges and growing uncertainties and fluctuations in the water availability in Germany to a greater extent, and specify the next steps to that end. In the German context, the National Water Strategy of 2023 and the yet-to-be-developed German Strategy for Adaptation to Climate Change have a key role to play here. Their effectiveness will depend, among other things, on whether they are backed up with sufficient resources, suitable institutions and processes.

The upcoming negotiations on the post-2030 Agenda and biodiversity governance offer a window of opportunity for further development at the international level. The GBF adopted in 2022 will be implemented through national strategies and action plans, which are currently being developed in many countries. In this context, the approach recommended by the WBGU of a multifunctional mosaic of land uses – in which land and biodiversity protection and land use are considered together in order to achieve multiple benefits for nature and humans – can help strengthen the landscape water balance and the storage capacity of water in nature (WBGU, 2020, 2024).

Box 5.1-1

Adaptation, limits to adaptation and limits of controllability

Adaptation in ecological systems includes autonomous adaptations to the changing climate and its effects – e.g. to changes in water supply – by means of ecological and evolutionary processes. In human systems, adaptation can be not only reactive but also proactive. Furthermore, the IPCC distinguishes between incremental and transformative adaptation – the latter referring to adaptation in which fundamental characteristics of a socio-ecological system are changed.

The IPCC uses the term 'limits to adaptation', which are defined as "the point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions" (IPCC, 2022b: 7). A distinction is made between hard and soft limits to adaptation. If a hard limit is reached, no adaptation measures are possible that would avoid unacceptable risks. In the case of a soft limit, there are ways of avoiding unacceptable risks through adaptation measures (IPCC, 2022b: 84), but these are not currently available and require, for example, greater financial or technological efforts. The IPCC identifies water-related limits to adaptation in different regions depending on the extent of climate change. Above 1.5 °C of global warming, limited freshwater resources represent potential hard limits for small islands and for regions dependent on glacier and snow melt. At the latest when global warming reaches 3 °C, the projections show soft limits for some water-management measures in many regions and hard limits in parts of Europe. According to the IPCC, a transition from incremental to transformative adaptation can help overcome soft limits to adaptation (IPCC, 2022b: 129).

The term 'limits of controllability' used in this report is conceptually based on the 'hard limits to adaptation' defined by the IPCC. Limits of controllability describe the transition to water-related crisis situations that entail unacceptable risks. Avoiding these requires forward-looking and potentially transformative action. If they can no longer be avoided, the risks must be dealt with in the best possible way in order to minimize damage.

5.2 Need for action and principles of action

The WBGU recommends climate-resilient water management that is based on democratically negotiated goals, principles and rules on tolerable risks and an appropriate scope of adaptation measures (Section 5.3). As a basis for this negotiation process, the WBGU proposes seven principles of action (see Section 6.1.2 on implementation). The principles comprise a new approach to declining stationarity, resilience and risk prevention, the consideration of blue and green water, the key role of science, the monetary and non-monetary valuation of water, and implementation by a proactive state while promoting self-organization. In addition to the seven principles, a consistent climate and biodiversity policy is a basic prerequisite for maintaining room for manoeuvre. The principles also inform the discussion on how societies can adapt to unavoidable changes.

5.2.1 Safeguard water as a common good for people and nature

Water must be distributed and stored as a global, life-giving common good according to the needs of all people and nature. Nature-based, technical and institutional solutions for ensuring a resilient water supply with impeccable water quality must take into account and balance the multifunctionality of water for humans and ecosystems.

Water is a scarce common good and a vital resource; it must therefore be distributed in a socially balanced way and managed with foresight. A consequence of recognizing water as a common good is a state responsibility for distributing the burdens of water scarcity and deteriorating water quality among societal groups in a socially balanced way, while safeguarding the characteristics and functionality of the ecosystems affected – and their services. The distribution of water and the conservation and creation of water reservoirs must adequately take into account the needs of all humans and nature as well as the global interactions via the hydrological cycle (One Water). In the case of a strained water availability, this may require examining the extent of existing or intended uses and nature's water requirements in a region, and first answering the question as to the extent to which vital minimum human needs can be met. Other uses should be weighed with a view to their overall impact and made more efficient and water abstraction substituted by alternative resources wherever possible, e.g. rainwater harvesting, water reuse; or else, in extreme cases, some uses should simply no longer be practised.

Exacerbated water-related challenges and regional water emergencies of planetary dimension can have very different impacts on social groups and societies. The ability to cope with crises is lowest among vulnerable groups affected by poverty, especially in low- and middle-income countries. However, this ability is also limited if there is mismanagement in the water sector, regardless of the economic circumstances. Many regional water emergencies are also characterized by a spatial discrepancy between those responsible and those affected, which means that causal chains are not always obvious. Polluters often do not have to pay the costs of their water-damaging behaviour. At the same time, many of those affected do not have access to the technological infrastructure and infrastucture needed for control and adaptation that are necessary for timely crisis prevention and preparedness.

5.2.2 Increase adaptability in the face of continuous change

Systems for the provision and use of water should be kept resilient in the face of hitherto unknown fluctuations and ongoing changes that cannot be precisely predicted; they should also be re-coordinated on a scientific basis. Administrations, operators and users must prepare themselves for a highly dynamic situation. To achieve this, structures, as well as planning and decision-making processes, must be designed in an adaptable and correctable way and include all actors.

The assumption of stationarity – i.e. the idea that natural systems exhibit a degree of variability within a defined time window that can be predicted on the basis of empirical observations – is no longer valid. The patterns of the water balance that have hitherto been regarded as stationary – i.e. with seasonal fluctuations in precipitation, evaporation rates, groundwater levels and river levels within known ranges – are changing in sometimes short periods of time and continuously as a result of human intervention and climate change, leading to growing planning uncertainty (Milly et al., 2008; Chapter 4). This is referred to as the loss of stationarity.

Due to the inertia of the Earth system, these changes will continue for a long time, even if climate change and the degradation of ecosystems were halted, and their manifestations are not always precisely predictable, at least locally (Caretta et al., 2022; IPBES, 2018a). Water systems for affected sectors can therefore no longer be planned and managed for the foreseeable future on the assumption of stationarity, but must be kept resilient with adequate buffers, reserves and flexibility and especially in interaction with nature, and constantly adapted to the changes and to each other. What is needed is a long-term, adaptive and reversible approach to water management, the implementation of which helps to make involved stakeholder interests and path dependencies of water-infrastructure projects, patterns of use, legal regulations, institutions and agreements transparent, and to find political solutions.

5.2.3
Resilience and risk prevention instead of emergency response

The precautionary principle must be consistently applied to safeguard a climate-resilient water infrastructure and water quality. Risk prevention and risk minimization instead of emergency response should be the basis of planning processes and decisions in the entire water sector and sectors influenced by it.

Risk prevention and risk minimization must be the basis of planning processes in the entire water sector – even where the focus has hitherto been on emergency response. What is required is planning that is based on a comprehensive risk characterization, on the basis of which risks are appropriately managed in order to deal with increasing exacerbated water-related challenges and with uncertainties regarding the construction or adaptation of water infrastructure. To ensure a climate-resilient water infrastructure and water quality, the measures to be taken must be orientated towards resilience and precaution.

5.2.4
Managing blue and green water across sectors

Regarding regional and local solution approaches, blue and green water must be considered and managed jointly and in a cross-sectoral manner. Both have strategic, geopolitical relevance: in addition to river catchment areas, transboundary evaporation and precipitation patterns must also be taken into account. Coherence between policy levels and fields is a prerequisite for this.

A balanced consideration of the vital resource of water for humans and nature for a particular region requires an appropriate understanding of the role of green and blue water. This calls for a good knowledge of water availabilities, requirements and qualities.

At the regional level, active management of green water can have a stabilizing effect on the natural water balance and biodiversity when (re-)establishing a climate-resilient landscape water balance and water-sensitive urban design, e.g. through measures such as unsealing, reforestation or soil cover to reduce evaporation and improve soil moisture. In view of the increasing variability of water supply, strengthening buffers in the landscape that can absorb, retain and release water is one of the most important prevention and response strategies. The use of blue water can also support the local and regional natural water balance, e.g. through targeted rainwater infiltration or artificial groundwater recharge with river water or recycled water. This creates resilience to extremes such as long periods of drought.

At the international and national level, this means assessing the impacts of large-scale infrastructure projects (e.g. dams, aqueducts), geo-engineering (e.g. cloud seeding) and large-scale irrigation projects and land-use changes with possible transboundary impacts on evaporation and precipitation, and minimizing adverse impacts on green and blue water.

5.2.5
Enable a science-based discourse on challenges and options for action

The WBGU recommends initiating a science-based discourse on strategy development and options for action in the face of uncertainties, taking the concerns of citizens and stakeholders into account. To this end, the severity and dynamics of exacerbated water-related challenges and resulting regional water emergencies with a planetary dimension must be identified and understood, and options for action researched. Science should continuously inform policy-makers and take on a strong, advisory role, e.g. by scientifically monitoring the instruments used. Political and societal participation, education and collaboration should be promoted.

Research on the potential scale, regional distribution and range of exacerbated water-related challenges and the limits of controllability of water emergencies is still in its infancy. There is also a need for research into dealing with uncertainties and integrating long-term, potentially critical developments in today's decisions (policy, planning, prevention). Reliable projections and region-specific modelling are needed to improve our understanding of long-term dynamics, reduce the associated risks and ensure proactive and formative action – also in dealing with uncertainties (Chapters 3, 4).

A discourse should be facilitated that is conducted jointly by society, science, business and policy-makers. The following questions, among others, could be discussed. What risks regarding water supply and its continuity, water quality and the effects of extreme events are we able to, do we want to, or will we have to live with in the future? What can we do to avoid those that are or will be intolerable? How do we maintain as large a 'safe distance' as possible from limit states that are characterized by an increasingly shrinking room for manoeuvre? What should be avoided at all costs, especially with a view to a time horizon of several decades? Which changes can we accept and which can we still influence – in the water sector and beyond? How can we maintain our ability to deal with water-related risks in such a way that we can act proactively and formatively instead of just reacting?

5.2.6
Value water and appreciate the value of water

Policy-makers, public institutions, companies and financial markets should embrace and integrate the value of water and the systemic nature of water risks into their decisions. Economic decisions must be compatible with the long-term goals of sustainable water management.

The value of blue and green water resources for people and nature and the scale of water-related risks must be recognized and made transparent for policy-makers, the public, companies and investors. In both short-term decisions on use and long-term investment decisions, scarcities and risks should be taken into account, uses prioritized and efficiency improvements promoted. This requires adequately taking the value of water for humans and nature into account in all interventions in the water balance, e.g. in land-use changes, construction measures, water abstraction and use, granting corresponding rights, in public planning, private investment and use behaviour. Where necessary, this should be made visible by way of reporting obligations, water prices, pollution charges or payments for compensation measures. Staggered water tariffs or targeted support measures, e.g. from redirected harmful subsidies, should make it possible for everyone to meet their basic water needs. In order to adequately plan and efficiently implement investments in the water sector, bearing in mind possible exacerbated water-related challenges, to generate stable revenues and thus also make the investments more attractive, the capacities of water suppliers and regulators must also be improved, e.g. for planning and the accountable implementation of investments, as well as for recording and/or sanctioning abstraction and pollution. In addition, public and private investment decisions should take into account the growing risk of damage and value losses (stranded assets), particularly in the case of durable infrastructure. An important criterion should be not only the damage avoided but also the costs of any necessary future adaptations. This requires shorter revision periods as well as a certain error-friendliness and willingness to again correct and adapt selected solutions under certain circumstances.

5.2.7
Accelerate implementation – encourage and promote self-organization

The regulatory framework and all water-management instruments must enable accelerated implementation and involve informal, decentralized governance structures where appropriate. In particular, non-state, self-organized actors need to be involved and empowered.

Effective implementation governance requires appropriately scaled, regionally adapted institutional, technical and individual capacities as well as management competences. However, formal governance capacities are often not sufficiently developed or extensive enough, even in high-income countries, resulting in planning and implementation deficiencies or regulation-enforcement deficits. In view of the urgency of targeted action to implement water regulation, there is a need for interaction between a framework-creating proactive state and already practised, historically developed self-organization structures for improved, accelerated implementation. Self-organized governance structures should also be taken into account and, where appropriate, linked and integrated with formal governance (Section 8.2).

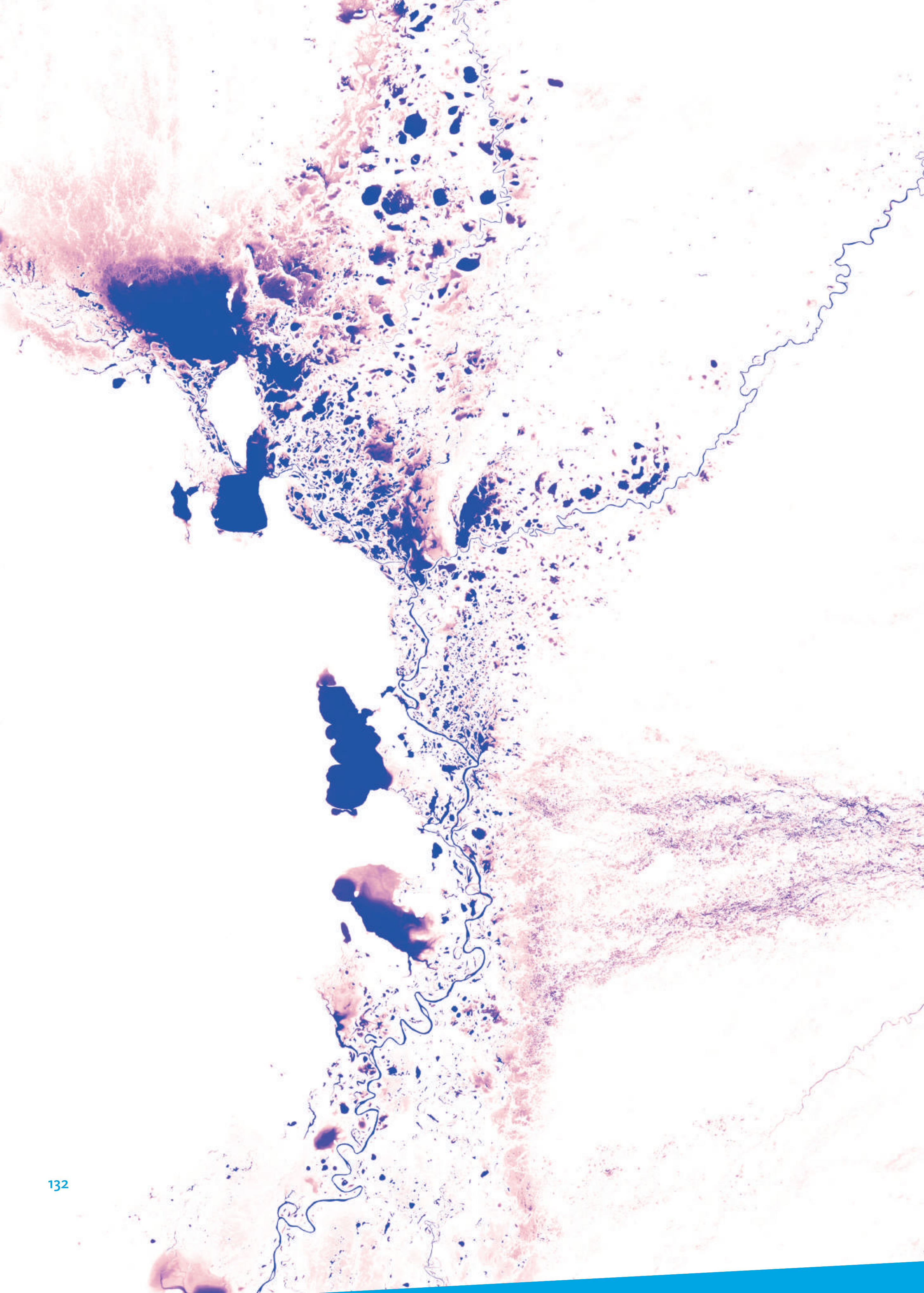
5.3
Beyond the limits

Adaptation strategies must be developed in good time to avoid a transition to unmanageable situations. In a business-as-usual scenario, i.e. without decisive countermeasures, the room for manoeuvre in dealing with water-related risks becomes increasingly limited (Fig. 5.1-1). Even in extreme cases, such as a collapse of the local water supply, there are still options for action, although these are increasingly reactive (e.g. leaving the area). Proactive, creative action to prevent or mitigate regional water emergencies is then no longer possible in many cases. Adaptation strategies should therefore be chosen in such a way that maladaptation is avoided and proactive and creative action remains possible.

Once all adaptation options have been exhausted (Box 5.1-1), decisions for an orderly retreat must be made in good time. This applies to all policy areas, also outside the water sector. Policy-makers and society need to discuss how best to hedge risks: what is insured privately, where does the state step in, where does it no longer step in, and how can infrastructure be dismantled with foresight? Where necessary, the options and needs for action for organized migration between and, above all, within countries must be examined. With regard to the supply of water for different needs, the limits of adaptation in a region are reached, for example, when

- the habitability of a place or region is increasingly limited by a lack of water, and in-migration is limited or no longer possible;
- agricultural production is threatened by droughts and seasonal water shortages due to reduced glacier runoff, jeopardizing the livelihoods of a potentially very large number of people;
- water pollution in surface waters and saltwater intrusion into groundwater have a negative impact on the health of the population and the ecosystems of a region;
- a region's hydropower-based energy supply is destabilized by (seasonal) water shortages;
- extreme events (water shortages and flooding) cause societal destabilization that significantly limits the ability to manage crises.

Enforced out-migration or flight due to such circumstances can involve a massive reduction in quality of life, e.g. loss of economic livelihoods, cultural identity and social ties. The consequence would be a permanent loss of the familiar living environment. This can be aggravated by the fact that neighbouring target regions of migration may themselves already be under pressure from water emergencies (Chapter 4). Conflicts of use must also be borne in mind. If a regional water crisis nevertheless occurs, disaster prevention and management will play a key role. To this end, contingency plans and emergency-aid programmes must be prepared and funded at an early stage in regions that are at risk. This applies in particular to low- and middle-income countries. In addition, strategies for crisis communication should be prepared and possible target regions should be identified for the temporary or permanent accommodation of those directly affected by a water emergency.



Climate-resilient water management

6

What is needed is climate-resilient water management with a long-term view that considers both blue and green water in combination, and is able to react flexibly to changes. It should take multiple benefits into account and avoid unintended consequences. The aim is to strengthen and restore a climate-resilient landscape water balance everywhere. Key solution approaches are (1) the restoration of water-related ecosystems, e.g. river and floodplain landscapes or peatlands, (2) measures to maintain soil moisture in agriculture, and (3) water-sensitive urban design.

The existing overexploitation of water resources, the unequal distribution of water, the loss of ecosystem services, and health risks associated with water are, in many places, largely caused by misguided and ineffective water management (Chapters 2–4). In the future, the global water cycle is expected to undergo permanent, accelerated changes that will significantly exacerbate these challenges. Therefore, proactive, more effective and transformative adaptation measures are needed to maintain a safe distance from the limits of controllability in the face of increasing exacerbated water-related challenges (Chapter 3) and to avoid the occurrence of regional water emergencies that can reach a planetary dimension (Chapter 4, Section 5.1).

Up to now, neither current water management, which is dysfunctional in many regions, nor the management approaches aimed at overcoming shortcomings and deficiencies – such as the established Integrated Water Resources Management approach (IWRM; Section 2.4.1.1) – have been able to meet the requirements of climate change (Section 2.4.4; Dörendahl and Aich, 2021; Giupponi and Gain, 2017; Ludwig et al., 2014; Mendoza et al., 2018; Noureddine et al., 2021). In the WBGU's view, their further development is urgently needed, because only if water management is climate-resilient can it fulfil its key role in climate-change adaptation as a building block of climate-resilient development (IPCC, 2022b: 2769 ff.), the protection of ecosystems and in negotiating and overcoming conflicts of objectives and use in the water sector. At the same time, stronger and better coordinated integration of IWRM, ecosystem protection and climate-change adaptation can help create synergies, for example by using available resources more efficiently and using already established multisectoral structures (Dörendahl and Aich, 2021; Jimenez and Bray, 2022; UNEP, 2022; de Ruyter van Steveninck et al., 2018).

In order to provide impetus for the further development of existing management approaches and the more rigorous implementation of transformative adaptation in the water sector, this chapter presents the main features of the kind of climate-resilient water management that the WBGU considers necessary in the context of exacerbated water-related challenges and in view of the limits of controllability. Building on existing climate-resilient water-management approaches (e.g. BMUV, 2023b; World Bank, 2023b; GCEW, 2023b), Section 6.1 explains how exacerbated water-related challenges and emergencies can be dealt with successfully. Four requirements for the development, selection and implementation of specific measures are also proposed. Sections 6.2–6.4 address specific problems, challenges and transformation requirements in relation to the restoration of ecosystems, as well as in agriculture and cities, and illustrate possible solutions using practical examples.

Pantanal (Brazil, Bolivia and Paraguay)

6.1 Dealing with exacerbated challenges and emergencies

The exacerbated challenges in the water sector require a forward-looking, systemic and adaptable management of local, regional and global water cycles that preserves the multifunctionality of water in the long term, and helps to maintain a safe distance from the limits of controllability. In addition to effective infrastructure measures and the strengthening and restoration of a climate-resilient landscape water balance, climate-resilient water management is characterized by practices that recognize the loss of stationarity and are embedded in overarching transformation strategies. This includes management through authorization, planning and operation in a way that enables decisions to be made in the face of uncertainty and takes into account the societal factors influencing water cycles.

Climate-resilient water management is based on transdisciplinary and collaborative learning and decision-making processes across sectors and spatial scales, and incorporates empirical data, real-time information and future projections under different scenarios. It is based on democratically negotiated goals, values, principles and rules. The WBGU proposes the principles for action outlined in Section 5.2 as the basis for this negotiation process. Section 6.1.1 shows examples of how these can be implemented.

Numerous measures already exist today for establishing climate-resilient water management, which can be selected and combined with each other depending on the context. Concrete implementation depends on the local environmental and societal conditions determining the water availability and demand. At the same time, there is a need for the purposive development of new measures that can do justice to the described exacerbated challenges in the water sector in the short and long term (Chapter 3). For the development, selection and combination, establishment and, where applicable, operation or maintenance of measures in the context of climate-resilient water management, the WBGU proposes four requirements that reflect the overarching principles of action and should always be taken into account (Box 6.1-1; Section 6.1.2). They must also be reflected in budget and competence allocations.

How quickly and comprehensively the described vision of climate-resilient water management is already being realized regionally – and can be realized in the future – is determined, among other things, by overarching framework conditions. These include, for example, the availability of financial resources, technologies and skilled employees, governance factors and the societal acceptance of measures (Section 6.1.2.2; Chapter 8). In order to promote transformative adaptation (Box 5.1-1), obstacles to implementation and the associated power dynamics should be identified and overcome. Windows of opportunity should be used, e.g. reconstruction after extreme events or large-scale infrastructure measures in cities. Furthermore, unconventional and innovative solutions can be explored in specially funded real-world laboratories, enabling successful practical examples and practices to be institutionalized and disseminated more quickly (Fedele et al., 2019).

In the short and long term, it is important to avoid maladaptation in water management. Maladaptation means "current or potential negative consequences of adaptation-related responses that exacerbate or shift vulnerability or exposure [to climate risks] of a system, sector or group of the population [e.g. to other disadvantaged areas or population groups], or that erode sustainable development" (Reckien et al., 2023; Fig. 6.1-1). Avoiding maladaptation requires a critical examination of the complex causes of vulnerability, a differentiated and context-specific conceptualization and measurement of adaptation success, as well as planning, implementation of measures and learning processes together and at eye level with affected population and actor groups (Eriksen et al., 2021; Schipper, 2020). An intersectional approach, that critically analyses the causes of overlapping vulnerability factors, and adaptivity in water management are crucial prerequisites for this (Eriksen et al., 2021; Erwin et al., 2021; Fröhlich et al., 2018; Thompson-Hall et al., 2016). Nevertheless, there is an urgent need for further research to avoid maladaptation.

6.1.1 Implementing the principles of action for climate-resilient water management

As a basis for the democratic negotiation process for the goals, values, principles and rules of climate-resilient water management, the WBGU proposes the principles for action outlined in Section 5.2. In the following, examples of their implementation are given.

Safeguard water as a common good for people and nature

Water management should aim to adequately consider all the functions of water and thus the needs of all people and nature (Section 5.2.1). At a conceptual level, various interacting dimensions of justice can provide orientation, e.g. intragenerational, intergenerational and interspecies justice within a stable Earth system, representing the pillars of the overarching concept of Earth-system justice proposed by Gupta et al. (2023).

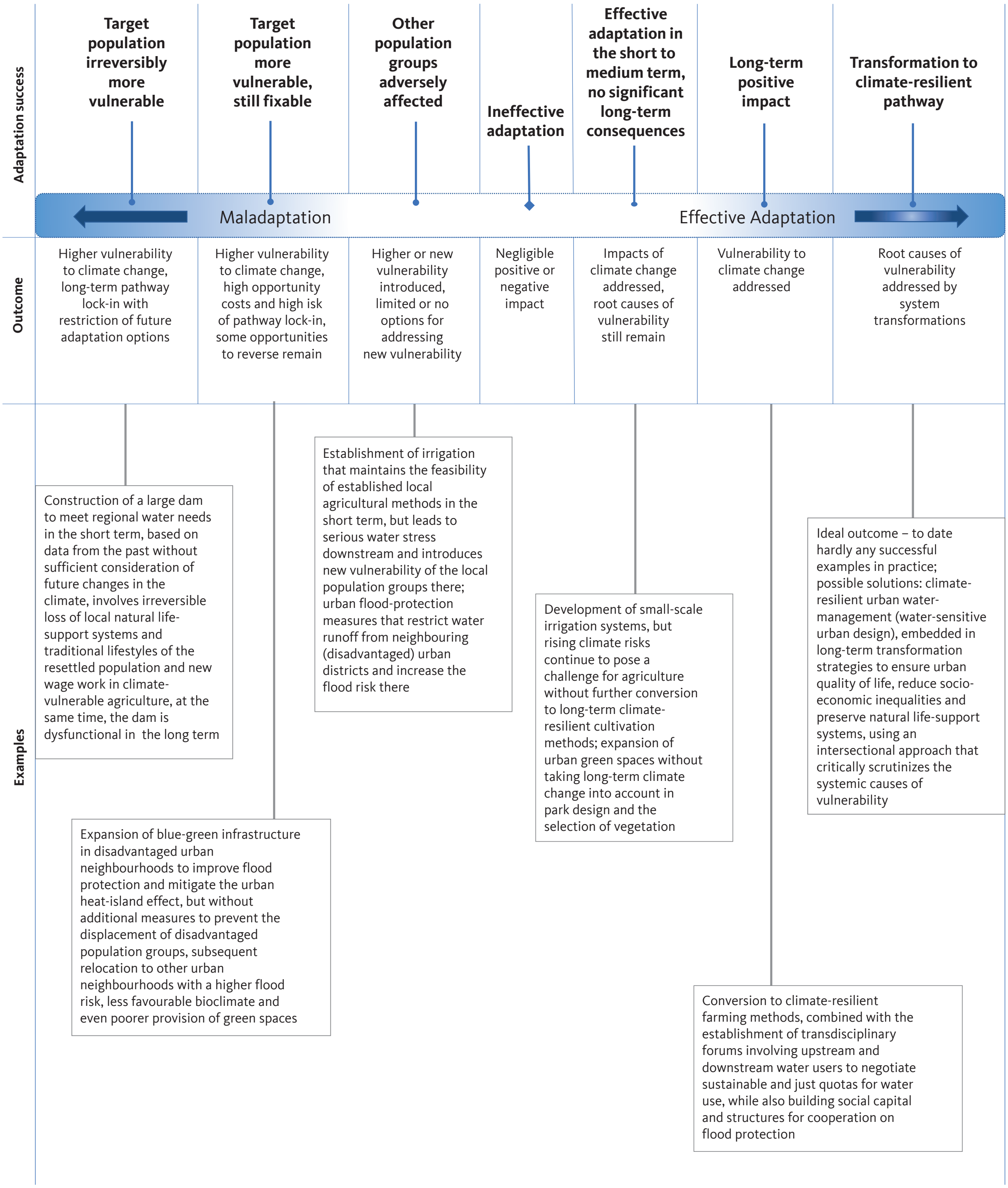


Figure 6.1-1
Continuum from maladaptation (left) to transformative adaptation (right) with examples of water-related adaptation measures. The success of adaptation varies over time and depends on the context, and various criteria and dimensions are decisive for the assessment, e.g. the impact on disadvantaged population groups and the contribution to systemic change (Reckien et al., 2023). Source: based on Schipper, 2020; examples: modified by WBGU

Box 6.1-1

At a glance: four requirements to be considered when developing, selecting and implementing measures

1. Assess water-related efficacy on different time scales: The efficacy of measures should be assessed with regard to specific water-related objectives and always with regard to their respective contribution to the restoration of a climate-resilient landscape water balance. Against the background of exacerbated water-related challenges, the assessment must include different time horizons, uncertainties, impact delays and adaptation limits.

2. Analyse feasibility in the respective context: The feasibility of measures should be assessed on a context-specific basis, taking into account the availability of technologies, financial resources, institutional capacities, their acceptance and their requirements in terms of land and resources – also with regard to their long-term operation and any adjustments that may become necessary over time.

3. Focus more on potential multiple benefits: Possible multiple benefits for climate and biodiversity protection and health, social and economic benefits of measures, and effects on the reduction of inequalities should be anticipated, evaluated and taken into account in the assessment of measures.

4. Avoid unintended consequences: In order to avoid maladaptation and other unintended water-related, ecological, health, social and economic consequences, all impacts of measures should be identified, evaluated and taken into account using a systemic and transdisciplinary approach.

The four requirements are explained in more detail in Section 6.1.2.

At the implementation level, integrating ecosystem-based adaptation (EbA) approaches into water management, e.g. by integrating them with the IWRM approach, can be helpful in order to specifically address water functions for ecosystems and thus to support ecosystem services (Dörendahl and Aich, 2021). The Water-Energy-Food-Ecosystem Nexus approach (Section 2.4.1.3) can be used to take into account the complex interactions between water, energy and food systems as well as hydrological, biological, social and technological factors in local water management. The integrated use of different approaches helps to identify and overcome conflicting objectives and realize multiple benefits (IPCC, 2022b: 653).

Increase adaptability in the face of continuous change

The assumption of stationarity – i.e. the idea that natural systems exhibit predictable variability within a defined time frame on the basis of empirical observations – is no longer valid in the face of progressive climate change. In order to do justice to the increasing loss of stationarity, structures and processes for planning and decision-making in water management must be designed in an adaptable and correctable way and include all actors (Section 5.2.2). To enable water management to react more flexibly to changing framework conditions, planning must always include two time scales: on the one hand, short-term infrastructure measures adapted on the basis of current data are necessary; on the other hand, planning requires a long-term perspective that should extend at least until 2050 and, where necessary, beyond. Traditional infrastructure approaches in water management, such as the construction of dams or long-distance water pipelines with a realization, use and depreciation period of several decades, will endure for a long time but have often not been sufficiently adaptable or flexibly planned. Forward-looking infrastructure planning must take into account and integrate the various temporal, spatial and systemic limits of measures, expected dynamics and planning uncertainties (BMUV, 2023b: 50). The combination of different measures from the entire spectrum of purely technical to more nature-based solutions opens up the possibility of using their respective strengths and compensating for their limitations in a targeted manner.

Progressive climate change, large-scale land-use changes, changes in 'atmospheric rivers' and overarching technological developments (e.g. cooling-water requirements in the course of increasing digitalization or additional water requirements in the context of the energy transition; Box 7.4-2) result in continuously changing water supply and water demand. In response, there is a need for greater flexibility in water demand and new management approaches that determine the water availability and all demands in advance, including through the use of real-time data. The management methods selected must be constantly monitored, their results analysed and, if necessary, adjusted at short notice. To achieve this, infrastructural solutions need to be more decentralized, modular and adaptive. A range of possible measures for the restoration of ecosystems, in agriculture and in cities can be found in Sections 6.2-6.4.

Resilience and risk prevention instead of emergency response

In order to ensure a stable water supply in the sense of resilience and risk prevention (Section 5.2.3), even in the case of extreme events and particularly long periods of drought, it is necessary, among other things, to diversify water portfolios. For the supply of drinking water this means making facilitating the use of independent blue-water resources where necessary (e.g. extraction from different aquifers; use of local groundwater resources supplemented by a connection to regional interconnected networks). Conventional drinking-water resources can also be substituted and thus conserved by using alternative fresh-water resources, such as via water recycling and seawater desalination. More attention should be paid in general to the multiple use of local and regional water resources in the sense of water recycling.

Managing blue and green water across sectors

In view of the increasing variability of water supply and increasing water extremes, strengthening buffers in the landscape that can absorb, retain and then release water plays a decisive role in climate-resilient water management – on land of all use levels (Section 5.2.4). In addition to natural blue-water systems, this will require greater consideration of the green water stored in soils and plants (in terms of quantity and effectiveness) in water management in the future. Green water can buffer extreme events to a certain extent. A local water availability can be stabilized, for example, by means of targeted decentralized rainwater collection and infiltration, which increases soil moisture and groundwater recharge. The most important long-term goal of climate-resilient water management is the comprehensive conservation, strengthening and restoration of a climate-resilient landscape water balance and the resulting necessary reorganization of land use in rural and urban areas.

Enable a science-based discourse on challenges and options for action

A science-based discourse on strategy development and options for action in the face of uncertainties is also required (Section 5.2.5). The discourse can provide information to water management and be informed by it. At the implementation level of climate-resilient water management, the use of differentiated approaches and instruments to assess and evaluate the effectiveness, feasibility, multiple benefits and unintended consequences of measures is essential in order to systematically consider alternatives in the face of long-term uncertainty (Section 6.1.3). Examples of suitable methods include multi-criteria analysis with an emphasis on multiple benefits (e.g. Alves et al., 2018a) and approaches that use the 'decision scaling' method, such as the World Bank's Decision Tree Framework (Ray and Brown, 2015) and Climate Risk Informed Decision Analysis (CRIDA; Mendoza et al., 2018). Their use enables a collaborative process for risk-based decision-making that combines a bottom-up analysis of vulnerabilities and the risks of measures with projections of climate change and hydrological changes under different scenarios (Box 6.1-2).

Value water and appreciate the value of water

The value of blue and green water resources for people and nature and the scale of water-related risks must be recognized and made transparent for policy-makers, the public, companies and investors (Section 5.2.6). Transparency is also necessary in the financing of measures, since the competition for funding is high in view of scarce financial resources and rising financing requirements for a wide range of transformation areas. Against the backdrop of long-term uncertainties, funding solutions for locally adapted measures must be found that will also, if necessary, enable future, further adjustments to measures that have already been implemented, and make investments attractive for both public and private investors. In addition, growing risks of damage and loss of value must be taken into account when making investment decisions. In particular, large-scale infrastructure projects designed for the long term, such as the construction of dams or long-distance water pipelines, tie up financial resources over a long period of time and run the risk of becoming stranded assets, e.g. if increasing water scarcity makes a dam unprofitable. In order to mobilize and steer private investment, a regulatory and fiscal framework is needed within which multiple benefits are rewarded and unintended negative consequences are priced. These and other strategies for structuring funding approaches and the necessary framework conditions for investment decisions are discussed in more detail in Section 8.3.

Accelerate implementation – encourage and promote self-organization

Climate-resilient water management requires a regulatory framework and instruments that make accelerated implementation possible and – where appropriate – integrate informal, decentralized governance structures (Section 5.2.7). State control should be demanded in compliance with the principle of subsidiarity and ensured in the spirit of a proactive state. At the same time, it is the state's responsibility to involve and empower non-state, self-organized actors and structures, and to promote and demand civil-society involvement in the sustainable management of water resources at the local level. Based on the principles of climate-resilient water management, the aim is to ensure that state control and self-organization complement each other. Long-term and infrastructure-dependent planning cycles are required which are simultaneously characterized by a high degree of agility and flexibility as well as an ability to act at short notice when dealing with sudden and unexpected shifts in water supply. The effectiveness of the measures should be ensured by effect- and effectiveness-orientated governance. At the same time, it requires highly context-specific, pragmatic governance that makes multiple benefits possible while minimizing risks caused by unforeseeable, unintended consequences. In concrete terms, this means that overarching communication and coordination mechanisms are of great importance. An exchange across different sectors and policy areas is urgently needed and should also include non-state actors. Participatory dialogue forums can facilitate exchange between state and non-state actors (Section 8.2.3). Standards for the distribution of available water resources require regular review. Governmental and non-governmental cooperation across national borders, within and between catchment areas and following an ecosystem approach, is essential for climate-resilient water management.

The WBGU welcomes the current efforts in Germany to incorporate the guiding principle of water-sensitive urban design into the German Federal Building Code (BauGB; Section 6.4.1) and the intended standardization of multifunctional land use as a new guiding principle and as a factor to be taken into account in urban land-use planning (BMWSB, 2024: 9). Both amendments to the German Federal Building Code have great potential to contribute to the implementation of the climate-resilient water management proposed in this report.

6.1.2
Four requirements for the development, selection and implementation of measures

For the development, selection, combination, establishment and, if applicable, the operation or maintenance of measures in the context of climate-resilient water management, the WBGU defines four requirements that reflect the overarching principles of action and should always be taken into account.

6.1.2.1
Assess water-related efficacy on different time scales

The effectiveness of a measure should be assessed with regard to its specific water-related objectives and always with regard to its contribution to maintaining, strengthening and restoring a climate-resilient landscape water balance, the most important long-term objective of climate-resilient water management (Section 6.1.1). The impact on the landscape water balance should be assessed not only for measures to improve groundwater recharge or rewetting but also for measures to provide and treat drinking water, to improve the quality of surface and groundwater or to minimize the consequences of flash floods, floods and droughts. For example, they should be tested to see whether they stabilize soil moisture, keep water in the landscape for longer and thus contribute to the creation of natural buffers, and whether they maintain or increase the resilience of water systems.

The effectiveness of measures depends, among other things, on technical factors, whereby a rough distinction can be made between quantitative aspects (e.g. with regard to the absorption, storage and retention of water) and qualitative aspects or, if applicable, limitations (e.g. with regard to the absorption, accumulation and transformation of substances in the water). While organic pollution can generally be removed from domestic wastewater by plant- and pond-treatment plants, this is only possible to a limited extent for persistent substances and pathogens (bacteria, viruses; Arden and Ma, 2018; Castellar et al., 2022). By combining different measures, their respective strengths can be used and their limitations compensated for (for examples of efficient wastewater treatment: Section 7.1.2).

Furthermore, contextual factors – e.g. specific climatic, spatial planning, urban development, ecological and political framework conditions – influence effectiveness. Due to the exacerbated water-related challenges and particularly due to the loss of stationarity, the impact-relevant framework conditions are changing. The effectiveness can therefore change continuously without stabilizing in the long term. For example, as a result of climate change, specific nature-based solutions may no longer be implemented locally or may become less effective. Some conventional technical measures such as dykes, reservoirs and drainage systems can become overwhelmed, damaged and dysfunctional as a result of more frequent and more intense extreme events (UBA, 2023d).

Today, many technical infrastructures are dimensioned on the basis of historical data on water demand, water availability and the previous frequency of extreme events, and are not designed for future climate changes. For example, the dimensioning of a flood dyke is based on a so-called 'hundred-year flood' ('HQ_{100}'), which refers to a flood discharge that is statistically reached or exceeded only once in 100 years. How likely it is that the functionality of facilities for supplying drinking water, for wastewater disposal (e.g. sewer networks, wastewater-treatment plants) or flood protection will be restricted by the local effects of climate change cannot yet be reliably assessed on the basis of the current data. However, it is clear that planning uncertainties in this regard will increase considerably. Climate protection and measures to prevent pollution are therefore of crucial importance for the preservation of water quality and water quantity (Section 5.1; Chapter 7).

As a basic principle, measures must be planned and implemented in such a way that technical adaptation to the consequences of climate change (changed precipitation patterns, extreme events) can be realized with minimal effort during their life-cycle. Consideration of different time scales is also relevant because there can be considerable delays between when the implementation of measures starts and the desired effects unfold, e.g. after the construction of dams or the conversion of a pine monoculture stand into a mixed forest. Other measures may even have a negative effect in the short term despite a predominantly positive effect in the long term. For example, prolonged waterlogging due to localized water-retention measures can restrict the agricultural cultivation of land in the short term. However, it will ultimately have a positive impact on agriculture if it stabilizes the local water cycle in the long term.

Delays can be compensated for by a combination of short- and long-term measures. For example, protracted measures to transform areas towards a climate-resilient landscape water balance, some of which can take several decades, can be supplemented by short-term local measures such as the development of irrigation systems in agriculture. Solutions that are effective in the short term must be designed in such a way that they restrict solutions that are effective in the long term as little as possible, and no undesirable path dependencies are created.

6.1.2.2
Analyse feasibility in the respective context

Whether the establishment and operation of a specific infrastructure measure is locally feasible depends largely on the availability of technologies, financial resources and institutional capacities. These factors are variable depending on the context; they can change over time (e.g. due to geopolitical exacerbated challenges; Section 3.2.2) and are co-determined by governance factors (Chapter 8). At the same time, the need for specific knowledge, financial resources and technical equipment varies considerably between different measures – in terms of both the initial investment required and the longer-term effort needed to maintain functionality and, if necessary, adapt to new developments. In order to ensure that implemented infrastructure measures are sufficiently adaptable, changing framework conditions and uncertainties must therefore be taken into account from the outset when assessing their feasibility.

This also applies to the land and resource requirements of measures, which may also conflict with other uses and conservation objectives. This could be the case, for example, if the use of certain raw materials or energy consumption is to be reduced overall, or if additional land is required for agriculture or climate and biodiversity protection in the long term. It should therefore also always be assessed whether and how measures to preserve, strengthen and restore a climate-resilient landscape water balance can be implemented as part of an integrated landscape and water-balance approach (Section 6.3; Section 6.5.3).

Land and resource requirements also play a role in the feasibility of water-reuse measures. For example, the space requirements of plant- and pond-treatment systems are often too high for densely populated urban areas (Castellar et al., 2022; Boano et al., 2020) – in their conventional design, they are only suitable for rural areas with a low population density and a large amount of available land. Conventional technical solutions for the advanced treatment of municipal wastewater, on the other hand, sometimes require a lot of energy or chemicals. Advanced technical approaches to turn heavily contaminated water back into 'safe drinking water' (that meets legal requirements) generally require a great deal of expertise and sophisticated technology. In addition, they use an even greater amount of energy and special materials (e.g. coated polymers, rare earths) or generate considerable waste streams (e.g. concentrates in membrane-filtration processes).

A lack of societal acceptance can also limit the feasibility of some measures, e.g. if there are reservations among the population regarding the use of 'recycled water' as drinking water. Accompanying measures to meet this challenge are conceivable. For example, the increased use of treated wastewater as drinking water in Singapore was accompanied by a large-scale public awareness campaign by the government, which aimed to increase acceptance (Duong and Saphores, 2015).

In addition, the feasibility of a measure is determined by the willingness of the actors involved to implement it. In agriculture, for example, it is important, politically and societally, to recognize the role of farmers as water actors and to provide financial incentives (Section 6.3.3). The feasibility and effectiveness of such accompanying measures for increasing acceptance and the willingness to implement them are in turn context-dependent, which should also be taken into account when analysing the feasibility of a measure.

6.1.2.3
Focus more on potential multiple benefits

Where possible, measures should be designed to be multifunctional. This means that, on the one hand, they address the different functions of water for people and ecosystems and, on the other hand, strive for ecological, health-related, social and economic benefits that go beyond water-related effects. For example, the restoration of peatlands and other wetlands can protect biodiversity and provide multiple ecosystem services (Section 6.2). The expansion of agroforestry can improve local food security and support the livelihoods of the population (Rosenstock et al., 2019; Section 6.3). The expansion of blue-green infrastructure in cities may entail health and social benefits (Section 6.4). Greater use of nature-based solutions offers particular potential. Their multiple benefits are often based on more conservation of regulating ecosystem services (e.g. improving water quality) with less overexploitation of provisioning ecosystem services (e.g. provision of materials). Both globally and regionally, regulating ecosystem services (or Nature's Contributions to People) are currently being progressively lost (Brauman et al., 2020).

The full use of multiple benefits is becoming increasingly relevant, as more climate, biodiversity and health protection is urgently needed. Water-related measures can make an important contribution to this. In the long term, benefits for water-related objectives may arise in turn, for example, if the restoration of ecosystems creates buffers in the landscape and also contributes to the mitigation of global warming, which again facilitates the applicability of nature-based solutions. If adaptation to and mitigation of environmental changes are considered in an integrated manner, both can benefit, which underlines the importance of multisectoral cooperation (Boyd et al., 2022).

Multiple benefits also depend on targeted planning and implementation. Possible positive effects of measures for climate protection and biodiversity, human health and well-being, as well as other sustainable-development goals, should therefore be anticipated and targeted in planning, evaluated where possible and taken into account when selecting measures. Here too, different time horizons and possible delays in impact must be taken into account, and different spatial levels must be considered in an integrated manner.

The reduction of social and health inequalities, which are linked to the unequal distribution of environmental impacts and resources and are exacerbated by climate change, can also be a benefit (Stroud et al., 2022). To this end, the needs of disadvantaged groups must be taken into account, e.g. urban green spaces should be sufficiently accessible and suitably designed (Section 6.4). Furthermore, water-related measures – especially large-scale ones – can offer windows of opportunity to improve the framework conditions for healthy and sustainable lifestyles and thus counteract the emergence of inequalities, e.g. in the fields of nutrition, exercise and housing (WBGU, 2023).

One example is possible positive effects on the mobility behaviour of city dwellers. If, for example, large-scale measures to adapt water infrastructure also affect road space, care can be taken to ensure that sufficient areas are available for pedestrians and cyclists. In this way, active mobility can be promoted, with numerous ecological and health benefits (WBGU, 2023).

6.1.2.4
Avoid unintended consequences

In addition to negative effects in the sense of maladaptation (Fig. 6.1-1), there can also be other unintended consequences. Many measures have multiple water-related impacts, in some cases involving major and transboundary shifts in water distribution. This can result in conflicts of objectives and interests that need to be identified and overcome. For example, the construction of a new dam can increase the resilience of the regional drinking-water supply in the short term and enable the use of hydropower, but in the long term it can significantly change the flow regime of the downstream watercourse, lead to increased evaporation losses and impair water quality as a result of algal blooms. Other examples include long-distance water pipelines with effects on the water availability in the catchment area, or geoengineering to generate artificial precipitation with changes in natural precipitation across national borders.

Measures can also have unintended ecological, health-related, social and economic consequences. Examples include a loss of local biodiversity as a result of the construction of large reservoirs or the discharge of concentrates from seawater desalination into the sea (Section 6.2), the possible promotion of infectious diseases through the expansion of agroforestry (Rosenstock et al., 2019; Section 6.3) or the displacement of disadvantaged population groups by the economic upgrading of urban districts and the formalization of informal spaces following the expansion of blue-green infrastructure in cities (Section 6.4).

The fact that various intended and unintended consequences influence each other is illustrated by the Diama dam in Senegal. Its completion in 1986 led to an improvement in the water supply for regional agriculture and the generation of hydropower. However, it also prevented the migration of river prawns between different sections of the river – leading to a marked increase in the incidence of the parasitic infectious disease schistosomiasis (bilharzia), because in some places there were no more river prawns to predate on the water snails that are intermediate hosts of the parasites (Sokolow et al., 2015). In addition, unintended consequences can have negative repercussions on water-related targets, e.g. higher greenhouse-gas emissions from a reservoir in tropical regions contribute to the exacerbated water-related challenges through their contribution to climate change (Kumar et al., 2023a).

Unintended consequences can be categorized according to whether they are knowable and avoidable (Fig. 6.1-2; Suckling et al., 2021), a key starting point for preventing them. Consequences that are knowable and avoidable upfront can be prevented by targeted planning, but this requires a systemic approach and the

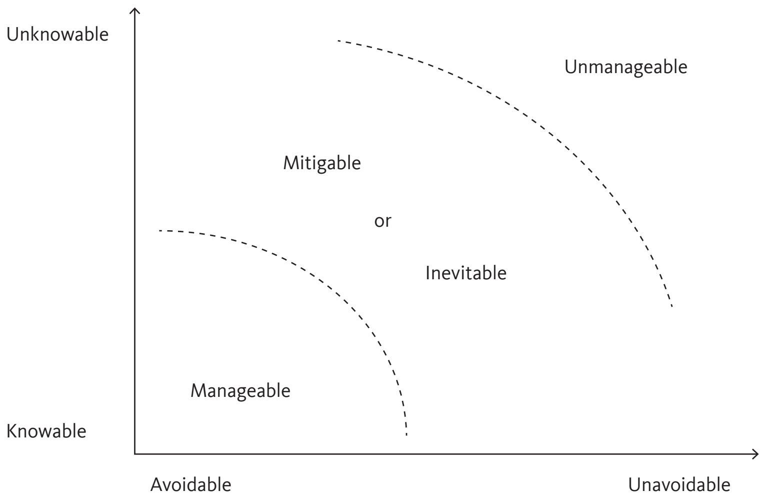


Figure 6.1-2
Possible categorization of unintended consequences according to whether they are knowable and avoidable. Consequences that are knowable and avoidable can be prevented by targeted planning. Consequences that are knowable but cannot be avoided can be mitigated by accompanying measures. Consequences that are avoidable in principle but not knowable can be partially prevented with foresighted action, taking uncertainties into consideration. Shifting unintended consequences into the 'knowable and avoidable' category makes it easier to prevent them.
Source: Suckling et al., 2021

corresponding political will. Consequences that are knowable but cannot be avoided due to specific framework conditions can be mitigated by accompanying measures. Consequences that are avoidable in principle but unknowable due to a lack of data can be partially avoided by acting with foresight and taking uncertainties into account. Crucial factors here are continuous evaluation, consistently including the social consequences of measures in modelling and decision-making in the sense of a social-hydrological approach, and ensuring that planning is fault-tolerant, flexible and adaptive with decentralized and modular measures (Walker et al., 2015).

If it is possible to shift unintended consequences into the 'knowable and avoidable' area, it becomes easier to prevent them (Sowby and Hotchkiss, 2022). An advanced, combined assessment of environmental and health impacts, e.g. in the form of a harmonized impact assessment of measures, would be advantageous in this context (Osofsky and Pongsiri, 2018; SRU, 2023). There should also be open discussions with interdisciplinary teams about possible project impacts based on relevant catalogues of possible consequences (Sowby and Hotchkiss, 2022). Participatory planning in the sense of a transdisciplinary approach can help to incorporate different perspectives, needs and concerns and ensure the inclusion of different actors (Walker et al., 2015). Care must be taken here to ensure that the dialogue is open enough, for example by not laying down fixed technical planning criteria from the outset (Farmer et al., 2015). It is also crucial not only to formally offer participation to marginalized actors, but also to facilitate participation. This can be done by reducing barriers to access, e.g. with tailored information services, financial compensation, spatial accessibility, organizational support and the provision of non-discriminatory spaces.

6.1.3
Instruments for assessment under uncertainty

It must be possible for water-management actors to assess whether the implementation of a measure brings multiple benefits to society, and to compare different measures. The requirements explained in the previous section must therefore be translated into an assessment methodology. One particular challenge here is the growing uncertainty, which makes an assessment based on historical expectations hardly expedient.

Projections for climate change, its effects and socio-economic developments result in a variety of possible scenarios that can be broken down to the local level 'top-down'. However, given the variety of uncertain factors, there is a risk that measures will be prioritized that take all dimensions of uncertainty into account, but are not expedient or are oversized taken as a whole. It can therefore be helpful to tackle the problem 'from the bottom up' and step by step. Taking into account local vulnerabilities and risks classified as unacceptable, the four requirements for measures outlined above can first be specified in a specific context and then linked to the results of climate models to inform risk analyses and decisions. Methods that enable such an approach with consistent and replicable results already exist (Beek et al., 2022), e.g. 'decision scaling' (Box 6.1-2; Brown, 2011; Brown et al., 2011; Brown et al., 2012; Hallegatte et al., 2012). Examples of approaches that use this method are the World Bank's Decision Tree Framework (Ray and Brown, 2015) and Climate Risk Informed Decision Analysis (CRIDA; Mendoza et al., 2018).

As part of the bottom-up process, relevant aspects need to be identified and attributed, and the period under review needs to be defined. If important effects are neglected or the time period is too short, this can lead to

Box 6.1-2

Decision scaling

The 'decision scaling' method was developed to respond to the uncertainties resulting from climate change in planning and design processes. Put simply, decision scaling describes a process that first analyses which types of climatic changes would cause problems, and then uses climate models to assess whether these types of change are likely (Brown, 2011).

The advantage of decision scaling in comparison to approaches based on a top-down scenario analysis is that it starts with known variables: the existing system and its performance under different scenarios and designs. It is only in the subsequent steps that uncertainty is increasingly taken into account and the complexity increased (Mendoza et al., 2018). Decision scaling is an interactive process involving relevant stakeholders from politics, business and society.

Brown (2011) describes the decision-scaling procedure as follows:

In a first step, relevant stakeholder groups jointly define the objectives of a decision and performance indicators for evaluating different alternatives. A risk analysis looks into which climate-change impacts are important, and determines threshold values that, if exceeded, would be unacceptable and require preventive avoidance measures.

The behaviour of the system under changing climatic conditions is then modelled. Complex or very simple models can be selected, depending on the context. The widest possible range of different conditions should be considered in order to be able to draw conclusions about the vulnerability or resilience of a system based on different decision alternatives. The analysis can show that a system hardly reacts at all to climate change, or that one measure is superior to another among all the changes considered. In this case, it may be unnecessary to analyse which future climate changes will occur and with what probability. However, it is generally to be expected that this analysis will reveal climate risks for the system and its weak points.

The final step determines the probability that the climate changes previously identified as relevant for the system will occur. Not until this point in the process are climate models needed. As a result, the decision-scaling method provides a list of the decisions to be favoured for different climatic conditions, and an initial estimate of the probabilities of these conditions occurring.

misjudgements regarding what risks are acceptable, e.g. if value-creation losses or effects on health and biodiversity are not adequately taken into account. However, the inclusion of each additional effect and the consideration of longer time periods increases the complexity of the analysis – partly because the uncertainty increases.

When assessing measures, there is also the challenge of how impacts, multiple benefits and side-effects can be measured and made comparable. This applies in particular to effects for which a monetary quantification – for example via market prices or the hypothetical willingness to pay – is difficult or impossible. There is also the question of how to deal with target conflicts and competing uses. Due to the large number of effects to be considered and stakeholders affected, target conflicts are to be expected in various dimensions, e.g. between desired effects or effects to be avoided, between neighbourhoods or regions, and on different time scales, e.g. between different generations. Conflicting targets and prioritization between different goals can only be resolved locally and in a context-specific manner. It requires the development of capacities and expertise that support local decision-makers.

A widely used approach for assessing measures is cost-benefit analysis (CBA). This attempts to record all the costs and benefits associated with a measure in monetary terms, thus making it possible to decide between different measures. CBA reaches its limits when monetary values of impacts, multiple benefits and side effects cannot be measured, or at least not adequately. In this case, it is expedient to use assessment methods that include both monetary and non-monetary effects. One example is multi-criteria analysis (MCA), which is already frequently used in planning processes in the water sector. It records a measure's effects, multiple benefits and undesirable side effects and evaluates them in relative terms. The overall assessment of a measure depends crucially on the weighting of the various effects, so that prioritization can be based on the weighting. It should be implemented via a societal negotiation process that integrates preferably all affected stakeholders (see e.g. Alves et al., 2018b for flood risks).

When selecting a measure or combination of measures and in further planning, consideration should also be given to how distribution problems can be addressed and how the losers of the measure (e.g. farmers whose land is taken out of agricultural use) can be adequately compensated. It should also be determined whether unintended consequences can be avoided or minimized by adapting the design of the measure or by implementing accompanying measures. Finally, the financing of the measures must be made possible, and this can also be a challenge in the face of increasing uncertainty (Section 6.1.1; Section 8.3).

6.1.4
Governance by planning and authorization

Climate-resilient and socially balanced water management can only be realized if tasks are assigned to the right actors in the respective national context. In this respect, 'governance by planning' involves a number of challenges that need to be overcome (Box 6.1-3).

These challenges are particularly evident in the case of the EU Water Framework Directive, which pursues an ambitious and now defined goal for climate-resilient water management with the requirement to achieve a good ecological water status, combined with a corresponding ban on deterioration (Chapter 2). A good ecological water status is to be achieved by planning measures and managing water bodies. These are i.a. implemented locally by individual case-by-case decisions such as discharge permits or refusals.

Despite extensive planning for more than two decades, the EU-wide water status has not improved significantly. There is a lack of any effective implementation of these objectives by means of plans and specific official case-by-case decisions. The latest case law of the European Court of Justice (ECJ) seeks to counteracts this deficit. The Court of Justice has interpreted the Water Framework Directive in such a way that authorization for a specific project – in this case the deepening of the River Weser to improve navigability – is to be refused if it jeopardizes the achievement of the good status of a surface water body as defined in the management plan (EuGH, 2015).

As a result, there is also a corresponding obligation to assess the impact of a project on water bodies in advance (EuGH, 2020). Only if the water-management plans pre-structure the downstream case-by-case assessment (Kloepfer and Durner, 2020) will they be effective in practice. The internal obligations must also apply to those who discharge pollutants or use the water. The ECJ is thus the actor that has effectuated the member states' obligations under water law. However, this approach is not sufficient. A court can only interpret a legal norm if it has jurisdiction and is called upon to do so. It clarifies individual questions that are relevant in the respective proceedings and does not act in a quasi-legislative capacity. The principle of the separation of powers is thus also involved here. In principle, only constitutional courts have the power to reject standards, although ECJ rulings in the context of referral proceedings on the interpretation of EU law have a greater scope than individual case rulings, which only bind the respective parties. Although the ECJ's specification efforts lead to better enforcement of EU-wide water-protection law, they ultimately remain selective and are not systemic in nature. Furthermore, EU law, as a supranational legal system that can also be enforced by the courts against the member states, is a special case that cannot be transferred to other regions.

Nevertheless, this example makes it clear that climate-resilient water management must ensure that tasks are assigned to the right actors in each case. To a certain extent, failures can be compensated by other actors. The conflicts of interest must already be clarified by clear

Box 6.1-3

Governance by planning

Planning as a form of governance that is independent of individual cases and geared towards the future is a reflection of the precautionary principle. Starting with the status quo, the future development is forecast, taking various scenarios into account. A normative goal is then formulated, which is to be achieved as effectively as possible by means of a plan. Planning aims to balance conflicting interests, coordinate measures and expectations, and to develop a conceptual plan of action that is geared towards connectivity. Within the planning authority's scope, plans govern target achievement in an abstract-general form, which is why plans are dependent on subordinate implementation (Schlacke, 2021). Planning also facilitates legislation, which can be restricted to defining goals and procedures, leaving the concrete measures to the planning authority – usually the administration.

However, this is also a weakness of planning, especially in the EU's water governance. EU legislators have set highly ambitious targets in this field, such as maintaining or achieving a good chemical, ecological and quantitative water status. The member states or their administrations have a duty to analyse their water status, identify measures with which to achieve a good water status, and transfer them into a legally binding action and management plan. The EU obliges member states to adopt action plans in many environmental areas – such as climate-change mitigation, air-pollution control and land use (nitrate inputs). Implementation is often lacking: plans are not drawn up or not updated, or the measures specified in them are not taken. In addition, in a federal country such as Germany, for example, it is the responsibility of 16 federal states to draw up and implement plans. Sometimes implementation is further delegated to the smallest units in the state, the local municipalities, which are often overburdened by the task. Dematerialized planning and the delegation of implementation to the smallest administrative units, which are often inadequately staffed or funded, harbour a high risk of implementation and enforcement deficits. This problem is all the greater the more scope for decision-making is delegated to the actors who have to implement the unspecific plans by taking individual measures (Durner and Ludwig, 2008). If policy-makers and legislators do not exercise sufficient oversight – e.g. by passing on their power to govern via planning obligations to lower policy levels, which then comply with these obligations, but are unable to implement them adequately – then the precautionary mandate of planning is thwarted. Furthermore, planning processes are sometimes cumbersome, as they require the availability of sufficient (environmental) data for the necessary forecast of future developments, which makes it difficult to react quickly to new developments (Schlacke, 2023).

specifications in the laws – such as construction bans on floodplains – and not simply delegated to planning. Planning should not be a compulsory exercise for administrative authorities; instead, it should coordinate and resolve conflicts in a precautionary manner. In this way, the authorities have a steering effect for individual case decisions. Otherwise, structural regulatory and enforcement deficits arise.

The reverse is true for infrastructure planning. Instead of delegating these tasks to the technically competent authorities, which can make these decisions for a project on a case-by-case basis, legislators have recently taken them over themselves, and are carrying them out by granting statutory authorization for facilities such as the expansion of watercourses (legal planning). At first glance, this may appear to increase the democratic legitimization of planning decisions and to speed up the process. However, the functional limits of parliamentary decisions are reached here. Due to the limited knowledge of technically complex topics on the part of the legislators, their planning decisions are already so predetermined in practice by the necessary expert knowledge that the parliamentary decision seems to be nothing more than a formality (Durner, 2021).

Against the backdrop of the exacerbated water-related challenges, and in order to maintain or restore a climate-resilient landscape water balance, the WBGU believes that, in addition to the right choice of actors, it is also necessary for the responsible government authorities to take the four requirements outlined in Section 6.1.2 into account in future (assessment of water-related efficacy on different time scales, analysis of feasibility in the respective context, greater focus on possible multiple benefits, avoidance of unintended consequences) when making planning and authorization decisions. Under German water, environmental and planning law, this should take place based on official deliberations and discretionary decisions. In practical terms, this could mean, for example, that building bans are issued after flood events in potential future flood zones. The consistent consideration of the four requirements presents authorities that have to make planning and authorization decisions under water-protection law with major challenges overall, which will be exacerbated by the increasing need to act and make decisions under uncertainty in the future. To date, there has been little systematic consideration of how existing planning and decision-making processes need to be changed in order to implement measures that do justice to the exacerbated water-related challenges. Correspondingly, there is an urgent need for research here (Section 6.6).

6.2 Solution-space ecosystems

Ecosystems provide a multitude of services that form the life-support systems for humans and nature. Ecosystem services that are directly related to water and thus have an impact on and significance for water management include the maintenance of healthy habitats, the regulation of the climate, the quantity and quality of freshwater resources, the quality of coastal waters, the formation, protection and decontamination of soils, the regulation of hazards and extreme events, and the regulation of pests and diseases (IPBES, 2019b). The extent to which water-related ecosystem services can be provided depends on the intactness, functionality and size of the habitats concerned and thus, in the Anthropocene, also on spatial planning by humans. Landscapes, soils and their ecosystems can only adequately fulfil their functions as buffers and reservoirs of water if they are designed in a more nature-oriented way than in the past, i.e. if they are restored. This means, among other things, less ground sealing, less industrial agriculture, more rewetting, more reforestation and more urban retention and infiltration areas.

6.2.1 Restoration for climate-resilient water management

Restoration refers to the re-creation of a functioning ecosystem that is sufficiently resilient after its restoration to be able to cope with disruptions – caused, for example, by extreme events such as sudden flooding or prolonged dry periods – in such a way that no permanent damage is done to the ecosystem and its biodiversity. Resilient ecosystems are able to ‘swing back’ to a state close to their original state after a disturbance or worsening of the environmental conditions, without exceeding the threshold that would trigger a fundamental structural reorganization of the ecosystem with potentially far-reaching effects on ecosystem services and biodiversity. One aim of climate-resilient water management should therefore be to increase ecosystem resilience.

However, as the original state of an ecosystem is usually not exactly restored after a disturbance, but rather a new near-natural state is achieved, the implementation of restoration measures can also be understood as a process towards a new ecosystem state. In the following, the WBGU uses the terms ‘restoration’ and ‘restore’.

There are numerous measures for water-related restoration across different ecosystem types (Table 6.2-1). In addition to technical measures, various species can also act as 'ecosystem engineers' and influence the water quantity and the availability of nutrients in aquatic habitats. Examples include the beaver, whose introduction leads to increased water storage, or the water vole, which can induce the drainage of (excessively) wet soils. Revegetation, rewilding and the targeted introduction of ecosystem engineers can thus be measures to restore certain ecosystem types and contribute to climate-resilient water management (Harvey and Henshaw, 2023; Polvi and Sarneel, 2017).

In addition to setting a target state for the ecosystem, the choice of restoration measures should also take into account that novel (or emerging) ecosystems may develop as a result of biotic (e.g. invasive species) and abiotic (e.g. climate-change-related) changes (Hobbs et al., 2009). Novel ecosystems may, for example, have different species compositions or functions from the previously prevailing local ecosystem types (Hobbs et al., 2009). It is then possible that the selected restoration measures will not be effective in the novel ecosystems. Furthermore, the novel ecosystems may, for example, have effects on the hydrological cycle which are not yet foreseeable, and would necessitate additional restoration measures in the medium to long term. A lot of research is still needed in this field. One example of novel ecosystems are post-glacial ecosystems (Bosson et al., 2023).

When choosing and planning restoration measures, it is essential that all relevant actors are involved in the spatial planning process. In view of the limited availability of land, restoration is usually associated with conflicts with other land-use objectives. These must be balanced out with the aim of generating multiple benefits (WBGU, 2020). The use and protection of land can be successfully combined in the long term by planning according to the model of a multifunctional landscape mosaic (WBGU, 2024). Ecosystem restoration, as part of climate-resilient water management, plays an important role in this context.

6.2.2 Restoration of wetlands

All ecosystems are important for climate-resilient water management. For example, mountains are the Earth's 'water towers' (Viviroli et al., 2007; Section 4.4), while grasslands and forests are essential for the infiltration, storage and filtering of water. Wetlands are important

Table 6.2-1
Overview of selected ecosystem types and examples of applicable restoration measures.
Human use of different intensities and the respective restoration measures can be coordinated by applying and implementing the multifunctional mosaic approach; this helps reduce conflicts between objectives and measures and generates multiple benefits for biodiversity and humans.
Source: WBGU

Restoration measures / Ecosystem types	Lakes and shore zones	Peatlands	Marshland areas	Rivers and floodplains	Forests	Grasslands	Alpine landscapes	Urban ecosystems	Cultural and agricultural landscapes	Coastal ecosystems
Introduction of ecosystem engineers	•	•	•	•	•	•	•			•
Rewetting	•	•	•	•						
Restoration of natural watercourses	•	•	•	•			•	•	•	
Reforestation, agroforestry	•		•	•	•		•		•	
Sediment management	•	•	•	•						•
Structuring of river-bank slopes	•			•				•	•	•
Creation of riparian buffers	•			•				•		
Construction of technical fish ladders				•				•		
Infrastructure dismantling and conversion	•	•	•	•			•	•		•
Integration of near-natural structural elements	•	•	•	•				•	•	•

both as ecosystems in their own right and as links between different ecosystem types. According to the Ramsar Convention, wetlands are defined as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres" (UNESCO, 1971: Art. 1).

According to the latest research, wetlands cover almost 9 % of the world's land surface (Meli et al., 2014) and store a large proportion of global terrestrial carbon. Peatlands alone store more than 600 billion tonnes of carbon worldwide, which corresponds to around 44 % of all the carbon stored in the soil and thus exceeds the carbon stored in other forms of vegetation, including forests (IUCN, 2021). Wetlands thus make a significant contribution to climate regulation.

In addition to their importance for mitigating climate change, wetlands provide a range of ecosystem services. They store water, maintain the groundwater table, provide habitats for specialized animals and plants, and contribute to biodiversity conservation. They also contribute to a stable supply of drinking water and provide raw materials and food, e.g. peat and fish. They protect riverbanks and coastlines from flooding and erosion, serve as transport routes and offer opportunities for recreation and tourism. Last but not least, they are an important element of many local religions and traditions (Wang and Ma, 2016; Deng et al., 2022; Davidson et al., 2019; UNEP, 2021b). Wetlands are of key importance for the preservation of natural life-support systems. They also provide enormous economic and societal benefits; the provision of ecosystem services by wetlands accounts for almost 40–45 % of the monetary value of the ecosystem services of all ecosystems worldwide (Davidson et al., 2019; UNEP, 2021b).

Since the pre-industrial era, it is estimated that more than 80 % of the world's wetlands have been lost due to changes in land use and drainage, and most of the remaining wetlands have been degraded (UNEP, 2021b). Wetlands continue to be lost, and in arid regions the rate of loss is almost 10 % above the global average (Wang et al., 2023). Droughts and dry periods lead to reduced water volumes, which will continue to decline due to the increasing effects of climate change and the rising global demand for water (Wang and Ma, 2016; UNEP, 2021b). The construction of dams, uncontrolled fires, pollution and deforestation are altering wetlands, leading to species loss and affecting their ability to provide water, raw materials and food (UNEP, 2021b).

The resilience of ecosystems can only be increased if the diverse water-related ecosystem services of wetlands – but also of all other ecosystem types – are preserved and protected. The following section uses the example of swamps, peatlands and riverine landscapes to illustrate how the requirements formulated in Section 6.1 (water-related efficacy, feasibility, multiple benefits and unintended consequences) can be applied when choosing restoration measures for climate-resilient water management. An example of a restored wetland is shown in Figure 6.2-1.

6.2.2.1
Swamps and marshes as an example

Forested freshwater swamps and non-forested freshwater marshes exist worldwide in tropical and temperate regions (Keith et al., 2022). They are frequently or continuously flooded, do not accumulate large amounts of peat, and are often located in the middle of agricultural land or urban landscapes (Finlayson, 2016). They are fed by surface water or groundwater, are rich in nutrients and provide food and habitats for a wide variety of

Figure 6.2-1
Example of a restored wetland in Texas (USA). Under the 'Wetland Reserve Program' (or its successor, the 'Agricultural Conservation Easement Program'), landowners can receive government financial and technical support for restoration measures.
Source: United States Department of Agriculture/Natural Resources Conservation Service Texas, CC BY 2.0

waterfowl, reptiles, invertebrates and mammals. Marshes and swamps can also be found in arid and semi-arid regions, e.g. the Mesopotamian Marshes at the mouths of the Tigris and Euphrates rivers or the Macquarie Marshes in Australia. Because of the climatic conditions, wetlands in these regions in particular are in direct competition with other water uses such as agriculture, livestock farming or industry (Minckley et al., 2013; Martínez-Santos et al., 2008; Castaño et al., 2018; Quijano-Baron et al., 2022).

Swamps and marshes have a significant influence on the water cycle, for example they augment the groundwater reserves or change the water flow and runoff (Bullock and Acreman, 2003). In terms of *water-related efficacy,* their restoration can therefore play a decisive role in keeping water in the landscape and increasing local water supply for humans and nature (Bullock and Acreman, 2003; Ramsar Convention on Wetlands, 2018). After heavy rainfall events, swamps and marshes can regulate the flow of water in the landscape and thus offer protection against flooding and erosion, slow down the flow of water and store excess water (Meli et al., 2014). Restoration measures can furthermore have benefits in the form of improved nutrient storage and water quality (Singh et al., 2019).

In addition to *feasibility* constraints, which can occur during restoration, regardless of ecosystem type – e.g. potential land-use conflicts or the often very costly control of invasive species – the supply of water is a fundamental challenge for the restoration of swamps and marshes, especially in arid and semi-arid regions (Weidlich et al., 2020; Maleki et al., 2018; Stapleton et al., 2023).

This situation is further exacerbated by global climate change and the associated regional changes, e.g. in precipitation levels and patterns (Sections 2.2, 3.1.1). This can lead to increasing conflicts over the use of water resources between other human demands and the restoration measure, particularly with regard to agriculture or industry. Therefore, to account for the complexity and variability of these ecosystems over time, space and especially with regard to the increasing influences of climate change, the most important issue in restoration is: what can or will influence the local hydrological regime now and in the future? (Casanova et al., 2023). Soil quality, too, can have a limiting effect on restoration, e.g. in the case of increased erosion or higher salinization levels after agricultural use (Zhao et al., 2021). The uncontrolled discharge of water from the Tigris and Euphrates rivers in southern Iraq after the second Iraq war in 2003, for example, has partly restored some former marshland areas, but restoration failed in other areas because of the high salinization level of the soil and water (Richardson et al., 2005).

The restoration of swamps and marshes can also be accompanied by many different *multiple benefits*. Both habitats are home to a unique, often endemic diversity of species and are resting and feeding grounds for migratory species such as certain birds (Minckley et al., 2013; Vansteelant, 2023; Kačergytė et al., 2021). In addition, improving water and soil quality and flood protection can increase agricultural productivity (Tomscha et al., 2021). Restoration also helps to preserve the livelihoods and culture of local communities, and can generate additional income, e.g. from landscape tourism (Ramsar Convention on Wetlands, 2018).

Depending on the region, the restoration of swamps and marshes can also have *unintended consequences* that should be avoided. These include, for example, a possible change in the local hydrological cycle. This can happen if the planting of new vegetation changes evaporation and local precipitation patterns (te Wierik et al., 2021).

Furthermore, a possible lack of water-related efficacy of the measures could have an impact on other users and neighbouring areas beyond the restored site and thus also negatively impact the preservation of important natural life-support systems and the local economy (e.g. Bring et al., 2022).

Planning must therefore take into account the water inputs from the catchment area in which the measure is to be implemented and, in particular, the links to other wetland and dryland systems (Casanova et al., 2023). The introduction of formerly native or invasive species can have an impact on species composition or species dynamics and lead to changes in ecosystem structure and function (Weidlich et al., 2020; DeBerry and Hunter, 2024). Restoration can also lead to the release of nutrients contained in the soil and their increased input into the ecosystem, especially if the area was previously used intensively for agriculture (Audet et al., 2020).

6.2.2.2
Peatlands as an example

Peatlands are highly specialized ecosystems. Their main characteristics are high water saturation, the accumulation of organic material, especially peat, and a lack of nutrients. Peatlands can be found all over the world, although they are particularly common in the boreal and temperate zones. Peatlands are highly endangered due to changes in land use, e.g. agriculture or peat extraction. Their drainage is responsible for 5–10 % of annual global anthropogenic CO_2 emissions (Loisel and Gallego-Sala, 2022). In Germany, almost 90 % of all peatlands have already been drained. The remaining peatlands, which cover around 4 % of Germany, are mainly found in the North German Plain, i.e. north of the Harz Mountains from Lower Saxony to Mecklenburg-Western Pomerania and south-east to the Ore Mountains in Saxony, as well as in the south of Germany in the Prealps (BfN, 2024).

Degraded, i.e. mostly drained, peatlands are restored by rewetting. This is primarily done by building sheet pile retaining walls, dams and dykes that keep water within the area. The targeted introduction of ecosystem engineers such as beavers, or the manual resettlement of peat mosses can also contribute to peatland restoration (Law et al., 2017; Hugron et al., 2020).

The *water-related efficacy* of peatland restoration is primarily connected with the retention of large quantities of water in the peatland area. Peatlands act as a natural sponge and can slowly release absorbed water over time (Acreman and Holden, 2013). They can thus help mitigate floods and heavy rainfall events and stabilize the groundwater table. During dry periods in particular, they can help to maintain water levels in rivers and lakes, thereby also helping to secure the water supply for people who live in their vicinity, thus supporting climate resilience (Xu et al., 2018; Ritson et al., 2016; Gatis et al., 2023).

The *feasibility* of peatland restoration depends initially on the availability of land. As peatlands have usually been drained for other forms of land use, the aim of rewetting usually leads to conflicts over land use. Affected actors should therefore be involved in the planning of peatland rewetting at an early stage in order to find solutions that take equal account of ecological and socio-economic objectives and to balance them out as far as possible (Fleming et al., 2021). In order to rewet peatlands sustainably, drainage systems (e.g. drains and canals) must be removed or blocked. Depending on the local conditions and the regulatory framework, permits must be obtained to remove drainage measures or, if absolutely necessary, to build technical infrastructure for water retention. For cost reasons and in order to make the success of peatland restoration more likely, construction measures introduced for water retention should be designed to be near-natural but robust (Ritzema et al., 2014).

A fundamental prerequisite for the feasibility of peatland restoration is the assured supply of water of adequate quality. Apart from land use, the effects of climate change – such as changes in precipitation patterns and temperatures – also influence peatland restoration. In regions with insufficient rainfall or extreme temperature fluctuations, it can be difficult to permanently achieve the water levels required for rewetting and for ensuring the formation of new peat and the survival of the typical peatland vegetation. The fact that ecological processes in peatlands are often very slow must also be taken into account in planning. It can take decades or even centuries for a restored peatland to regain its full ecological functionality – or perhaps become a novel ecosystem (Kreyling et al., 2021; Zak and McInnes, 2022).

The rewetting of peatlands requires long-term commitment and monitoring (Strobl et al., 2019; Haapalehto et al., 2011). Both are necessary in order to be able to counteract *unintended consequences* such as internal eutrophication (Banaszuk et al., 2011) and to realize *multiple benefits*. In addition to their value for water management, peatlands are also of great importance for climate-change mitigation and biodiversity.

Drained peatlands release considerable amounts of CO_2 because the carbon stored in the peat reacts with oxygen when it comes into contact with air. The rewetting of peatlands stops this, prevents the spontaneous ignition of peatland fires and can bind carbon through the formation of new peat. The restoration of peatlands therefore has an immediate climate-change-mitigation effect. A further lasting effect is that peatlands contribute to regional and global climate regulation by slowing down evaporation processes (Helbig et al., 2020). It is of great importance for biodiversity that the restoration of natural water levels and vegetation patterns leads to increased structural diversity within the peatlands. This creates different microhabitats that can support a range of species (Strobl et al., 2019). In this way, peatlands can host a large number of rare animal and plant species that are highly specialized to the peatland habitat. Innovative approaches such as paludiculture show how humans can still continue to use peatlands in the future while achieving further multiple benefits (Martens et al., 2023).

6.2.2.3
Riverine landscapes and floodplains as an example

The straightening and channelization of river courses and the associated drainage of floodplains have historically played a key role in the increasing use of riverine landscapes by humans, while the accelerated drainage of landscapes has led to a greater risk of flooding downstream (Wolf et al., 2021). Straightening and channelization – e.g. to facilitate shipping traffic – also lead to variable water levels due to accelerated runoff or backwater during extreme events, putting both neighbouring settlements and many plant and animal species under stress (van Veen and Sasidharan, 2021; Rollins-Smith and Le Sage, 2023). The water level is often kept as constant as possible by means of barrages and dams to safeguard shipping traffic. However, barrages are obstacles to fish migration and cause the water to back up during heavy rainfall events. A study from 2020 shows that in 36 European countries alone, there are a total of around 1.2 million barriers such as dams, weirs, fords and similar structures in river courses (Belletti et al., 2020). Extreme examples of the use of watercourses are reservoirs, which are created with the help of dams to secure the water supply for humans; they interrupt the natural course of the river – and with it the connections between ecosystems which are important for migratory species and for gene exchange (Cid et al., 2022; Thieme et al., 2023).

The first problem for ecosystems in and along straightened rivers and streams is the increase in flow velocity, which entails the risk of displacing fauna and flora downstream and washing out nutrients and organic material (Brown et al., 2018). River-engineering measures also lead to a reduction in biodiversity due to the loss of habitat complexity, floodable riparian forests and meadows, gallery forests and swamp zones close to the river banks that act as water reservoirs (Zhou and Endreny, 2020). Another problem is the narrowing of the riverbed, which prevents the river from periodically flooding the adjacent landscape and thereby offsetting rising water levels. When periods of low precipitation lead to lower water levels, ecosystems along the river can dry out and die (Costello et al., 2022). With the loss of riparian and gallery forests, shade is lost and smaller rivers warm up (Parmesan et al., 2022). This development is intensified by climate change, which is having a major impact on the characteristics of the ecological communities. Cryophilic species are displaced by thermophilic species that can also cope with reduced oxygen levels in the water (Parmesan et al., 2022; Costello et al., 2022).

The restoration of riverine landscapes aims to reverse the negative impacts on ecosystems, restore multifunctionality and stabilize the water balance, which is important for the *water-related efficac*y of the restoration (Wohl et al., 2015; Brown et al., 2018). Key measures are the removal of river engineering structures and the restoration of natural, meandering river courses, depending on the type of river (e.g. whether in lowlands or mountain landscapes, in cities or in agricultural landscapes) and depending on river-regulation measures implemented in the past (RCC, 2024). Economic or safety-related considerations are often the reason for dismantling river engineering structures in the first place. In some cases, it is more costly to repair dilapidated structures than to remove them (Habel et al., 2020; Cornwall, 2023; Bellmore et al., 2019). Increasingly, ecological considerations such as the restoration of natural river courses and their characteristic ecosystems and species composition also play a key role (Duda and Bellmore, 2022). Most dam-removal projects worldwide are carried out in the USA (Cornwall, 2023). The draft of the EU Nature Restoration Law also includes plans to achieve the EU Biodiversity Strategy's goal of restoring at least 25,000 km of free-flowing river courses by 2030 (DG ENV, 2023). The aim is to restore the health and biodiversity of rivers, thereby strengthening climate resilience and reducing water-related risks, e.g. from extreme events, for communities. However, this is only possible within narrow adaptation limits. If priority is given to securing the water supply, not all reservoirs and their dams are suitable for decommissioning – unless there are alternative ways of supplying water over long distances, e.g. via pipelines.

The ecological effects of river restoration differ in time and space, and depend on the regional context (Foley et al., 2017; Bellmore et al., 2019). Dam removal represents a short-term disturbance from which the aquatic and terrestrial ecosystems can usually recover in the medium to long term. However, the function and condition of the restored, and sometimes novel, ecosystems are not always identical to their original state. A transition takes place from the lentic, i.e. rather stagnant, deeper water habitat of the reservoir in front of the dam, to a lotic, i.e. flowing habitat, accompanied by a change in the composition of the species community (Foley et al., 2017; Bellmore et al., 2019; Duda and Bellmore, 2022). The (re)introduction of species results from restoring spatial connectivity and migration opportunities (Foley et al., 2017). This can lead to an increase in biodiversity and the abundance of different life stages of species, as well as the distribution of nutrients and organic matter, which in turn can increase resilience and productivity as important *multiple benefits* (Magilligan et al., 2021; Bellmore et al., 2019; Duda and Bellmore, 2022). If the measure involves a former reservoir, in addition to the removal of the dam an important role is played by natural revegetation or the supportive replanting of the emerging areas and slopes along the restored river; this also offers protection against erosion (Duda and Bellmore, 2022; Figure 6.2-2).

Restoration projects after dam removal should, where possible, be jointly planned and implemented together with Indigenous and local communities and the affected population, as in the case of the removal of the Iron Gate Dam in the Klamath River in the USA. The long-term success of restoration projects can be ensured in this way (Habel et al., 2020; Cornwall, 2023; Matanzima and Mosuoe-Tsietsi, 2023). The restoration of original uses, former landscapes (aesthetic value), the productivity of water bodies, the microclimate and the reintroduction of native species can bring *multiple benefits* for the population (Cornwall, 2023).

The *feasibility* of dam removal depends on many different factors. For example, sedimentation in the reservoir is one factor that determines the geomorphological and ecological effects that dam removal will have on the surrounding area (Foley et al., 2017; Doyle et al., 2005). The release and distribution of the accumulated sediments can have positive ecological effects, e.g. through the transport of nutrients or the creation of new habitats downstream; but they can also have negative consequences, e.g. when habitats for other species are destroyed (Bednarek, 2001; Bellmore et al., 2019). Another example of an *unintended consequence* of dam removal is the release of PCB-contaminated sediment at the Fort Edward Dam in the Hudson River in 1973 (Bednarek, 2001; Foley et al., 2017). One possibility for

Figure 6.2-2
Example of the removal of large dams (Elwha River, USA). From 2011-2014, two large dams were removed from the Elwha River (Washington, USA), the Elwha Dam (left) and the Clines Canyon Dam. This restored the original water regime to over 70 kilometres of the river. The exposed gravel banks at the former Lake Aldwell reservoir (right) were later planted with native flora (Roussel et al., 2024).
Source: Paul Cooper, CC BY-NC 2.0

better control of the sediment release could be a gradual removal of the dam (Duda and Bellmore, 2022; Foley et al., 2017). Sediment can also be actively excavated and removed, although this can increase the time needed and the project costs, especially for the removal of particularly large dams (Duda and Bellmore, 2022).

The recovery of the ecosystem after the removal of a dam also depends on the reintroduction of different organisms. In some cases, it will be necessary to actively (re)introduce certain species and ecosystem engineers (Bellmore et al., 2019). At the same time, *unintended consequences* should be considered. For example, the removal of dams can also lead to the spread of non-native and invasive species (Bellmore et al., 2019; Duda and Bellmore, 2022). It is also possible that the structure and function of the ecosystem after the restoration measures do not correspond to the initial state (novel ecosystem; Foley et al., 2017). There is a need for further research on the diverse impacts of dam removal and on comparing the initial state before dam construction, the ecological state after dam construction and after dam removal (Bellmore et al., 2019; Duda and Bellmore, 2022).

6.3 Solution-space agriculture

Agriculture all over the world is facing major challenges. It is expected to secure food supplies and livelihoods for local people and the global population, adapt to climate change and help limit it, and protect biodiversity and ecosystems (partly) as a basis for its own productivity. Resources such as land and water must be used skilfully in order to achieve food-, climate- and biodiversity-related goals simultaneously. For land stewardship and biomass use inter alia in agriculture, the WBGU has developed multiple-benefit strategies that contribute to achieving these three goals and can alleviate the 'land-use trilemma' (WBGU, 2020). The management of water – from precipitation, surface water, groundwater and soil moisture – in agriculture must be organized in a similar way, and be closely interlinked with goals relating to food, climate and biodiversity. For example, in the case of (sometimes) water-intensive adaptations to ensure food security, sufficient water must remain for ecosystems and future uses, and the influence of agriculture on local water balances must also be taken into account.

To this end, compromises and synergies must be found in landscape planning between agricultural areas with different intensities of use and intervention in the water balance on the one hand, and restored and natural areas with their water requirements and water-related ecosystem services on the other (Sections 6.1, 6.5). Furthermore, climate-resilient agriculture must not only deal with fluctuations in the water availability when growing crops, but also maintain and create buffers for available water in the landscape, e.g. by means of near-natural water bodies, river meadows, hedges, trees and in soils. Farmers are automatically also green-water caretakers and should also be considered, supported and integrated in this role more strongly in the future, so that they can meet their obligations to protect natural resources and the biodiversity of soils, grasslands, forests and aquatic ecosystems.

Action is also needed to collect better data and projections on water abstraction and availability, and to expand knowledge on adaptation measures. Financial incentives are often necessary to facilitate the corresponding transformations. Suitable examples are compensation mechanisms between farmers and other water users (e.g. water funds), reforms of water-related agricultural subsidies and livelihood-securing services for the transformative transition, or more comprehensive abstraction charges. The details of how these should be designed are still insufficiently researched in some cases. Finally, the future potential of adaptation measures to reduce climate risks should be better studied.

This section focuses on the need for water-related action in agriculture. Since agriculture is part of local and global material flows, other agricultural practices and the food and energy systems in which they are embedded also contain essential levers for protecting water and other resources, the climate and biodiversity, as well as food security for all humans (WBGU, 2020). These should always be taken into account.

6.3.1 Agriculture's interventions in the water balance

Agriculture is greatly affected by climate change and water-related climate risks (Caretta et al., 2022; Section 3.1). Accordingly, it must adapt in a water-sensitive way and, at the same time, scrutinize all its practices to ensure their suitability for the climate and biodiversity. Many adaptation measures influence the consumption of blue water, e.g. through irrigation in response to rising temperatures and evaporation, or to locally declining precipitation. However, existing and adapted agricultural practices themselves also impact on the water balance and water availability (e.g. via green water) and thus also on the scope for further adaptation options:

Rain-fed agriculture is practised on approx. 80 % of the world's agricultural land (UNESCO, 2024). Whether precipitation seeps away or runs off, evaporates or is stored in soils and plants depends on a range of very different factors. These include the natural relief, variable landscape structures such as fallow land, hedges, trees and river meadows, planted crops and agricultural methods which, among other things, influence soil composition and cover.

In some cases, wet soils are drained for agricultural use; an extreme example is the draining of peatlands. For example, in north-west Europe and the USA, according to older estimates, a third and 17–30 % of agricultural land, respectively, is subject to drainage activities (Gramlich et al., 2018). In addition to natural water reservoirs in the landscape, wetlands are also being lost as a result. In the case of peatlands, large quantities of carbon stored in the soil are furthermore released in the form of CO_2 (Section 6.2). The agricultural use of drained peatlands, especially grazing by ruminants or the planting of energy crops that are alien to these locations, is also counterproductive when it comes to climate-change mitigation.

Around 20 % of the world's agricultural land is irrigated from various surface- and ground-water bodies, producing 40 % of agricultural output (UNESCO, 2024). However, diversions and excessive water abstraction (in addition to pollution and interventions e. g. for energy production or navigability) contribute to the fact that 56 % of watercourses and 44 % of lakes in the EU are not in a good ecological condition. Some watercourses dry up seasonally, and groundwater levels and the levels of lakes and artificial reservoirs fall (EEA, 2021; Section 2.2).

The challenges for agriculture caused by climate change include different regional precipitation and evaporation patterns; in addition to greater fluctuations and extremes, local changes in mean values are often still subject to a high degree of uncertainty (Caretta et al., 2022). Against this backdrop, it is of particular importance to secure the survival of an agricultural sector in which fundamental changes are necessary, as well as securing the livelihoods of farmers.

6.3.2 Combine adapted cultivation methods with green water-related measures

To ensure that agriculture is climate-resilient, cultivation must become more flexible and robust in the face of variations in water availability. Furthermore, agriculture itself must contribute to maintaining and creating buffers for available water in the landscape and groundwater bodies. These buffers can be natural, technical or hybrid solutions. The approaches are diverse and locally specific.

Adaptations in crop cultivation include (1) the improvement of crop cultivars and agronomic practices, e.g. switching to more drought-resistant varieties or adapting fertiliser use; (2) changes in cropping patterns and crop systems, such as different times for sowing and crop diversification; and (3) efficient on-farm irrigation and water management, e.g. drip irrigation or local collection and storage of excess rainfall in ponds, retention basins or cisterns. Alternatively, it might be better to channel this water into natural vegetation zones and local water bodies, where they will also strengthen or restore the regional hydrological cycle or teleconnections between more distant locations. In some cases, groundwater reservoirs can also be recharged in a targeted manner (managed aquifer recharge; Zhang et al., 2020).

Direct contributions to the water balance in the landscape, especially to green water, are made by (4) measures to maintain the moisture and water-storage capacity of soils and to specifically modify surface runoff, infiltration and evaporation (Box 6.3-1). This includes, for example, improving soil cover through mulching, undersowing or intercropping, which also improves the surface and soil

Box 6.3-1

Measures for maintaining soil moisture

The IPCC (Caretta et al., 2022; Tab. 6.3-1) defines water and soil-moisture conservation as adaptation measures such as terracing, mulching and contour ploughing (along contour lines) or the storage of water in sand that accumulates in special dams in temporarily water-bearing riverbeds (Stern and Stern, 2011). There are major overlaps with the techniques and practices summarized by the World Food Organization under Soil and Water Conservation (FAO, 2024b), which are intended to prevent the erosion, compaction and salinization of soils and improve both water storage in soils and soil fertility. For example, terracing slows and reduces surface runoff, reduces soil erosion and increases water infiltration (Deng et al., 2021). The water-related efficacy of terraces as a buffer during prolonged aridity was demonstrated during a drought in Ethiopia in 2015 (Kosmowski, 2018). A disadvantage of terracing can be a reduction in the area under cultivation, which, under certain circumstances, can lead to a reduction in yield. Influences of terracing on the water cycle and especially surface runoff must be taken into account by means of large-scale adaptation concepts. Poorly constructed steps can collapse and increase soil erosion. Multiple benefits result from the greater landscape heterogeneity. It creates habitats, facilitates symbiosis among organisms and helps to preserve biodiversity (Deng et al., 2021).

Mulching with arable residues can lead to conflicts of interest, e.g. with the use of the residues as animal feed; this can impede the feasibility or implementation of this measure (Giller et al., 2009). Because the effectiveness of water and soil-moisture-conservation measures is highly context-dependent, they must always be adapted to local agro-ecological and socio-economic conditions (Caretta et al., 2022). Only in this way can they make an important contribution to sustainable land management with long-term agricultural productivity and environmental health. If warming exceeds 1.5 °C, however, their effectiveness decreases significantly relative to the rising water risks (Caretta et al., 2022; Fig. 6.3-2), although their effectiveness can be increased by combining them with other measures.

Box 6.3-2

Agroforestry

Agroforestry reduces crop heat stress and water loss through evaporation by providing shade and wind resistance. Woodland grazing also maintains the water content of grassland soils and protects livestock from heat stress. Agroforestry measures have generated multiple benefits in Brazil, for example, where they led to an increase in the value of land (Schembergue et al., 2017).

In arid and semi-arid regions of Latin America, agroforestry measures have made it possible to reduce the use of fertilisers and other agricultural inputs, thereby cutting costs and excessive nutrient and pollutant inputs into ground and surface water (Krishnamurthy et al., 2019). The effectiveness of these measures is estimated to be high, but only if the increase in the global average temperature is limited to 2 °C (Caretta et al., 2022).

Unintended negative consequences for land and water resources can result from agroforestry measures, particularly if species are planted that are not adapted to the respective location (Etongo et al., 2015). The same applies to the planting of species whose water consumption is particularly high (Krishnamurthy et al., 2019). This illustrates the need for a multidimensional assessment of efficacy and a context-specific analysis of suitability and feasibility.

Two examples for agroforestry are shown in Figure 6.3-1.

Figure 6.3-1
Examples of agroforestry. Left: Napier grass intercropping in a coconut-based agroforestry system in Tumkur, Karnataka (India). Right: Agroforestry system suitable for semi-arid conditions based on cyphus and aloe vera in Agra, Uttar Pradesh (India).
Source: World Agroforestry Centre/S.K. Dalal, CC BY-NC-SA 2.0 (left); World Agroforestry Centre/Devashree Nayak, CC BY-NC-SA 2.0 (right)

Table 6.3-1
Examples of water-related adaptation measures in five categories. The same categories are also used in Fig. 6.3-2.
Source: Based on parts of Table 4.8 in Caretta et al., 2022

Type of adaptation	Description and examples
1. Improved crop cultivars and agronomic practices	› Improved crop cultivars, e.g. short-duration paddy varieties (Nepal); saline-tolerant rice cultivars (Bangladesh); drought-tolerant maize varieties (Malawi, Nigeria, Zimbabwe, Uganda) › Improved agronomic practices, e.g. conservation agriculture (especially minimizing soil disturbance, better soil cover, crop rotation) to conserve soil moisture (Malawi, Tanzania); climate-smart agricultural practices (Zambia); alternate wetting and drying and direct seeding of rice (India)
2. Changes in the cropping pattern and crop systems	› Changes in cropping pattern: introduction of sugar cane and rice (Costa Rica); crop diversification (Ethiopia, Zimbabwe, Tanzania) › Changes in the timing of sowing and harvesting (e.g. China, India, Pakistan) › On-farm diversification, e.g. an integrated crop-livestock system (France)
3. Irrigation and water-management practices	› Irrigation, e.g. construction of local irrigation infrastructure (Chile); funding of community wells (Canada); drilling of borewells (Thailand); spate irrigation (Sudan); night-time irrigation scheduling to reduce evaporative demand (UK) › On-farm water management and water-saving technologies, e.g. use of surface pipes for irrigation water conveyance (China); drip irrigation (China); water-saving measures (India)
4. Water and soil conservation	› On-farm water and soil conservation measures (e.g. Burkina Faso); terraces and contour bunds (Ethiopia) › Water harvesting through on-sand dams (Kenya); in-situ and ex-situ water harvesting (Uganda, India) › Watershed conservation programmes (e.g. Ethiopia) › Restoration of water bodies, e.g. creation of artificial lakes (Portugal)
5. Agroforestry and forestry-related responses	› Agroforestry-related measures (India, Kenya, Nigeria); farmer-managed natural regeneration (FMNR; Ghana) › Forestry-related measures, e.g. coastal reforestation by planting salinity-resistant trees (Bangladesh, Colombia)

quality, reduced ploughing, or cultivation based on the natural relief, including the creation of terraces. The drainage of wet soils should be reduced or, especially in the case of peat soils, stopped and reversed (Section 6.2.2). Rededication for sustainable use can include paludiculture, e.g. production of reeds, sedges, rushes, reed canary grass in fens, also for biogas production or the cultivation of special peatland plants such as cranberries in upland bogs. The elimination of drainage measures can also increase resilience to drought in neighbouring areas. Finally, (5) the cultivation of small-scale landscapes using such elements as hedges and trees, e.g. in agroforestry (Box 6.3-2), can create water buffers and reduce evaporation and heat stress for crops, animals and humans by providing shade and wind resistance.

Individual measures are usually combined at farm level, and these combinations are analysed in the literature under various (not always equally and clearly defined) terms. For example, 'conservation agriculture' to improve soil quality and moisture usually involves reduced ploughing, increased soil cover, mainly through mulching, and crop rotation (Twomlow et al., 2008; Thierfelder et al., 2015), whereby the respective effects of these components – and possibly additional pesticide or fertiliser use – should be carefully differentiated (Giller et al., 2009). Concepts of 'regenerative agriculture' emphasize, among other things, soil health and agricultural biodiversity and combine, for example, practices for soil quality and moisture, local nutrient cycles and agroforestry (Giller et al., 2021; Schreefel et al., 2020; Elevitch et al., 2018). There are also examples in Brandenburg (Gut and Bösel, 2024), where the fields of a corresponding real-world laboratory funded by the Federal Ministry of Food and Agriculture (BMEL), among others, are also part of the Global Network of Ecohydrology Demonstration Sites of the UNESCO Intergovernmental Hydrological Programme (Finck Stiftung, 2024a, b). These two and other concepts are also sometimes summarized under the heading of 'nature-based solutions' (Budding Polo-Ballinas et al., 2022).

Finally, individual farms and areas must be considered in the context of the landscape. Small-scale, diversified agricultural areas and their water-related adaptation measures should be embedded in an integrated landscape approach in the sense of a mosaic approach (WBGU, 2020, 2024).

In its most recent report, the IPCC analysed the evidence on water-related adaptation measures, most of them in agriculture (Caretta et al., 2022; Tab. 6.3-1). It considered both current positive effects and any maladaptations, as well as their expected effectiveness in reducing future local risks, depending on the extent of global warming (Fig. 6.3-2).

The water-related effects of climate change, challenges and necessary adaptations vary greatly from one location to another. Overall, it can be seen (Fig. 6.3-2, left half) that water-related adaptation measures can have positive water-related impacts and multiple benefits under current conditions. They have positive effects of an economic nature (especially in low- and middle-income countries; not shown in the chart), for vulnerable population groups, on the water balance and the environment (especially in high-income countries) and in institutional and socio-cultural terms (Caretta et al., 2022: 635 ff.; Fig. 6.3-2). Examples include the higher agricultural yields and household incomes achieved by smallholder farmers cultivating drought-tolerant maize varieties in Zimbabwe (Makate et al., 2017), or the adjusted timing of wheat sowing in Pakistan (Rahut and Ali, 2017). Whether and to what extent today's adaptation measures will still yield multiple benefits if climate change continues has not been thoroughly researched. In addition, ethnological studies on dealing with climate change increasingly point out that solution strategies developed from local knowledge systems – such as adapting the agricultural calendar or relocating livestock farming to protect against sudden flooding – generally make short-term coping possible, but do not achieve a long-term adaptation and successive transformation of the entire production system towards climate resilience (Oladele and Amara, 2024; Makate, 2020; Crate and Nuttall, 2009; Hornidge and Scholtes, 2011). At the same time, research work repeatedly emphasizes that national adaptation strategies in many countries, for example in Sub-Saharan Africa, continue to make insufficient use of the potential of local knowledge systems in the transformation of agriculture. The WBGU recommends greater integration of local knowledge systems into the development of adaptation strategies for increased climate resilience (Filho et al., 2023).

Particularly adaptation approaches that rely on an increase in income – and primarily on an intensification of agricultural production – experience unintended negative effects or maladaptations. These include the overuse of groundwater, increased costs and an increased use of synthetic fertilisers and pesticides (Caretta et al., 2022: 643). For example, a study from Tunisia found that although the planting of olive trees in an area previously dominated by barley cultivation and livestock farming would be profitable for farmers as an adaptation measure to climate change, the necessary irrigation would use excessive amounts of groundwater. As an alternative adaptation measure, intercropping with cacti, which can serve as a water source for livestock and help reduce soil erosion, could also improve farmers' incomes without increasing water use (Daly-Hassen et al., 2019).

This illustrates (Fig. 6.3-2, bottom row) that individual measures will often not be sufficient to adequately reduce risks in agriculture in the future. As a rule, combinations of measures will be necessary, which ultimately have to be embedded in a holistic, ecologically sustainable agriculture and an integrated landscape approach (WBGU, 2020). The effectiveness of different adaptation approaches is highly dependent on the respective location and context as well as on the crops used (Caretta et al., 2022: 647).

It also transpires (Fig. 6.3-2, right half) that the future effectiveness and potential of the approaches mentioned to reduce the risks of future climate change are limited. Because the water and temperature extremes are exacerbated as warming increases, the possible contributions will actually decline further, and considerable residual risks are to be expected even after the measures are realized (Caretta et al., 2022). This applies in particular to adaptation measures aimed at improving crop cultivation and irrigation. However, even measures for improved soil moisture and agroforestry, which show the greatest potential up to 1.5 °C and 2 °C warming, are likely to become significantly less effective if the rise in temperature is greater (rows 1–2 and 4–5 in Table 6.3-1 and Fig. 6.3-2).

6.3.3 Farmers are also green-water caretakers: areas of action for implementation

The approaches for improving water management and adapting to climate change are largely known. Some have already been in use for a long time and on a large scale in certain regions and may be transferable to other areas, although there is still a need for research into potential, limits, transferability and possibilities for improvement in individual cases. Measures should be taken e.g. in the following four areas in order to make these approaches generally available (specific recommendations for action and research follow in Sections 6.5.3 and 6.6.3):

Knowledge, expertise and data: Many measures are in the individual's self-interest and, in principle, also within an individual farm's sphere of influence, assuming that the corresponding information and skills are present.

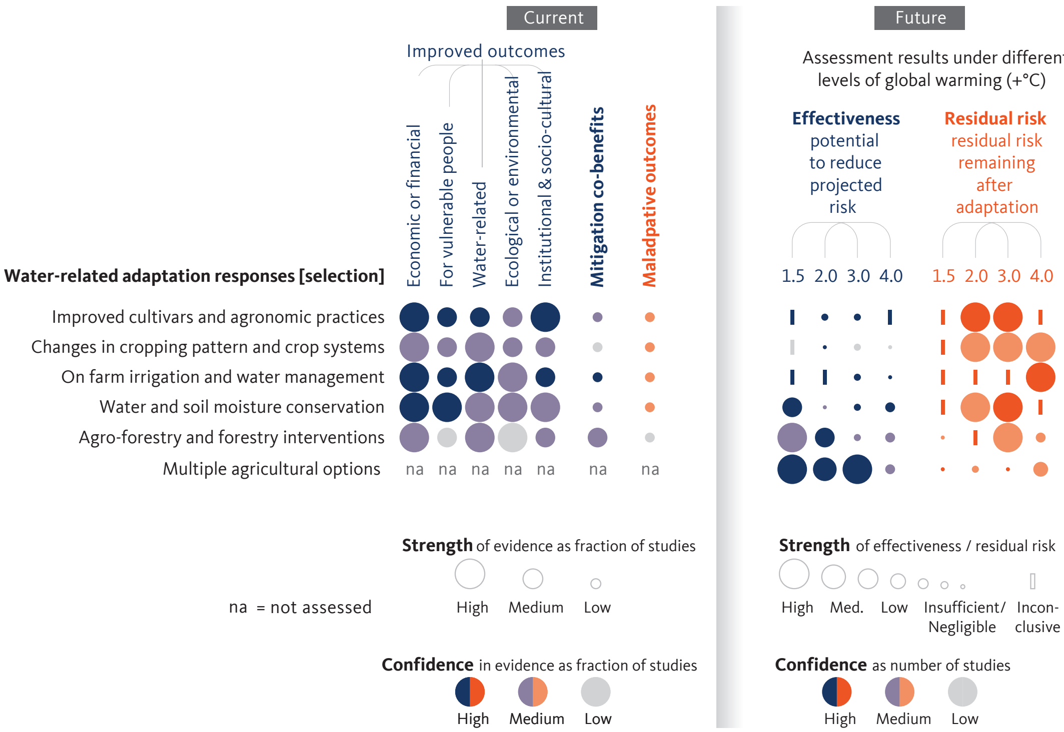


Figure 6.3-2
Current and future effectiveness of water-related adaptation measures in agriculture. Left-hand side: current positive impacts and multiple benefits, including for climate-change mitigation, as well as maladaptations. Right-hand side: future effectiveness of adaptation measures and residual risk from climate-change impacts for varying levels of global warming. Uncertainties in the assessment and risks increase significantly above 1.5 °C of global warming.
Source: extract from Fig. 4.29 in Caretta et al., 2022

Relevant data on water availability and abstraction and projections of water availability should be collected and continuously updated and made available to farmers; knowledge on adaptation options should also be communicated. In the case of irrigation measures with shared water resources, it is also necessary to record the withdrawals (preferably in real time using digital methods) and, if possible, the return flows to determine the actual consumption. The data serve as a basis for effective management, possible regulation and, if appropriate, the pricing of withdrawals, which can be combined with financial support and the promotion of sustainable water use (see below). On this basis, total water consumption can be recorded and incentives can be created for efficient irrigation, as well as for more effective management of rainwater by reducing surface runoff and improving water storage in soils and landscape elements such as hedges, ponds or retention basins.

When efficiency increases, however, rebound effects should be anticipated and, if necessary, addressed through regulation (Grafton et al., 2018). Efficiency improvements alone, for example in irrigation measures, have in many cases not led to a significant reduction in total agricultural water consumption; in some cases, there has even been an increase in consumption. This happens if efficiency gains are not used to make savings but to increase yields or earnings. This is the case, for example, if productivity was previously limited by a lack of water, if more water-intensive crops are grown, or if larger areas are cultivated or irrigated (Grafton et al., 2018; Perry et al., 2017; Hamidov et al., 2022; Xu et al., 2021b).

Appreciate agriculture as green-water management and incorporate it into integrated landscape and water management: Adaptation measures that influence the water balance and quality on a larger scale – e.g. by creating buffers, increasing groundwater recharge or maintaining ecosystem services – also benefit other water users or the general public. Positive side effects include the protection of buildings and infrastructure from extreme events, the preservation of biodiversity and recreational areas, and local climate regulation.

Land users should therefore be seen more as water actors. Farmers in particular, who are inevitably also green-water caretakers, should be given more support in this role. This should be reflected in the political and societal approach to and appreciation of agriculture, in farmers' education and training and their involvement in water-management processes (Sections 8.2, 8.3.3), and in water-related financial incentives (see below). Conversely, it may be expedient to involve traditional water actors such as water utilities or water authorities more closely in a fundamental transformation of land management and agriculture (WBGU, 2020), as some of the additional water-related benefits of such a reorganization are relatively 'tangible'.

Financial incentives and safeguarding the transformation: To ensure that farmers can become sufficiently active, positive financial incentives should be increased in addition to any regulation of consumption. In some low- and middle-income countries, sufficient access to resources and capital first needs to be created. *Firstly,* this includes compensation mechanisms between farmers and the beneficiaries of the conservation and improvement of water resources, such as water funds (Section 8.3.3). However, in some cases transformative adaptation measures only become effective over a longer time horizon, and part of their impact consists of multiple benefits for the general public that do not directly generate income for farmers. Thus, in order to provide start-up or bridging finance and, for example, remunerate the provision of ecosystem services, water-related agricultural subsidies can *secondly* be integrated into these compensation mechanisms or paid separately; however, they should be linked in any case to public goods and transformative change. For example, 'Green Water Credit' funds have been developed in Kenya, Morocco, China and Algeria, from which farmers receive payments for water-related measures, and downstream users such as water suppliers or energy producers make payments that are supplemented by public funds and development financing (ISRIC, 2024; Fig. 6.3-3). Some drinking-water suppliers in German cities also make compensation payments to farmers for water-related measures, for example in Augsburg (swa, 2021; Section 8.3.3). *Thirdly*, to reduce the risks of the transformation for farmers, this should be accompanied by establishing options that secure livelihoods. Support could be provided, for example, in the form of time-limited income support for farmers in transition phases, subject to appropriate conditions, or partial cover for possible reduced yields when trialling new cultivation methods.

Research on the potential of adaptation measures: Finally, the potential of adaptation measures to reduce climate-related risks as climate change progresses should be better researched. The IPCC has drawn attention to considerable gaps in this field (Caretta et al., 2022).

6.4 Solution-space cities

By 2050, the global urban population will have grown to an estimated 6.6 billion people, with two thirds of humanity living in cities (UN, 2019). At the same time, the effects of climate change are being felt more and more acutely in many cities around the world. In addition to growing pressure on water resources due to increasing use, more frequent and longer periods of drought are leading to increasing water shortages, and the number of cities worldwide where a water emergency has had to be declared is rising (Section 4.2). More frequent and heavier extreme precipitation, intensified by urban surface sealing and overburdened drainage systems, is causing more and more flood damage. Increasing heat stress,

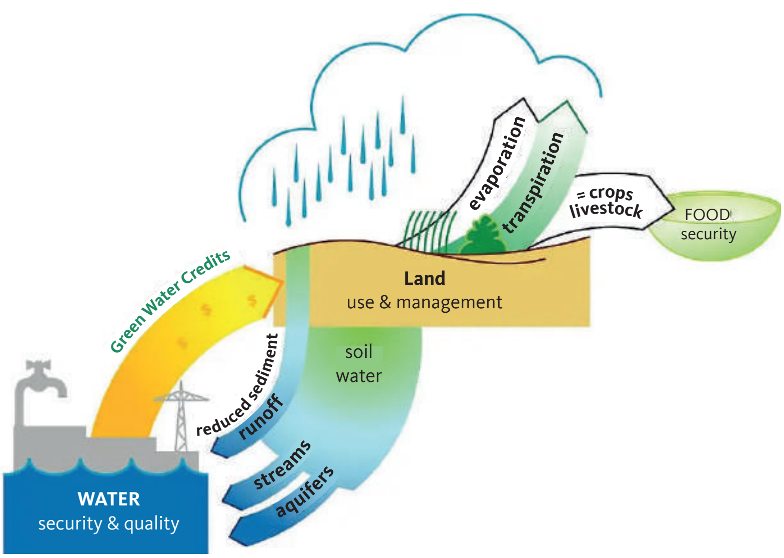


Figure 6.3-3
The basic idea behind Green Water Credits. Farmers who take measures to maintain soil moisture and reduce erosion, thereby also stabilizing the water balance and reducing sediment inputs, are additionally remunerated by other water users who benefit, such as water suppliers and energy utilities.
Source: ISRIC, 2024

exacerbated by the urban heat-island effect, is leading to a rising number of heat-related deaths (Section 4.2). Yet the vulnerability of the urban population varies considerably, both between different cities and within individual cities and urban neighbourhoods (WBGU, 2016).

In view of the increasing exacerbated water-related challenges in many regions (Chapter 3), there is an urgent need in cities around the world to accelerate adaptation to climate change. This includes, in particular, expanding and improving the water-related infrastructure accordingly and establishing adequate management strategies. At present, however, inadequate water infrastructures and mismanagement in the water sector are contributing to urban vulnerability to climate risks in many cities. They also cause local and regional health and environmental problems, particularly as a result of water pollution caused by the water supply not functioning reliably and inadequate wastewater systems (GCEW, 2023a). The comprehensive and rapid establishment of climate-resilient urban water management is therefore of key importance for a sustainable and just city design of the future.

6.4.1 Establish water-sensitive urban design as a guiding principle

Climate-resilient water management in cities goes beyond incremental adaptation; it means designing the entire urban infrastructure from scratch in a way that makes it more resilient to the impacts of extreme events, and promotes rather than hinders the local water cycle. This makes it possible to buffer the increasing water extremes more efficiently. In recent years, the concepts of 'water-sensitive urban design' and 'sponge city' have become established as concepts for this (Wong et al., 2020; Rogers et al., 2020; Han et al., 2023; LAWA, 2021). The WBGU supports the concept of water-sensitive urban design characterized by a largely near-natural water cycle that also contributes to a healthy urban climate and strengthens ecosystem services. In this respect, the WBGU strongly endorses the current efforts in Germany to include the guiding principle of water-sensitive urban design in a new Section 1b of the German Federal Building Code (BMWSB, 2024: 9).

If water-sensitive urban design is to succeed, it is necessary to ensure that water can perform its functions for urban ecosystems, i.e. to meet their water requirements with water of sufficient quality. Climate-resilient urban water management also involves ensuring access to clean drinking water and an adequate sanitation infrastructure for the entire urban population today and in the future – even under more rapidly changing conditions. One long-term goal of climate-resilient water management is to integrate urban water cycles into the natural landscape water balance of the entire water catchment area. On the one hand, this means that the precipitation in a city can completely evaporate or seep into the ground locally according to the naturally prevailing conditions. On the other hand, wastewater discharges from settlements do not contaminate receiving waters with persistent pollutants.

The principles for action of climate-resilient water management proposed by the WBGU should also be applied in cities (Sections 5.2, 6.1.1). This includes, among other things, overcoming existing path dependencies, avoiding future ones, as well as considering climate projections in different scenarios and making preparations for them. A comprehensive toolbox of proven measures based on technical and nature-based elements and their combination can be used to implement climate-resilient urban water management (Table 6.4-1). A sharp distinction between grey and blue-green infrastructure is neither necessary nor expedient: different measures can be combined in hybrid approaches to meet the context-specific requirements and conditions (Fig. 6.4-1; Depietri and McPhearson, 2017; IPCC, 2022b). The WBGU recommends taking into account the four requirements for the development, selection and implementation of measures in the context of exacerbated water-related challenges also in cities when implementing climate-resilient urban water management (Box 6.1-1). The efficacy and feasibility of measures are also greatly influenced by the technical possibilities for implementation in existing or new buildings and urban infrastructure, and the available resources (Section 6.1.2).

6.4.2 Climate-resilient water management in the context of urban transformations

Cities have a key role to play in the transformation towards sustainability. In addition to effective climate adaptation and preserving natural life-support systems, it is essential to ensure urban quality of life (e.g. access to affordable, climate-adapted housing, and enabling inclusion and urban *Eigenart* [diversity]), as quality of life represents an important resource for urban transformations (WBGU, 2016). This should also always be taken into account in climate-resilient urban water management.

Because people in socially disadvantaged urban neighbourhoods are often much more vulnerable to climate risks, reducing social inequalities also contributes to improving climate resilience. The challenges for sustainable transformations vary greatly depending on

Table 6.4-1
Examples of measures suitable for water-sensitive urban design. They are based on technical and nature-based elements. Also shown are examples of aspects to be considered in accordance with the four requirements proposed in Section 6.1.2 for the development, selection and implementation of measures in the context of climate-resilient water management. By implementing measures for water-sensitive urban

Measures	Aim	Efficacy on different time scales
Stormwater retention basins (retention and overflow basins, storage channels)	Protection against urban flash floods	Can be implemented and are effective in the short term; technical climate adaptation simple
Reet bed filters for rainwater treatment	Improved water quality	Can be implemented and are effective in the short term; improved groundwater recharge in the long term; technical climate adaptation simple
Constructed wetlands	Improved water quality	Can be implemented and are effective in the short term; technical climate adaptation simple
Bioswales or infiltration trenches	Protection against urban flash floods and droughts	Accelerated infiltration of rainwater in the short term; improved groundwater recharge in the long term; technical climate adaptation simple
Water-permeable surface coverings	Protection against urban flash floods and droughts	Accelerated infiltration of rainwater in the short term; improved groundwater recharge in the long term; technical climate adaptation simple
Roof and façade greening	Protection against urban flash floods	Absorption of rainwater and release through evapotranspiration effective in the short term; technical climate adaptation difficult in existing buildings
Unsealing and greening of roadsides, central reservations, tram tracks	Protection against urban flash floods and droughts	Accelerated infiltration of rainwater in the short term; improved groundwater recharge in the long term; technical climate adaptation simple
Urban parks and greening of public spaces	Protection against urban flash floods and droughts	Accelerated infiltration of rainwater in the short term; improved groundwater recharge in the long term; delays in effect are possible; climatic changes may affect the vegetation and efficacy; technical climate adaptation simple
Flood polders	Protection against riverine flooding	Quickly effective through the provision of alluvial areas; changing runoff conditions can limit efficacy; technical climate adaptation simple
(Re)wetting and restoration of urban wetlands and riparian forests (Section 6.2.2)	Protection against urban flash floods, droughts and riverine flooding	Accelerated infiltration of rainwater and more alluvial areas in the short term; improved groundwater recharge in the long term; delays in effect are possible; technical climate adaptation difficult

design, potential multiple benefits can be used to a greater extent and unintended consequences avoided.
Source: WBGU

Feasibility in the specific context	Possible multiple benefits (examples)	Possible unintended consequences (examples)
Required space and financial resources high; implementation in existing urban areas complex and expensive; costs of maintenance and adaptation low	Improved watercourse quality by avoiding combined sewer overflows; creation of recreational areas	Breeding grounds for disease-transmitting vectors (mosquitoes) in stagnant waters
Space requirement low; implementation costs moderate; costs of maintenance and adaptation low	Biodiversity protection	Waterlogging of cellars, negative economic and health consequences
Space requirement moderate; implementation in existing urban areas complex and with moderate costs; costs of maintenance and adaptation low to moderate	Biodiversity protection; health protection (removal of pathogenic microorganisms)	Breeding grounds for disease-transmitting vectors (mosquitoes) in stagnant waters
Space requirement low; implementation costs low to high; costs of maintenance and adaptation low	Improved water quality due to increased rainwater infiltration; biodiversity protection	Pollutant entry from traffic areas into soil and groundwater impairs health and environment
Implementation in existing urban areas complex and resource-intensive; implementation costs moderate to high; costs of maintenance and adaptation low	Positive health effects due to improved microclimate: unsealing reduces the urban heat island effect and heat stress	Pollutant entry from traffic areas into soil and groundwater impairs health and environment
Implementation in existing urban areas costly and resource-intensive; irrigation may be necessary; implementation costs moderate to high; costs of maintenance and adaptation low	Biodiversity protection; insulating effect and buffering of temperature fluctuations; improved microclimate, less heat stress indoors and in the close vicinity	Negative health consequences, e.g. allergic reactions, toxic effect of inhaled fungal spores
Space requirement low; simple and quick implementation; irrigation may be necessary; implementation costs low to high; costs of maintenance and adaptation low	Biodiversity protection; improved microclimate, shade provision; filtering of air pollution; noise protection; promotion of health-promoting and sustainable mobility	Negative health consequences, e.g. allergic reactions, increased local exposure to air pollution possible; visibility restrictions
Space requirements may be high; possible: 'pocket parks', greening of previously unused areas; implementation in existing urban areas complex or limited; possible conflicts with space requirements for housing and mobility (possible solution: 'triple inner urban development'; WBGU, 2023); irrigation may be necessary, which may be difficult to realize; implementation costs moderate to high; costs of maintenance and adaptation low to moderate	Biodiversity protection; improved microclimate, shade provision, filtering of air pollution; noise protection; improved air circulation in neighbouring districts; health-promoting spaces for recreation, exercise and mobility; reduction of social and health inequalities	Negative health effects, e.g. allergic reactions; displacement of disadvantaged population groups from economically upgraded neighbourhoods (green gentrification)
Space requirement high; implementation in existing urban areas complex or limited; possible conflicts with other urban land uses; implementation costs high; costs of maintenance and adaptation low	Biodiversity protection; positive health, ecological and social effects similar to urban parks	Loss of breeding grounds when there is flooding
Space requirement high; implementation in existing urban areas complex or limited; possible conflicts with other urban land uses; water requirement may increase in the long term due to climate change; implementation costs high; costs of maintenance and adaptation moderate to high	Biodiversity protection; health-promoting spaces for recreation and exercise; positive health, ecological and social effects similar to urban parks	Desiccation of parts of the wetland can severely impair ecosystem function

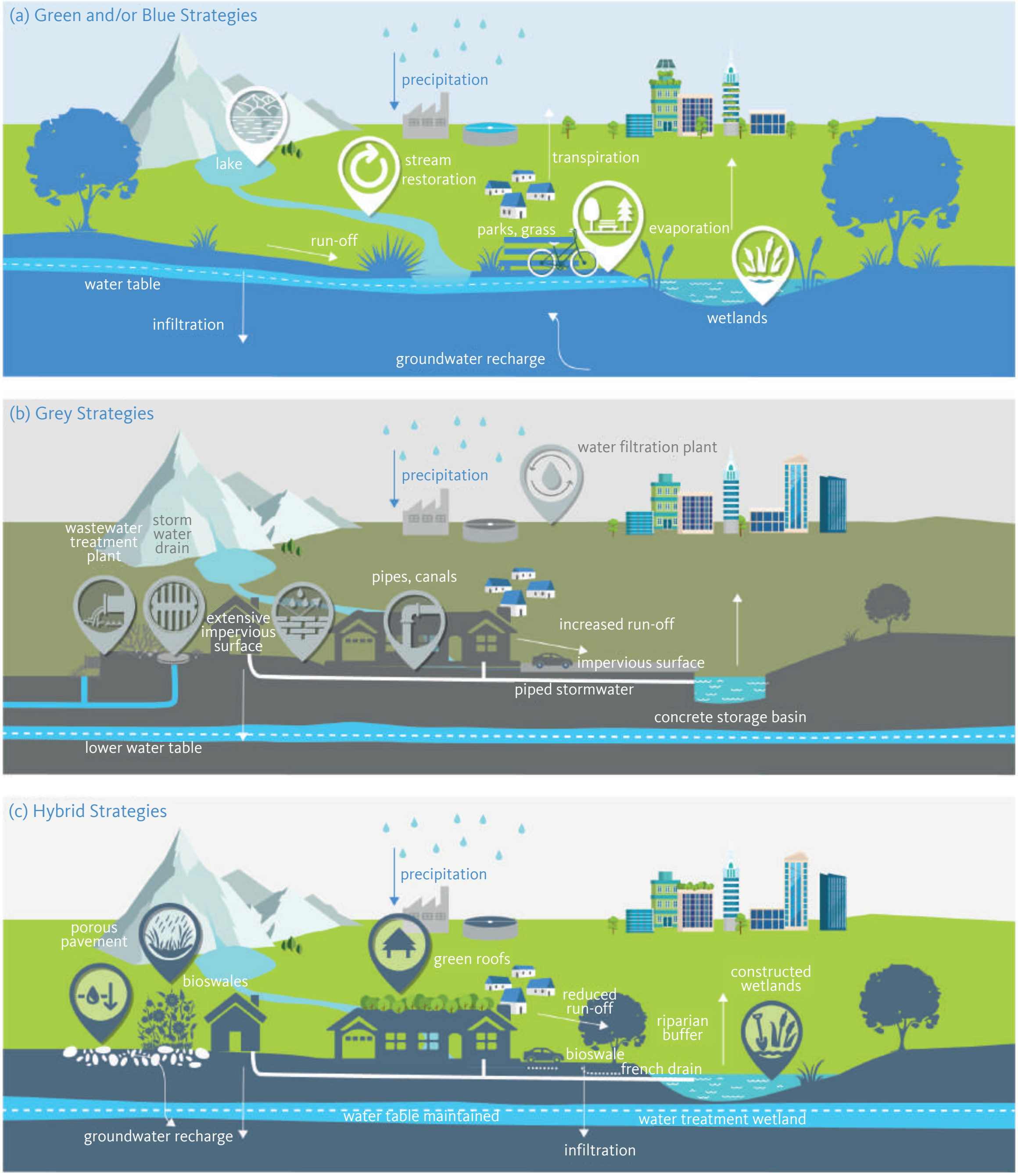


Figure 6.4-1
Strategies for adapting urban water infrastructure to climate change. A comprehensive toolbox of measures is available for implementing climate-resilient urban water management, whereby a distinction is made between grey and blue-green infrastructure. In hybrid strategies, different measures are combined to meet local requirements and framework conditions.
Source: IPCC, 2022b, based on Depietri and McPhearson, 2017

the type of city involved (WBGU, 2016). These are also reflected in the different context-specific requirements for climate-resilient urban water management.

In high-income countries, a sustainable and climate-resilient conversion of existing infrastructure, including the building stock (WBGU, 2016), is particularly important. Measures requiring more space and invasive interventions (e.g. construction of new supply and disposal pipelines) can sometimes only be realized to a limited extent or at great expense in existing urban districts.

For low- and middle-income countries, ongoing urbanization offers a window of opportunity, since much of the urban infrastructure is yet to be built or expanded in the coming decades (WBGU, 2016). However, insufficient resources and deficits in urban governance often lead to the emergence of informal neighbourhoods and slums. They are much less protected against climate risks because, in addition to an inadequate building structure (e.g. cramped housing conditions, insufficient protection against heat), they often do not have an adequate infrastructure for drinking water and sanitation (Section 7.3). Rapidly improving these fundamental problems with limited resources is therefore an important goal. One example of transformative measures in the sense of climate-resilient water management in low-income countries is the expansion of decentralized and non-piped sewage systems, as explained in Section 7.3.2 with the example of Lusaka, Zambia.

6.4.3 The expansion of blue-green infrastructure as an urban multiple-benefit strategy

The expansion and improvement of blue-green infrastructure is a special multiple-benefit strategy in cities. It includes rainwater-retention areas with multi-purpose functions such as urban parks and sports areas, also wetlands and woodlands, near-natural flood polders, vegetation in streets and green roofs and façades. On the one hand, blue-green infrastructure can provide protection against urban flash floods and droughts and plays an important role in water-sensitive urban design. On the other hand, it has the potential to develop positive effects that go beyond its water-related functions by providing various other ecosystem services (LAWA, 2021; WBGU, 2023).

In this way, blue-green infrastructure in cities provides numerous opportunities for multiple ecological, health and social benefits. Urban green spaces provide habitats for many different species and promote biodiversity and climate-change mitigation (Whitmee et al., 2024). They also play a key role for the physical and mental health of the urban population, as they enable people to spend time, exercise and engage in social activities in contact with nature. In this way, they can strengthen social cohesion, which can also have a positive effect on health and well-being (WBGU, 2016, 2023). Activities in contact with nature can also promote sustainable and healthy lifestyles in general (WBGU, 2023). Furthermore, urban green spaces help improve air quality and mitigate the urban heat-island effect, reducing exposure to air pollutants and heat. Disadvantaged population groups benefit particularly from urban green spaces if they are sufficiently available, accessible and geared to their needs. Social and health inequalities can be reduced in this way. When expanding blue-green infrastructure, care should also be taken to avoid maladaptation and negative unintended consequences, such as triggering allergic reactions or negative social effects if disadvantaged population groups are displaced through the 'green gentrification' of urban neighbourhoods.

A particular challenge for the expansion and improvement of blue-green infrastructure is the potential conflict over land use in existing urban neighbourhoods. In order to overcome such problems, it can be helpful to follow the guiding principle of 'triple inner development' (balance between increased building density, mobility and the creation of green and blue spaces, adapted to the respective regional conditions; WBGU, 2023). Possible solutions include the creation of many relatively small 'pocket parks' and the greening of previously unused, sealed public spaces (WBGU, 2023). In addition, future exacerbated water-related challenges must also be taken into account (Chapter 3): depending on local climatic conditions and developments caused by climate change, the artificial irrigation of green spaces may be necessary today or in the future.

The implementation of the Skybrudsplan in Copenhagen (Denmark) and the use of an alternative irrigation resource for urban greenery in Schweinfurt (Germany) are two examples of the implementation of climate-resilient water management in high-income countries that are related to blue-green infrastructure (Boxes 6.4-1, 6.4-2). The expansion of decentralized and non-piped sewage systems, which are of great importance for low- and middle-income countries, is explained using the example of Lusaka (Zambia) in Section 7.3.2.

6.5 Recommendations for action

6.5.1 Overarching recommendations for action

Establish a new approach to water management: living with uncertainty

A climate-resilient and socially balanced form of water management should be established everywhere that manages local, regional and global water cycles with foresight, and thus maintains the various functions of water for humans and ecosystems in the long term. Transdisciplinary and collaborative learning and decision-making processes across different sectors and spatial scales are needed to make action and decision-making possible in the face of uncertainty. This must be based on empirical data, real-time information and future projections under various climate scenarios on water availability and water demands, whereby a rising water demand in the course of the energy transition must also be taken into account. A digitalization campaign in the water sector at local and national level is urgently needed to collect, process and provide real-time data and to provide the basis for well-informed decision-making. The selected water-management practices must be constantly monitored, evaluated and, if necessary, adjusted at short notice on this basis. To achieve this, structures and processes for planning and decision-making in water management must be adaptable and correctable and include all relevant actors, and infrastructure must be designed in a more decentralized and adaptive manner.

Box 6.4-1

Practical example: blue-green infrastructure in cities – the 'Cloudburst Management Plan' in Copenhagen (Denmark)

In 2011, Copenhagen experienced extremely heavy rainfall of up to 100 mm per hour, causing damage of up to 800 million euros (The City of Copenhagen, 2012: 5; Arnbjerg-Nielsen et al., 2015). This event highlighted the inadequacy of the existing infrastructure for dealing with extreme events – and these will increase in the future. As a result of climate change, compared to other countries Denmark is most of all affected by 'too much' water; heavy precipitation such as in July 2011 could occur much more frequently in the future (Arnbjerg-Nielsen et al., 2015).

The city council therefore decided to optimize the city's infrastructure with the 'Cloudburst Management Plan' (Danish: 'Skybrudsplan'; The City of Copenhagen, 2012) to consistently focus on nature-based solutions for long-term climate-change adaptation. The aim of the infrastructure measures is to limit the rise in flood waters on roads and squares to a maximum of 10 cm during heavy rainfall events – with the exception of designated flooding areas (The City of Copenhagen, 2012: 12). The analysis of the distribution of water masses during the 2011 floods led to the realization that the city must be managed as a coherent water system in future. To achieve this, a combination of above-ground areas for decentralized retention and infiltration, controlled above-ground drainage in specially adapted roads, and underground pipes is planned (The City of Copenhagen, 2015: 28f.). The nature-orientated conversion and expansion of above-ground infrastructure by unsealing, the creation of more urban greenery and artificial bodies of water in parks, streets and squares plays a key role here. The expense of implementing the Cloudburst Management Plan is shared between the municipality of Copenhagen and the water-infrastructure operator HOFOR. The wastewater charges were increased to finance the total expenditure on the project; for a household of four, the average annual expenditure rose by 1,375 Danish kroner (approx. 185 euros; The City of Copenhagen, 2015: 42).

During the planning phase, the Cloudburst Management Plan was compared with a conventional solution, which would have focused on expanding the underground infrastructure, particularly the sewerage system and technical retention basins (The City of Copenhagen, 2015: 36). A socio-economic assessment, which took into account the construction and operating costs of both solutions, as well as the damage costs averted, showed that the total costs of the Cloudburst Management Plan were lower than those of the conventional infrastructure solution. They are also much lower than the expected cost of damage that would be caused under a 'business as usual' scenario, in which no adaptation measures would take place. The plan was based on a time horizon of 100 years (The City of Copenhagen, 2015: 36 f.). The analysis also took into account multiple benefits in various areas, e.g. health benefits and the economic enhancement of properties through the expansion of green spaces (Atelier Dreiseitl GmbH and Rambøll Group, 2013). In addition, an independent life-cycle analysis of the two solutions for the Nørrebro district has shown that the negative unintended environmental impacts of the Cloudburst Management Plan (including the contribution to climate change, summer smog, eutrophication of fresh waters) are substantially lower than those of the conventional infrastructure solution (Brudler et al., 2016).

The more than 300 individual projects that make up the Cloudburst Management Plan will be implemented step by step until the 2030s (The City of Copenhagen, 2015: 8). A final evaluation of the project is therefore not yet possible. However, some sub-projects that have already been completed, such as the remodelled green spaces 'Skt. Kjelds Plads' and 'Tåsinge Plads', as well as the green street 'Bryggervangen', are already being discussed as flagship examples at specialist conferences (Negrello, 2022; The City of Copenhagen, 2016; Xu et al., 2021a). In particular, the successful integration of rainwater management, biodiversity protection, health and quality of life, as well as the involvement of citizens and civil groups during the planning process are emphasized (Negrello, 2022; Xu et al., 2021a). At the same time, a critical social-science analysis is taking place of sub-projects of the Cloudburst Management Plan, such as the 'Hans Tavsens Park' in the Nørrebro district and the possible negative consequences of its redesign for disadvantaged population groups (Tubridy, 2020). When analysing possible multiple benefits of blue-green infrastructure, it is essential to discuss which population groups benefit less or might even be disadvantaged (e.g. by displacement effects) and how such negative consequences can be prevented (Anguelovski et al., 2019).

The expansion of blue-green infrastructure as part of the Cloudburst Management Plan illustrates transformative urban design in the sense of climate-resilient water management. The reorganization of public space implemented in Copenhagen for long-term crisis prevention indicates that a paradigm shift can initiate structural changes in urban development. In particular, the extensive review of technical and financial feasibility and the involvement of the population can serve as an example for other cities in high-income countries. However, the transferability to low- and middle-income countries with fewer financial and technical resources is limited.

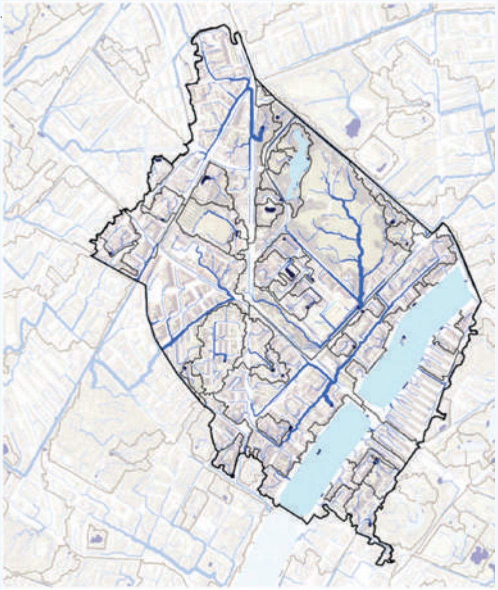


Figure 6.4-2
The 'Cloudburst Management Plan' in Copenhagen as an example of blue-green infrastructure in cities. Left: during heavy rainfall events, Copenhagen, in this case the 'Nørrebro' district, is managed as a coherent water system. Water is retained above ground and drained away in a controlled manner in specially adapted roads. Right: the roundabout on 'Skt. Kjelds Plads' was remodelled by unsealing and planting to create blue-green infrastructure enabling the local retention and infiltration of rainwater.
Sources: Brudler et al., 2016 (left); Negrello, 2022 (right)

Gear water management towards conserving, strengthening and restoring a climate-resilient landscape water balance

In order to be able to efficiently buffer the rising number of extreme events, it is necessary in the long term to restore a climate-resilient landscape water balance everywhere, and to protect and strengthen it where it is still intact. As some of the measures focusing on this only take effect after a time lag, it is necessary to combine them with measures that are effective in the short term without creating undesirable path dependencies. Starting from the integrated landscape approach proposed by the WBGU (2020), an integrated landscape and water-balance approach should be pursued that combines the protection of the climate and biodiversity, land requirements for food security, and the strengthening of natural buffers in the water balance on areas of all types of land use. As the green water stored in soils and plants plays an important role in these buffer functions, it is urgently necessary to give it greater consideration in future water management, and also to take into account the changes in precipitation and evaporation dynamics caused by climate change.

Interlink climate adaptation, water management and ecosystem protection more closely

Intact ecosystems are a basic prerequisite for making greater use of regulating ecosystem services to stabilize the water availability. Safeguarding the functions of water for ecosystems should therefore play a key role in water management in the future. To this end, it can be helpful to integrate Ecosystem-based Adaptation (EbA) approaches into water management, e.g. by dovetailing them with the IWRM approach. Synergies can also result from a closer and better coordinated linkage between the practical fields of water management (especially the implementation of the IWRM approach) on the one hand, and climate adaptation on the other, which currently exist parallel to each other, so that available resources can be used more efficiently, and already established multisectoral structures can be used. Orientation towards existing practical examples can be helpful here (Jimenez and Bray, 2022; UNEP, 2022; de Ruyter van Steveninck et al., 2018). The Water-Energy-Food-Ecosystem Nexus approach (Section 2.4.1.3) should be used to a greater extent to take into account the complex interactions between water, energy, food systems and ecosystems, as well as hydrological, biological, social and technological factors in local water management. On the basis of transdisciplinary research (Section 6.6.1), multisectoral projects at the interface of water management, health systems and ecosystem protection and restoration should be promoted, and their funding facilitated, particularly in low- and middle-income countries.

Diversify water portfolios, establish water reuse and increase flexibility in demand

In order to make the local drinking water supply more resilient in the face of long-term fluctuations in water availability and increasing extreme events such as droughts and floods, it is necessary to use different independent blue-water resources that are redundant and complement each other. Where locally necessary and technically feasible, alternative water resources such as desalinated seawater or recycled water from municipal wastewater-treatment plants should also be used to a greater extent. By doing so, adverse unintended consequences, for example for ecosystems or human health, must be avoided. Wherever feasible, the reuse of water of different quality levels should be made technically possible and already be anticipated in the construction of the water infrastructure and buildings. In order to make more flexible and precautionary management of water resources possible, digital water-information systems should be established across the board to document the dynamic water abstractions by private households, public institutions and industry, so that the supply can be adjusted by the provider, especially in the event of fluctuating availability. In the real-time monitoring of water consumption in households and businesses, artificial

Box 6.4-2

Practical example: use of alternative water resources for irrigating urban green spaces in Schweinfurt (Germany)

The effects of climate change, such as longer periods of drought, changes in the distribution of precipitation, a decrease in soil moisture and falling groundwater levels, also influence the supply of water in cities in Germany (UBA, 2021b). In view of this, a climate-resilient urban water supply of sufficient quantity and quality is urgently needed to ensure the public supply of drinking water and to cover water requirements for cooling and other processes in trade and industry. Furthermore, the demand for water to irrigate urban green spaces has already increased in many places and will continue to rise in the future (Kendzia, 2020).

In the following, the use of alternative water resources for the irrigation of urban green spaces in Schweinfurt (Lower Franconia, Germany) is presented as an example of innovative climate adaptation and water-resilient and resource-conserving urban development. Lower Franconia is a region with an average annual precipitation of less than 500 mm, so it has a very strained water balance in dry years. Water recycling by treating and re-using effluents from municipal wastewater-treatment plants can help meet the increasing water requirements of urban green spaces without further depleting the scarce water resources. For its part, urban greenery plays an important role in climate adaptation – both for stabilizing the water balance and for protecting health and biodiversity.

Apart from establishing decentralized rainwater-retention measures as part of the planned expansion of blue-green infrastructure, the irrigation requirements for urban green spaces, which were previously met by drinking water and local groundwater, are to be replaced by an alternative water resource. To this end, the city of Schweinfurt will treat the city's municipal wastewater in such a way that it can be safely reused. The city's wastewater is currently treated in a central treatment plant with a design capacity of 250,000 PE (9.7 million m^3/year) and discharged into the River Main. By 2027, in anticipation of the new requirements of the EU Urban Wastewater Treatment Directive, the wastewater-treatment plant will be equipped with a so-called fourth treatment stage, consisting of ozonation and biological activated carbon filtration. This results in a significant reduction in the load of organic trace substances flowing into the River Main as the receiving water body. A substream of the wastewater treated in this way is also to be disinfected using a UV system so that it can be reused for various purposes, especially for irrigation (Drewes, 2024).

The treatment, quality and various applications of the recycled water thus obtained have been extensively investigated as part of a project funded by the German Federal Ministry of Education and Research (BMBF) under the WavE funding programme (Future-oriented technologies and concepts to increase water availability by water reuse and desalination). The water quality achieved clearly meets the requirements of the EU regulation on minimum requirements for water reuse, in terms of both microbiological and chemical requirements. It can therefore be used safely for irrigation in sports and leisure areas, parks and green spaces, as an alternative water resource for future neighbourhood-development, for vegetable irrigation in agricultural production and for other commercial purposes (Ho et al., 2024). In Schweinfurt, the irrigation requirements of urban greenery are documented using real-time data on weather conditions and soil moisture, and these areas are thus watered as needed. This makes Schweinfurt the first city in Germany to use recycled water for urban applications across the board.

One challenge in the reuse of municipal wastewater is that there is often a spatial separation between the place of generation (wastewater-treatment plant) and the use (urban area) of this alternative water resource. A separate distribution and storage infrastructure is therefore required. Realizing this by fundamentally converting existing structures is often associated with high costs and with a great deal of effort for construction work. In Schweinfurt, therefore, a new dedicated, approx. 3.5 km long network from the wastewater-treatment plant back into the city was planned for the recycled water, while at the same time using existing structures in a minimally invasive manner: a DN 110 pressure pipeline was inserted into the city's existing main sewer, which significantly reduced the necessary construction work and simultaneously accelerated construction (Fig. 6.4-3; Drewes, 2024).

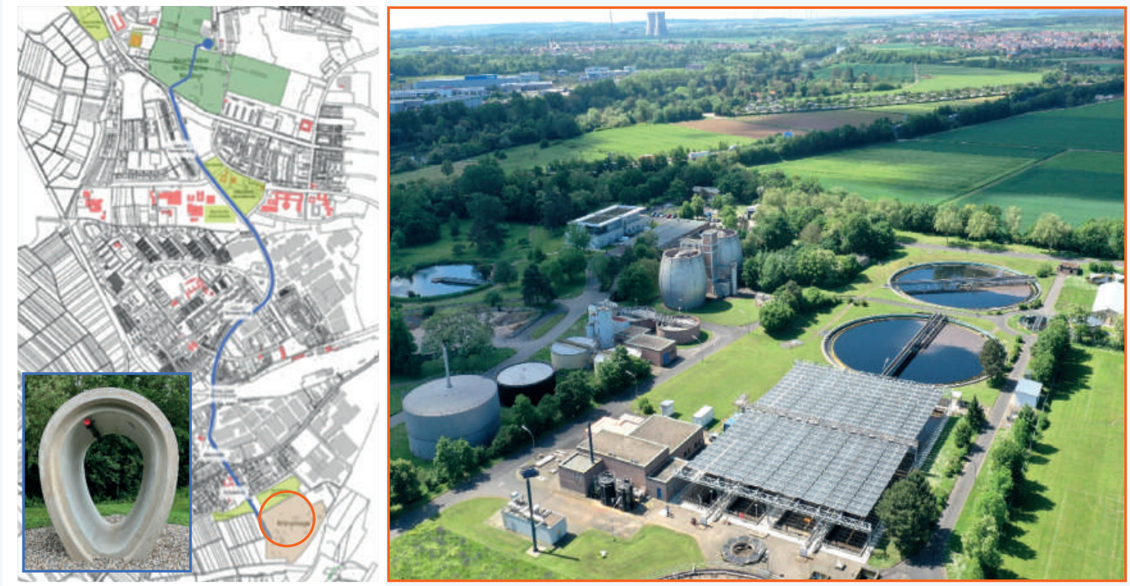


Figure 6.4-3
Distribution of recycled water in Schweinfurt (Lower Franconia, Germany). The treated wastewater is channelled from the wastewater-treatment plant (right-hand photograph and bottom of map) into the city through a DN 110 pressure pipe (left-hand photograph), which was inserted into the city's existing main collector in a minimally invasive manner.
Source: Stadtentwässerung Schweinfurt (map and right-hand photograph); Drewes, TU Munich (left-hand photograph)

intelligence should also be used in the future, although there is still a need for research in this area. Taking into account the water quality required for different purposes, decentralized water storage and water reuse can be established, especially for large consumers, which would contribute to more flexible water abstraction.

Evaluate the efficacy and feasibility, multiple benefits and unintended consequences of measures under increasingly difficult conditions

In order to deal in the short term with increasing extreme events, a broad range of adaptive, fast-acting and resource-efficient measures – from purely technical to more nature-based solutions – should be used in combination with long-term effective measures to restore a climate-resilient landscape water balance. The development, selection, combination, establishment and, where applicable, operation and maintenance of short- and long-term measures should be carried out flexibly according to specific spatial and temporal requirements and framework conditions, and be orientated towards four requirements: (1) the assessment of water-related efficacy on different time scales, with regard to specific water-related objectives and, in each case, with regard to their contribution to restoring a climate-resilient landscape water balance – taking into account uncertainties and impact delays in the given situation; (2) the analysis of feasibility in the respective context, taking into account the availability of technologies, financial resources, institutional capacities, their acceptance and their land and resource requirements – also with regard to long-term operation and any adjustments that may become necessary over time; (3) focusing more on possible multiple benefits for climate and biodiversity protection, as well as health, social and economic benefits and effects on the reduction of inequalities; and (4) avoiding maladaptation and unintended water-related, ecological, health, social and economic consequences by adopting a systemic and transdisciplinary approach. Measures should always be planned and implemented in such a way that technical adaptation to the consequences of climate change during their life-cycle can be realized with minimal effort. The planning bases used to date for infrastructure measures, such as the occurrence of a once-in-100-years flood event (HQ_{100}), must also be adapted on the basis of appropriate research (Section 6.6.1).

Further develop and adopt approaches for the assessment of options under uncertainty

In future, responsible government agencies should take into account the four requirements for the development, selection and implementation of measures in the context of exacerbated water-related challenges when making planning and authorization decisions (Section 6.1.2). Approaches for assessing and comparing different measures under uncertainty should be used consistently, further developed where necessary and their application promoted and encouraged. This requires developing capacities and expertise, especially to support local decision-makers, and the development of standardized, but simultaneously sufficiently flexible procedures. To this end, it is also important to create a legally secure planning basis that allows sufficient consideration of uncertainties and risks without hindering the short-term implementation of measures. The feasibility of complex impact assessments, multi-criteria analyses and processes of weighing up options under uncertainty should also be made possible where financial, institutional and personnel resources are limited, e.g. in low- and middle-income countries or at the municipal level in high-income countries. To this end, simplified versions of the corresponding instruments should be developed that nevertheless optimally fulfil the respective requirements.

Prevent maladaptation and unintended consequences by means of transdisciplinary learning and decision-making processes

When measures are being authorized and planned – and parallel to their establishment and, where applicable, long-term operation – open-ended discussions on possible consequences should be held including all actors and population groups who are involved and affected, as well as with the scientific community, in order to identify possible adverse effects of measures and to be in a position to take countermeasures at an early stage. Barriers to access for marginalized actors should be consistently avoided, for example by offering financial compensation and providing non-discriminatory spaces. The effects of measures should also be continuously evaluated using context-specific indicators. Important elements for developing such indicators are a critical examination of the complex causes of vulnerability and the consideration of the social consequences of measures in modelling and decision-making in the sense of a socio-hydrological approach.

Harmonize the systematic impact assessment of water-management measures

A harmonized impact assessment of measures, based on projections and scenario calculations, evaluation and monitoring tools from various disciplines as well as mapping or visualization platforms, could inform and support procedures of adaptive water management. The assessment of the efficacy, feasibility, multiple benefits and unintended consequences of measures could be carried out by independent scientific experts. This should be done in a discourse with all the actors involved and affected in order to enable transdisciplinary learning and decision-making processes. The results could then be discussed in relevant societal and political forums. Regarding the expert opinions obtained, attention should always be paid to the interdisciplinarity of the scientists involved. The inclusion of social-science disciplines makes it possible to analyse the population's perception of the measures as well as the institutions involved and implementation gaps. Even if such a complex impact-assessment process delays the implementation of the measures, it is urgently needed in view of the complexity of the challenges to be overcome, and should be carried out before the start of, and alongside, the implementation of the measures. Additional resources are needed to integrate systematic impact assessments more closely into water-related decision-making processes. Low and middle-income countries often lack the financial resources to develop and implement such mechanisms; bilateral and international support is needed here. An 'International Water Assessment Centre' already exists within the framework of the UNECE Convention, which also supports the implementation of projects. This could be supplemented by a coordination centre for impact assessment. The International Water Management Institute (IWMI) could act as an intermediary actor to promote methodological harmonization. Exchange platforms based at the International Water Association (IWA) could be created for the placement of regional water experts who carry out analyses of specific measures.

Use windows of opportunity to accelerate transformative adaptation

Transformative adaptation is urgently needed in the water sector, also before crises occur. After unconventional and innovative measures have been explored in real-world laboratories and obstacles to implementation have been identified by transdisciplinary research, successful practical examples and practices should be quickly institutionalized and disseminated. The German federal water-research programme 'Wasser: N' already emphasizes the need for best-practice examples of synergy effects by simultaneously considering multiple benefits of innovative water projects, also to increase their acceptance (BMBF, 2021a: 36). Using windows of opportunity – such as reconstruction after extreme events or large-scale infrastructure measures in cities – can accelerate transformative adaptation. Where possible, water-related measures should be used to simultaneously promote climate-change mitigation and biodiversity protection, and to improve the framework conditions for healthy and sustainable lifestyles, for example in the areas of nutrition, physical exercise and housing (WBGU, 2023: 75 ff.). This is possible, for example, when measures already require structural remodelling in cities. If the needs of disadvantaged groups are taken into account, social and health inequalities can also be reduced by this.

Create cross-border transdisciplinary forums in particularly vulnerable regions

Transdisciplinary forums should be created in areas that are particularly at risk from water emergencies in order to address the upcoming challenges and develop adaptation options together with stakeholders (Section 6.6.1). Structures have already been established within the framework of 'Transboundary Water Management' that can serve as a basis for such negotiation processes. It is important to initiate and strengthen such processes in different affected areas. Such forums could also host a general, science-based discourse on strategy development and options for action under uncertainties.

6.5.2 Recommendations for action for the solution-space ecosystems

As part of the UN Decade on Ecosystem Restoration, ten principles have been developed to support global efforts to restore ecosystems (FAO, 2021). These are of a rather general nature, but are of key importance for the systemic, synergistic and solidarity-based implementation of restoration measures in a multifunctional landscape mosaic (WBGU, 2024).

Promote the restoration of water-related ecosystems at all political levels

The restoration of water-related ecosystems should be given special attention in relevant policy processes at the UN, EU and national level. This explicitly includes water-related activities within the UN Decade on Ecosystem Restoration, the UN Water Action Decade, the 2030 Agenda for Sustainable Development, the Ramsar Convention, the EU Water Framework Directive, the EU Nature Restoration Law and the relevant national strategies, e.g. on sustainability, water and peatland protection. National projects, such as the federal 'Blue Ribbon Germany' (Blaues Band Deutschland) programme for restoring rivers and floodplains, should be further promoted to ensure that the goals can be achieved sustainably in the long term.

Promote the German Federal Action Plan on Nature-based Solutions for Climate and Biodiversity over the long term and implement measures decisively

The fields of action described in the German Federal Government's 'Federal Action Plan on Nature-based Solutions for Climate and Biodiversity' (Aktionsprogramm Natürlicher Klimaschutz, ANK) highlight a wide range of options for contributing to ecosystem restoration. The overview of measures shows, among other things, how to work towards a climate-resilient water balance in various ecosystem types. The restoration of a climate-resilient landscape water balance should also include the restoration of alluvial forests and meadows and, where appropriate, gallery forests with their ecological functions and ecosystem services, e.g. for increasing the water-retention and storage function in the landscape, or for settlement-free floodplains. The ANK also offers orientation on water-related research and a possible international contribution from Germany. One example of the measures mentioned in the ANK is the implementation of peatland protection as part of the National Peatland Protection Strategy. The strategy very comprehensively presents measures for the conservation, restoration and sustainable use of peatlands. The WBGU recommends promoting the ANK and related relevant strategies in the long term because of their great multiple benefits, and implementing the measures it contains promptly, which would also serve the interests of climate-resilient water management.

Initiate an early dialogue with land users, residents near restoration areas, and other stakeholders

In line with an integrated landscape approach (WBGU, 2020), an early dialogue in the planning process on restoration measures with all land users, residents near areas to be restored and other stakeholders is recommended. In this way, conflicts can be avoided, multiple benefits increased and the acceptance of restoration enhanced. Interdisciplinary and transdisciplinary supervision of the measures by experts from the fields of ecology, hydrology, agriculture and sociology can also be valuable. The implementation of the measures should follow a mosaic approach to spatial planning on a large-scale (WBGU, 2024).

Plan restoration measures with a view to the multifunctionality of the entire river system

Applying the mosaic approach (WBGU, 2024) leads to diverse river and floodplain landscapes with high biodiversity which fulfil such diverse functions as water-level stabilization, water purification, groundwater formation and regeneration, CO_2 sequestration, and the provision of habitats or recreation areas. In this way, sustainable use can be made possible along the entire river network – i.a. for shipping, fishing, tourism and drinking-water supply – and a near-natural, harmonious appearance can be restored.

Encourage the removal of barriers from river courses

In order to restore the connectivity of river courses and to make far-reaching ecological and water-related multiple benefits possible, barriers in river courses should be removed wherever expedient and possible. This not only applies to dismantling large structures (> 10 m, e.g. dams); the removal of smaller barriers (< 2 m) can also have an impact. It is often less costly and may be more readily accepted by society (Belletti et al., 2020). Dismantling or removing barriers in rivers is particularly important in view of the EU Biodiversity Strategy's goal of restoring 25,000 kilometres of free-flowing rivers by 2030 (compared to 2020). This goal is also referred to in the EU Nature Restoration Law.

Consider the possibility of emerging novel ecosystems in restoration measures and spatial planning

Sometimes the structure and function of an ecosystem after a restoration measure does not correspond to its initial state, so that novel ecosystems can even emerge. Such developments should always be taken into account when considering restoration measures and spatial planning. The expected – and in some cases already observed – dynamics in the development of novel ecosystems should lead to a reflection on the legally regulated 'good ecological status' (e.g. in the EU Water Framework Directive). This can possibly even mean an addition involving restoration to increase the resilience of ecosystems. Moreover, the range of different development possibilities of ecosystems following restoration measures should be communicated to stakeholders and the public, and various expectations of the target status should be discussed together in advance (Bellmore et al., 2019).

Use adaptive management for restoration projects

Adaptive management incorporating regular monitoring and robust modelling can help to anticipate the processes of ecosystem restoration and, if necessary, take timely follow-up measures. The success of restoration measures – e.g. in terms of sustainable gains in biodiversity and ecosystem services as an indicator of the health of affected water bodies – should be tracked by monitoring using scientifically proven methods.

6.5.3 Recommendations for action for the solution-space agriculture

Data collection on abstraction quantities, water-availability projections and a digitalization campaign for agriculture

On the one hand, the (real-time) collection of abstraction volumes and data on the status of groundwater bodies should be improved. On the other, projections and (real-time) data on water availability, potential demand and actual abstractions and consumption should be improved or collected and made available for the optimization of water use by individual farmers and as a transparent basis for overarching planning and regulation. Both should be part of a broader digitalization campaign for agriculture and, for example, be integrated into existing federal and state digitalization programmes in Germany (BMEL, 2022a, b). In order to improve publicly available local projections and the scientific monitoring of adaptation measures, appropriate capacities for agriculture and other sectors must be developed, in Germany for example at the level of the federal states (e.g. for assessing water-related investment risks; Section 8.3.1, Section 8.5.3.1).

Impart knowledge on water-related adaptation measures in agriculture and build best-practice networks

Farmers should be provided with knowledge and skills for climate-resilient water management in their training and further training via advice centres, specific training courses and with the help of support teams. Farmers should be involved in the further development of water-related adaptation measures to ensure their practicability. Alongside research on adaptation measures, greater emphasis should also be placed on the exchange of experience between regions and the use of knowledge from middle and low-income countries that have experience with relevant practices. In these countries themselves, e.g. in Sub-Saharan Africa, the potential of local knowledge systems should be better used in local adaptation and transformation strategies for agriculture (Filho et al., 2023). Corresponding advisory services and networking activities could be further expanded internationally, for example by the German International Cooperation Society (GIZ), and in Germany by the Federal Office for Agriculture and Food (BLE, 2024).

Integrate land actors and water actors in a joint management regime

Local 'blue-water actors', e.g. water suppliers or water authorities, should be brought together with 'green-water actors' – i.e. primarily land users – in a joint water-management regime based on an integrated landscape and water-balance approach (WBGU, 2020; Section 6.5.1). In this way, a systemic view of blue and green water can be ensured in the context-specific selection of water-related adaptation measures and nature-based, land-related climate-change-mitigation measures. Such integration is often still lacking, particularly at the local level, also in Germany (LAWA, 2022). In some cases, self-organized structures can also contribute and be promoted (Section 8.5.2). Local governance platforms with the participation of land and water users can also help to organize financial compensation mechanisms or external funding for joint projects (Section 8.5.3).

Create financial incentives and secure transformation efforts

Based on improved data, compensation mechanisms between land users and water users, e.g. water funds, should be established for water-relevant measures (Section 8.3). Agricultural subsidies should be reformed in a water-sensitive manner. If necessary, they can provide start-up or bridging funding for measures that have mainly long-term impacts, and can therefore be integrated into the above-mentioned compensation mechanisms. Furthermore, agricultural subsidies should be linked to the provision or safeguarding of common goods, including the reduction of water-related climate-change risks for the general public and ecosystems. In the EU, this affects the next cycle of the Common Agricultural Policy (CAP) starting in 2028, which should be reorganized into a Common Ecosystem Policy (CEP; WBGU, 2020). As cooperation between farmers and the public sector is essential when it comes to water risks, such a reform of agricultural subsidies could generate new leeway for negotiation. In addition, structures should be created in which farmers can try out sustainable and water-friendly methods, while society partially takes on the risk of yield reductions. This risk assumption could, for example, take the form of temporary flat-rate income support linked to the fulfilment of certain conditions, partial hedging or insurance of reduced yields when new methods are used, or the support of model farms with a new business model. Finally, the measures mentioned should also support a possible regulation or pricing of actual water abstractions and consumption on the basis of improved data, while keeping the social balance in mind. In the case of measures to encourage more efficient water consumption, rebound effects should be anticipated and, if necessary, addressed through regulation.

6.5.4 Recommendations for action for the solution-space cities

Establish climate-resilient urban water management everywhere

Urban infrastructure should be designed from scratch in accordance with the guiding principle of water-sensitive urban design in such a way that it promotes the urban water cycle and does not hinder it. In the long term, a water-sensitive urban design should aim to integrate urban water cycles into the natural landscape water balance of the entire water-catchment area. It is essential to consider medium and long-term climate projections under different scenarios in water management. Synergies between water-sensitive urban design and the reduction of the urban heat-island effect should be specifically targeted and used. In addition, ensuring urban quality of life and reducing social inequalities should always be considered essential contributions to improving urban climate resilience. Large-scale water-related infrastructure measures can also offer windows of opportunity to improve the framework conditions for healthy and sustainable lifestyles, for example by redesigning the road space accordingly.

Rapidly drive forward the development and improvement of climate-resilient urban water infrastructure

In view of the increasing exacerbated water-related challenges in many places, there is an urgent need to accelerate adaptation to climate change in cities around the world. This includes, in particular, the establishment of climate-resilient water management and the development and improvement of water-related infrastructure, whereby different measures can be combined in hybrid approaches, and the four requirements for the development, selection and implementation of measures should be taken into account (Box 6.1-1). Especially in fast-growing cities, the development and improvement of water-related infrastructure must be significantly accelerated, in order to keep pace with the rapid, often informal growth (especially in Africa and Asia). Special consideration should be given to informal neighbourhoods where, for example, decentralized and non-piped sewage systems can be used. The local population should be involved in planning and implementing these systems, informed about health benefits, and the capacities of previously informal service providers should be strengthened. Financing the development and improvement of climate-resilient urban water infrastructure in low- and middle-income countries should be increasingly promoted in bilateral and multilateral development cooperation.

Prevent negative consequences of blue-green infrastructure and avoid displacement effects

In order to prevent maladaptation and an increase in vulnerability and existing inequalities, care should be taken to avoid negative social, health and ecological consequences when developing and improving blue-green infrastructure in cities. The vegetation, for example, should be suitable for expected changes in the climate and have a low allergenic potential. Adequate measures should also be taken to prevent the displacement of disadvantaged population groups by the economic upgrading of neighbourhoods and the formalization of informal spaces. In order to be able to provide additional health and social benefits of blue-green infrastructure to disadvantaged population groups, urban green spaces should be sufficiently available, accessible and tailored to their needs; this requires transdisciplinary and collaborative planning processes and transparent financing.

Consideration of long-term water risks in all urban infrastructure measures

The public sector plays a key role in the provision of water-critical and water-sensitive urban infrastructure in basic public services such as drinking-water supply or flood protection via direct or indirect participation. The German government should support efforts to take greater account of water-related risks in existing procedures for assessing investments and projects, for example in procurement or tenders. This can increase the resilience of public infrastructure and raise risk awareness among private individuals, companies and administrations. International initiatives within the framework of the UN Development Programme and the Global Water Partnership already aim to integrate water-related risks more closely into national climate-change-adaptation plans, for example by providing guidelines for governments, and can serve as orientation (GWP, 2019; FAO, 2018). As part of the Climate-ADAPT initiative, the EU promotes and pools overarching initiatives to enable cities, companies and private individuals to promote measures to build resilient infrastructure and adapt existing assessment standards to water-related risks (EEA, 2024a). These efforts should be stepped up in future and can serve as a model. The federal 'Water: N' research programme in Germany also refers to the important role of research in flood protection (Section 6.6.1), e.g. through the development of improved planning instruments, forecasting models and assistance for flood-adapted urban planning (BMBF, 2021a: 33).

Develop emergency plans for urban water shortages

The number of cities that have declared a state of emergency due to water shortages is rising worldwide. Barcelona, Montevideo, Cape Town, Chennai and São Paulo are examples from the recent past (Section 4.2). The intensifying lack of water in cities and urban agglomerations is a growing global problem affecting many people; if left unresolved, it holds considerable potential for destabilization. This problem therefore deserves to be paid greater attention in international sustainability policy and requires forward-looking action, taking long-term forecasts and scenarios into account. Cities should develop action plans to increase the resilience of urban water supplies. Examples include a group of six African cities that are already trialling such approaches (Addis Ababa, Dire Dawa, Kigali, Musanze, Johannesburg, Gqeberha; Kuzma et al., 2023). The development of urban action and emergency plans is not only a task for the affected municipalities; international development actors are also called upon to provide financial and programmatic support (e.g. bilateral and multilateral development cooperation, World Bank, Asian Development Bank and African Development Bank).

Keep an eye on water-related limits to urban growth

Progressing climate change will confront many cities with existential water-related challenges, many of which are barely being addressed today. In particular, cities that will not be able to effectively solve the problem of water scarcity in the medium and long term with infrastructure measures alone (e.g. New Delhi, Lahore or Lima) should, after exhausting all other means, examine options for limiting urban growth or, in extreme cases, options for an orderly retreat in good time. International institutions should provide support to affected municipalities in low- and middle-income countries. The medium and long-term limits of urban expansion and the 'limits to growth in cities' should also be given greater consideration in research.

6.6 Research recommendations

6.6.1 Overarching research recommendations

Planning and decision-making processes under uncertainty

Systemic research is needed to clarify how existing structures and processes for planning and decision-making need to be changed to make it possible to implement measures that do justice to the exacerbated water-related challenges. The following questions are of particular importance: How can the interests potentially affected by planning and decision-making be identified, taken into account and weighed up when it is increasingly difficult to predict which interests will be affected and to what extent? Which actors are legitimized to make planning decisions when planning has to react more flexibly and quickly to changing conditions, and the decisions made in the process are becoming increasingly severe for those affected? What implications does an appropriate consideration of green water have for planning and decision-making processes? What implications does the continuously changing climatic variability have for planning and decision-making processes, particularly for the necessary forecasting decisions of the planning authority? What would planning and decision-making approaches that take account of permanent planning uncertainty ideally look like?

Instruments and indicators for quantifying different water demands under non-stationary conditions

Instruments and indicators should be developed to quantify the water demands that need to be met to guarantee various functions of water for humans and ecosystems (and thus for the preservation of ecosystem services). They should be suitable for identifying the need for action for ensuring the water supply in the short, medium and long term on the basis of currently collected data, data from the past, qualified future projections under various scenarios, and with the aid of artificial intelligence. Existing instruments and models must be expanded to better take uncertainties into account. In addition, (proxy) indicators should be developed to assess whether the various functions of water for humans and ecosystems are guaranteed locally and regionally. For the indicators mentioned, measurement methods are needed that can be implemented as comprehensively as possible with little technical effort, and can serve as a basis for projections of future developments. It is conceivable, for example, to combine remote sensing methods with stationary measuring stations, if possible using existing infrastructures and continuously collecting data. In the context of the multifunctionality of water, the development of instruments and indicators should also take into account overlaps between the water demands of different water functions, the possible multiple use of water resources for different functions, and water-quality requirements. The effects of large-scale technological infrastructure projects (e.g. large dams or aqueducts), geo-engineering (e.g. ‘cloud harvesting’), large-scale irrigation projects and land-use changes with potentially transboundary impacts on evaporation and precipitation should be assessed by appropriate research.

Context-specific indicators for assessing measures

Existing indicators for the assessment of measures, which can be used during their development, selection and combination, as well as when they are being established and, if applicable, during their operation and maintenance, should be further developed on a scientifically sound basis. The indicators should be suitable for assessing the efficacy and feasibility of measures, their multiple benefits and unintended consequences under dynamically changing conditions and on different time scales, taking uncertainty into account (Section 6.1.2). They should also be customizable for specific contexts in order to meet local requirements and framework conditions. Furthermore, systematic instruments should be developed that make it possible to weight different indicators and criteria in a manner that is flexibly adaptable to local requirements, that can be used in transdisciplinary and collaborative decision-making processes.

Approaches and tools for combined environmental and health-impact assessment

Evidence-based instruments for the combined health and environmental impact assessment of measures are needed to avoid unintended consequences, identify potential multiple benefits and promote climate-resilient water balance. Among other things, these instruments should draw on findings from ecotoxicological, epidemiological and Earth-system science, work with foresight, and also take possible future developments into account. To this end, the data basis should be strengthened, and conventional methods of technology assessment should be combined with innovative digital methods (e.g. artificial intelligence), as well as with models from climate-impact research and Earth-system analyses. This can improve the scientific basis for a harmonized impact assessment of measures (Section 6.5.1).

Evaluation of implemented measures, causes of vulnerability and maladaptation, and ways of avoiding them

In order to avoid maladaptation and promote agile policy adaptation, on the one hand more research projects should be funded to evaluate the impact of policy measures. On the other hand, (already implemented) practical water-related climate-adaptation measures, including short-term technical adaptation measures, should be systematically evaluated in terms of their water-related efficacy and their effects on vulnerability. Appropriately qualified approaches and instruments should be developed through research. In addition, the adaptation of planning bases for infrastructure measures used to date, such as the occurrence of a once-in-100-years flood event (HQ_{100}), should be informed through research (Section 6.5.1). Research into water-related infrastructures and management strategies adapted to climate change is one of the aims of the Future Research and Innovation Strategy of the German Federal Ministry of Education and Research (BMBF, 2023: 49). One focus should be on using transdisciplinary research and an intersectional approach to explore the context-specific causes of maladaptation and vulnerability, and to develop ways of preventing or reducing them. This also requires more critical social-science research on the role of power relations in the (re-)production of vulnerability and on the influence of the professional and social background of scientists on research methods and results. In addition, the social consequences of measures should be systematically taken into account in modelling and decision-making in the sense of a socio-hydrological approach. The German federal water-research programme 'Water: N' offers valuable starting points for this and emphasizes that, in addition to technical aspects, socio-ecological, ethical and legal aspects must also be increasingly taken into consideration (BMBF, 2021a: 36).

Evaluation of existing, and development of new, multisectoral projects in low- and middle-income countries

Existing multisectoral projects at the interface between water management, health systems and ecosystem protection and restoration, particularly in low- and middle-income countries, should be systematically evaluated by means of qualitative and quantitative transdisciplinary research. In particular, the effects on various overlapping vulnerability factors should be assessed. For successful projects, possibilities for long-term funding and institutionalization, as well as context-specific dissemination, should be researched and implemented. The need for best-practice examples is also highlighted in the German federal water-research programme 'Wasser: N' (BMBF, 2021a: 36). Established transdisciplinary or multisectoral approaches such as Planetary Health, One Health, and Population, Health, Environment (PHE) should be used for the development and implementation of new multisectoral projects, depending on the specific challenges and context. There is an urgent need for research into how Indigenous, local and traditional knowledge can be meaningfully incorporated on an equal basis into the development and implementation of such projects – as is increasingly being demanded but has hardly been realized to date. Since in many low- and middle-income countries local water management shows a clear social-group- and gender-specific differentiation with regard to the use of and responsibility for water resources, which in most cases contributes to increased vulnerability of women and gender-diverse people (Fröhlich et al., 2018), a rights-based and gender-transformative approach should always be pursued in multisectoral projects. A rights-based approach to resource governance is based on the three principles of participation, accountability and non-discrimination, and has developed from the interdisciplinary discourse on human rights, the goals of the 2030 Agenda for Sustainable Development, and transnational resource governance (Tambe, 2022).

Explore regional adaptation options in the water sector across the board

The regionally specific adaptation options of a society or an ecosystem depend on many factors. Possible adaptation measures should be systematically evaluated and, where necessary, newly developed – worldwide and especially in areas at high risk from water emergencies. Various factors should be taken into account: regionally available water quantity and water quality, observed and projected developments of extreme events under different scenarios, prevailing land use and pressure on land, regionally specific impacts of climate change, biodiversity loss and pollution, economic capacity, regional and social-group-specific vulnerabilities and coping capacities, technological possibilities and existing (water) infrastructure, societal awareness and willingness to adapt, prioritization of water uses, political framework conditions and available or necessary international support. Moreover, regionally different probabilities of 'overload' and dysfunctionality of the existing water infrastructure should be determined.

Measures to maintain, strengthen and create storage capacities in the water cycle

The loss of reserves (e.g. base flows from glaciers and permafrost soils as well as due to groundwater overuse), the increasing variability of precipitation and increasing extreme events play a key role in many exacerbated water-related challenges. Research should be carried out into how existing and new buffer capacities – especially soils and vegetation, aquifers and lakes or artificial reservoirs – can be maintained, improved or newly created (e.g. through adapted agricultural practices, groundwater recharge), to what extent they can contribute to mitigating the situation (especially if they are based on green water), and how ecological, climatic and social trade-offs can be dealt with (e.g. in reforestation, restoration of floodplain landscapes). Examples of technical buffer systems include hydropower reservoirs for water storage in hot and dry months, but also artificial ice reservoirs, which could represent local and medium-term adaptation strategies (e.g. ice stupas; Hock et al., 2019; Maharjan et al., 2023). Further research is needed to assess whether existing and planned measures are sufficient or appropriate, and to weigh up the advantages and disadvantages of such measures. The interaction of blue and green water to ensure buffer functions requires a better understanding and joint balancing and quantification of water flows, especially in view of changing water supply. This applies regionally and across national borders, because a balanced ratio between green and blue water is necessary, both for regional water cycles and for the global water cycle, to ensure that different water demands and required precipitation levels are met. Possible balancing approaches to improve buffer and storage capacities should be examined along the entire water cycle at the catchment-area level, and adapted measures developed on this basis.

Measures to guarantee the water supply in the case of decreasing groundwater availability

Technical water-recycling measures in combination with artificial groundwater recharge can help to support and accelerate the process of natural groundwater recharge, stabilize ecosystems and bridge peaks in supply and demand (i.e. feeding in surpluses during heavy rainfall and providing water in the event of deficits in times of drought). This can be achieved, for example, by recharging aquifers for irrigated agriculture with purified wastewater or with water from floods (successful practical examples include Morocco), as well as the development and use of technologies for water conservation and advanced wastewater treatment. Monitoring land-use changes by remote sensing, e.g. by satellite, could help identify sources of pollution and overuse and support the setting of consumption-based water fees to create incentives for the efficient use of water. This has already been implemented, e.g. as part of economic solutions in the Jordanian highlands and the Azraq oasis (Houdret and Heinz, 2022; World Bank, 2018). There is an urgent need for research into the context-specific design of such and similar measures.

Digitalization for more efficient management of water supply and water demands

Particularly in regions with strained water supplies, it is necessary to better document the demands of private households, trade and industry in terms of time and space, ideally in real time. Such digitalization enables a more flexible and precautionary management of water resources. To this end, research is needed into identifying the proper density of measurement points for the collection of data on water abstraction, ethical aspects of data collection, data processing, data security and provision, as well as possibilities for using artificial intelligence. Customized digital solutions should take into account the various framework conditions in countries with different income groups.

6.6.2
Research recommendations for the solution-space ecosystems

Research on hydrological prerequisites for the restoration of water-related ecosystems under climate change is essential to understand and predict the water dynamics of the respective ecosystem, and to ensure that the restoration of a climate-resilient landscape water balance is successful without negatively impacting surrounding areas. In particular, consideration should be given to the potential for achieving multiple benefits, such as reducing the costs of the measures taken and simultaneously improving biodiversity, through 'revegetation'(i.e. re-greening) and 'rewilding' (i.e. allowing natural processes to resume).

Give greater consideration to water-related issues and ecosystems in the German Future Research and Innovation Strategy

The perspective of the water supply and the protection and restoration of water-related ecosystems, especially freshwater ecosystems, should be given greater consideration and more closely integrated into the German Federal Government's Future Research and Innovation Strategy. For example, the mission entitled 'Advance climate protection, climate adaptation, food security and the conservation of biodiversity' could also include the importance of swamps, marshes and alluvial landscapes for climate-resilient water management in addition to the above-mentioned peatlands and forests.

Expand research into swamp and river landscapes

In order to do justice to different usage requirements of river courses and landscapes, more research is needed for the analysis of their diverse ecosystem services, also in view of different restoration measures. The RESI project of the ReWaM funding programme by the German Federal Ministry of Education and Research, for example, is making a contribution here. The findings gained should be incorporated into multifunctional spatial planning. In particular, the conservation of aquatic ecosystems in the face of climate change requires knowledge of ways to ensure the continuous supply of high-quality water, also in view of possible competition to meet the water needs of neighbouring agricultural areas.

Promote long-term studies on water input into raised bogs

A sufficient input of water from precipitation or other inflows is a prerequisite for the permanent revitalization of peatlands. This may no longer be guaranteed in a changing climate. The use of alternative, nutrient-poor water resources for the rewetting of peatlands should therefore be investigated. Furthermore, the further typification and mapping of peatlands also requires important research in order to effectively monitor, protect and restore peatlands and their contribution to climate-change mitigation and the conservation of specific biodiversity. For example, only about a third of the peatlands in the tropics have been mapped to date (Gumbricht et al., 2017).

Long-term studies on the removal of barriers, especially large dams, from river courses

There is still a lack of adequate long-term studies on the diverse effects of removing barriers, especially larger dams, from river courses, and on the comparison between the ecological status before construction, after construction and after removal of the barriers (Bellmore et al., 2019; Duda and Bellmore, 2022; Magilligan et al., 2021). Such research and monitoring projects should be initiated and supported in the long term. Care should also be taken to ensure that the projects are representative of different environmental conditions.

Boost socio-ecological research on the restoration of ecosystems

The services provided by water-related ecosystems and the influences of management and restoration should be comprehensively investigated, taking into account social factors and impacts. Furthermore, methods for the effective implementation of the integrated landscape approach for water-related ecosystems should be researched and the findings made available.

6.6.3 Research recommendations for the solution-space agriculture

New guiding principles and occupational profiles for agriculture and the practical further development of adaptation measures

If the climate targets in agriculture, including those relating to water, are successfully implemented, a transformation of the farming profession can be expected in the coming years. This will vary from region to region depending on the climatic and water conditions. In countries where agriculture is highly industrialized, for example, the occupational profile of farming with agroforestry still needs to be developed in detail. In view of rapidly advancing climate change, the simultaneous further development of water-related adaptation strategies and measures should begin with diverse approaches and be accompanied by practical research. Learning from experience, direct implementation and the continuous further development of regionally appropriate approaches will take centre stage. Last but not least, it will be important to understand how agricultural productivity will change in the course of sustainable management that takes climate and water into account, and how productivity can be secured.

Improve understanding of the feasibility, effectiveness and capacity of water-related adaptation measures in agriculture

For a better understanding of the feasibility, effectiveness and region-specific potential of water-related adaptation measures to mitigate climate-change-related risks today and in the future, instruments and metrics for measuring feasibility and effectiveness should be further developed (Caretta et al., 2022). Adaptation options such as changes in behaviour or capacity-building measures often cannot be covered in current climate and impact models. Suitable downscaled climate and impact models are needed that take into account economic, social, cultural and management aspects for a wide range of future adaptation options. When analysing adaptation options, multiple benefits for and trade-offs with sustainable development should also be taken more into account.

Improve mapping of the potential and limits of irrigation as an adaptation option

Especially global agricultural models that show possible yield increases through irrigation often do not take sufficient account of local water supply. Their assumptions about the effects of expanding irrigation may therefore be unrealistic (Caretta et al., 2022; Elliott et al., 2014). Water supply should be better integrated into these models in order to better understand the potential and limitations of irrigation to mitigate climate-change-related risks.

Improve understanding of interrelationships in the water-energy-food-ecosystem nexus

The improvement of the water-related data situation and the knowledge base in agriculture should be used to better understand how the interrelationships in the water-energy-food-ecosystem nexus change due to the exacerbated water-related challenges, and to project the changing water demands of different sectors under different climate conditions. This requires the development of systematic instruments for addressing and quantifying multiple benefits and trade-offs, e.g. with regard to ecosystem services, which is also important for projections (Section 2.4.1.3; Caretta et al., 2022; UNESCO IHP, 2022: 33; Liu et al., 2017, 2018).

Understand the shift and composition of future agricultural and forest ecosystems and adopt this knowledge in the mosaic approach

In some cases, climate change leads to a shift in habitats, connected with species migration and spatial shifts of e.g. managed agricultural and forestry or natural forest ecosystems, mainly to higher latitudes or locations. In this way, species and ecosystems more or less retain their previous temperature regime, but may have to adapt to new environmental conditions. These change processes and the role of water in them should be researched, as should opportunities, barriers and suitable measures to promote gradual adaptation in the ecosystem context, e.g. via changes in spatial planning to implement the mosaic approach, taking into account local water supply.

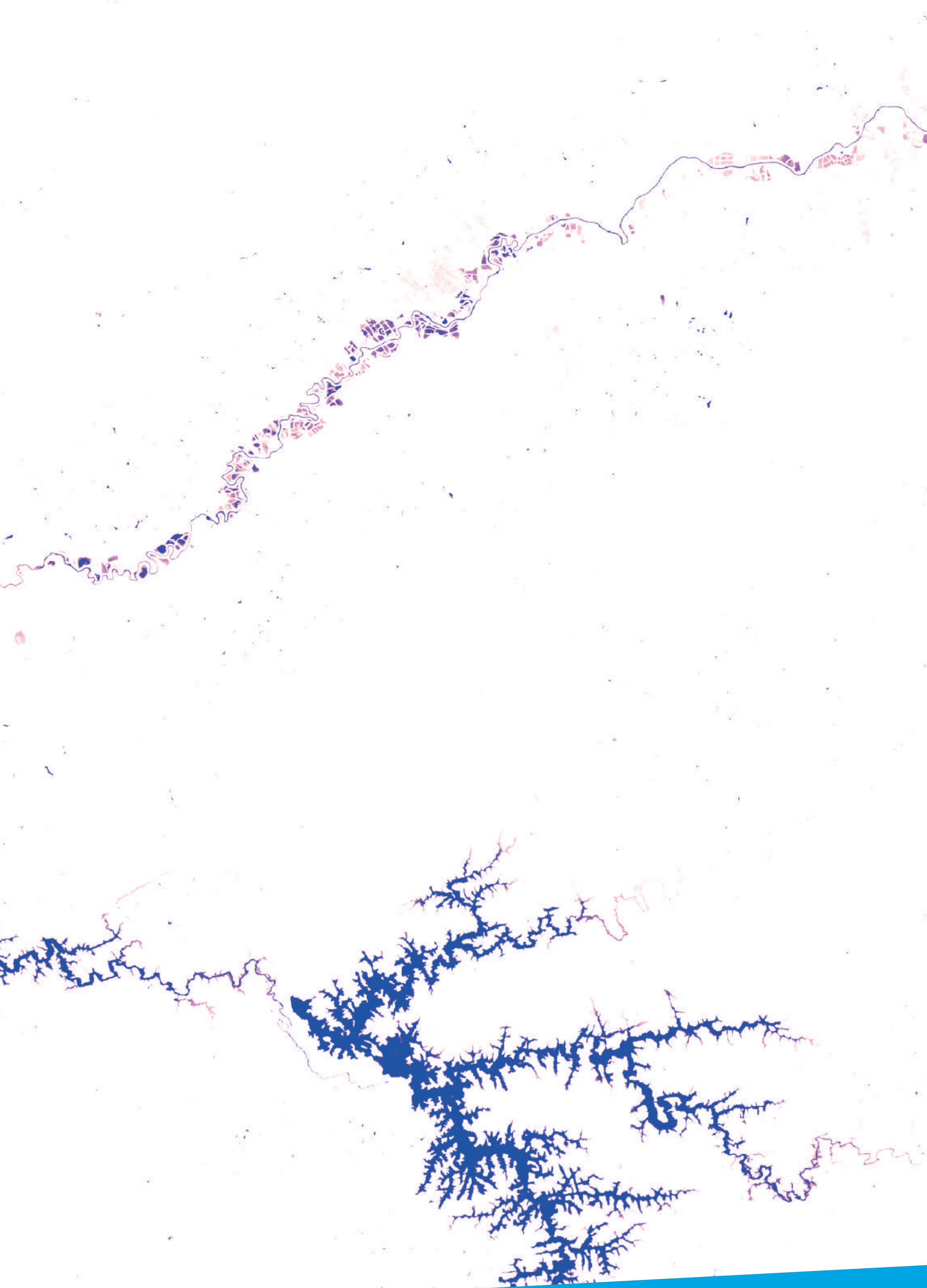
6.6.4
Research recommendations for the solution-space cities

Urban water shortages and global urbanization dynamics

In this age of urbanization, more and more cities are confronted by seasonal or permanent water shortages. The causes are limited water resources as urban growth accelerates, global climate change, the growing urban population and deficits in political and planning decisions, and decisions on building infrastructure. On the one hand, the measures for coping with water shortages are sufficiently well known, but there is first and foremost a lack of effective implementation of suitable adaptation measures. On the other hand, urban societies are faced with potentially existential challenges which, in extreme cases, lead to fundamental decisions, e.g. limiting the number of people moving to cities – or retreating in the event of imminent uninhabitability if, for example, a lack of water threatens to massively impair the quality of life. There is therefore an urgent need for research on the effective implementation of known – and the development of new – adaptation measures, on ways of overcoming the deficits mentioned, and on decision-making processes in the extreme cases described.

Adaptation measures in existing buildings and infrastructure

Transformative adaptation measures in the context of climate-resilient water management in cities that already have an existing infrastructure require innovative approaches in order to integrate resilience-enhancing solutions into existing buildings and infrastructures. In particular, the following questions should be investigated: How can new water-supply concepts be realized in existing buildings and infrastructure in the least invasive and most cost-effective way possible? How can synergies with requirements for further wastewater treatment (e.g. the required removal of organic trace substances as part of the new EU Urban Waste Water Treatment Directive) be used in order not only to relieve the pollution burden on water bodies but also to provide alternative water resources? The Water: N research programme offers valuable starting points here and points to great potential for sustainable and safe water reuse with regard to treated municipal wastewater (BMBF, 2021a: 30). The Future Research and Innovation Strategy of the German Federal Ministry of Education and Research (BMBF) furthermore emphasizes the potential importance for urban food systems (BMBF, 2023: 48).



Protection of water quality

7

Poor water quality caused by pathogens, chemicals, nutrients and heavy metals is harmful for people and ecosystems. The zero-pollution target should be achieved by avoiding pollutants and establishing a circular economy. Important building blocks are the global dissemination of the EU Regulation on the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) and the EU Urban Wastewater Treatment Directive, the reduction of substance discharges, the establishment of alternative wastewater-disposal concepts in low-income countries and the recovery of raw materials from wastewater.

Human activities impair the quality of water resources, as they cause the release of pathogenic microorganisms and a variety of dissolved and transported pollutants. This leads to significant adverse consequences for the health of humans and ecosystems worldwide (Section 2.3.3).

The consequences of climate change are exacerbating this situation (Section 3.1.4; Section 4.5). Extreme events show particularly clearly that water quantity and quality are closely linked and should not be considered separately: on the one hand, floods can lead to the mobilization of pollutants (van Vliet et al., 2023); on the other, pollutant-laden discharges of municipal and industrial wastewater and runoff from agricultural land are only slightly diluted during periods of drought and low levels in surface waters. The higher concentration of pollutants in receiving watercourses also leads to a lack of oxygen for aquatic organisms and to the qualitative pollution of the drinking-water supply (Rice and Westerhoff, 2015; Karakurt et al., 2019). In the summer of 2022, the massive proliferation of a brackish water alga (Prymnesium parvum) and the resulting fish die-off in the River Oder revealed the devastating effect of the discharge of pollutants in the form of salts into a body of water that was already under stress due to high water temperatures and low water levels.

This close link between water quantity and water quality plays a key role in the fulfilment of a variety of water functions. As drinking water, water is the most important foodstuff. At the same time, it is also a means of transport, for example in water-borne sewage systems for faeces and other waste from settlement areas. The resulting large concentrations of pollutants in the water, as well as additional discharges from trade and industry, e.g. the textile industry, regularly overtax nature's self-purification capacity. Adequate wastewater treatment is therefore required. Within plants, in addition to providing H_2O and transpiration, water also ensures the supply and removal of nutrients and other reaction products. After being released into the soil, groundwater or surface water, nutrients are mineralized and thus become available to plants. Water is also a carrier of energy: hydroelectric power stations use the kinetic and potential energy of water from elevated locations; thermal energy in water is used in geothermal energy and in cooling towers by evaporative cooling.

Water is thus a cross-cutting issue that plays an important role in a large number of areas and thus creates high levels of dependency. The vital functions of water and its cycles outlined above reach their limits when pollutants can no longer be removed from the water cycle or accumulate in environmental media. Especially problematic are substances that are both persistent and toxic and accumulate in the food chain (PBT substances: persistent, bioaccumulative, toxic) or are very mobile (PMT substances: persistent, mobile, toxic) and can spread over large distances.

In order to comprehensively and effectively combat the ever-increasing pollution of air, water and soil, in

Rio Paraíba do Sul (Brazil)

particular by PBT and PMT substances, the EU Commission has formulated the Zero Pollution Action Plan for Air, Water and Soil as part of the European Green Deal, which sets a zero-pollution target by 2050 (Europäische Kommission, 2021). Zero pollution means that pollution is reduced to a level that is not harmful to the health of humans or ecosystems. The concept of the circular economy is important for achieving this goal. Many harmful substances that are essential for technical processes cannot as yet be substituted. Especially in the case of persistent compounds, it is therefore necessary to keep them in technical cycles in future. The goal of the circular economy was formulated by the EU Commission in the Circular Economy Action Plan (Europäische Kommission, 2020). It focuses on the transition from a linear to a circular economy by promoting the sustainable use of resources, reducing waste and supporting the reuse and recycling of products and materials.

Both the Circular Economy Action Plan and the Zero-Pollution Action Plan for Air, Water and Soil are legally non-binding political strategies and part of the European Green Deal. They require further specification by subsequent measures such as the adoption of directives and regulations.

In its flagship report 'Healthy living on a healthy planet', the WBGU recommends establishing the zero-pollution guiding principle and the circular economy required to implement it internationally (WBGU, 2023: 186). In view of water's transport function in the spread of environmentally relevant substances, as explained above, this recommendation is reaffirmed here. The current challenge is to implement the guiding principles of zero pollution and the circular economy to maintain water quality in water cycles, both in high-income and low- and middle-income countries.

The approaches for protecting water quality range from avoiding substances in product manufacture to establishing closed cycles for substance recovery and regulating application practices in agriculture and treatment processes to minimize substance emissions (Fig. 7.1-1). Which of these approaches is actually necessary depends on the type and source of the pollutants.

Possible legal control instruments include ecodesign specifications, i.e. requirements on avoiding substances during the manufacture of products, preventive and repressive bans with authorization requirements (substance approvals), rules on substance recovery and wastewater treatment, as well as the regulation of diffuse sources,

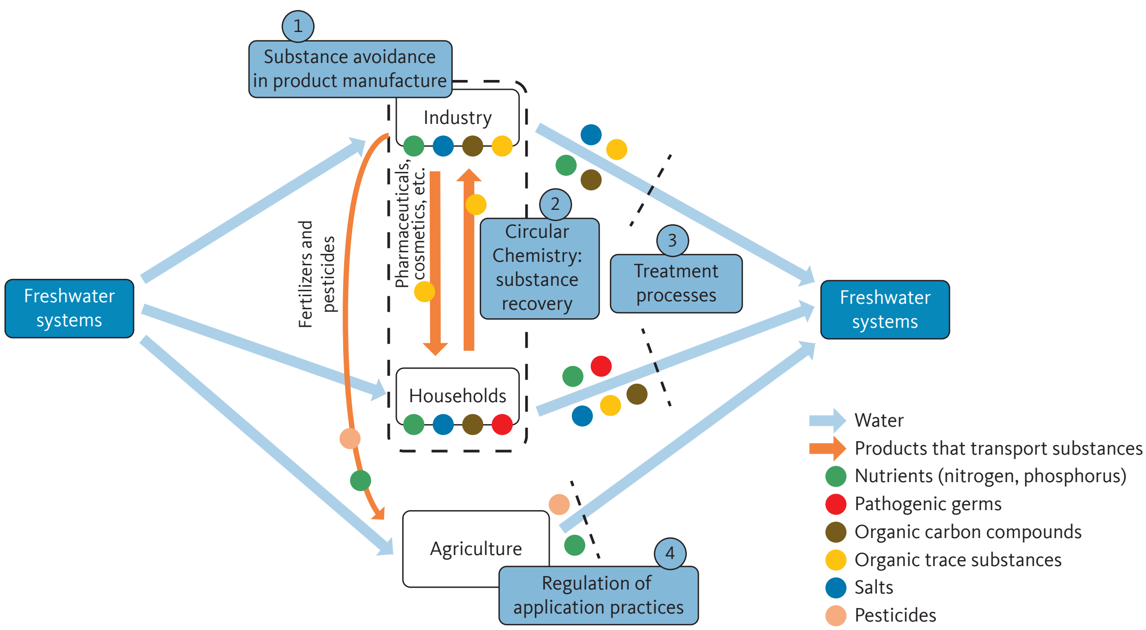


Figure 7.1-1
Approaches to the design and practical implementation of Zero Pollution.
(1) Substance avoidance in product manufacture, e.g. as a result of the restriction by the EU REACH regulation on marketing chemicals and putting them into circulation; (2) substance recovery, e.g. of metals, biopolymers and phosphorus from industrial and municipal wastewater in the context of circular chemistry; (3) treatment processes, e.g. advanced treatment stage (as provided for in the EU Urban Wastewater Treatment Directive) or alternative wastewater systems for the collection and treatment of domestic wastewater in low- and middle-income countries; (4) regulation of application practices, e.g. measures to reduce nutrient and pesticide inputs on agricultural land.
Source: WBGU

for example in relation to pollutant inputs from agricultural land use.

This chapter discusses innovative approaches that can contribute to the concrete implementation of the zero-pollution model for different types of pollution worldwide. For example, the governance approaches of the European Chemicals Regulation on the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH; Section 7.1.1) and the recently amended EU Urban Wastewater Treatment Directive (Section 7.1.2) can serve as pioneering concepts for implementing a zero-pollution model not only for EU member states but also outside the EU. Internationally, the Science-Policy Panel on Chemicals, Waste and Pollution Prevention adopted by the UN Environment Assembly could take up these governance approaches and support their global dissemination (Section 7.1.3). This chapter also discusses diffuse substance inputs into the water cycle and approaches to regulating them (Section 7.2).

Alternative wastewater-disposal concepts for low- and middle-income countries are also introduced (Section 7.3). The ‘Citywide Inclusive Sanitation’ (CWIS) concept aims to provide wastewater disposal and treatment by the flexible use of various centralized and decentralized solutions for all population groups and districts, taking local resources and capacities into account. This corresponds to the guiding principle of zero pollution and follows the principle of safeguarding water as a common good for people and nature (Section 5.2.1).

Approaches to avoiding water-related risks resulting from the growing demand for raw materials in the course of the energy system transformation (Section 7.4.1) and the recovery of raw materials from wastewater (Section 7.4.2) are discussed as central components of a circular economy.

7.1 Substance-related European Union law for the protection of water quality

7.1.1 EU legislation on chemicals

In the European Union, the Regulation (EC) No. 1907/2006 on the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH regulation) adopted a regulatory approach to chemicals that allows for marketing restrictions and bans as well as compulsory registration. The regulatory approach of the REACH regulation makes it possible to subject chemicals to authorization or restriction following mandatory registration (the “R” in REACH) and assessment; it thus directly addresses the production and marketing of environmentally relevant substances. This is in line with the principle of risk prevention (Chapter 5). The REACH regulation is to be further developed at the EU level in the context of the EU Chemicals Strategy for Sustainability as part of the European Green Deal.

In its 2023 flagship report, the WBGU commented on the further development of the REACH regulation and here reaffirms the recommendations made there (WBGU, 2023). The transition from individual substance assessments to group-based bans proposed by the EU is to be welcomed. The WBGU advocates a ban on the entire PFAS substance group (following Cousins et al., 2020), whereby justified exceptions should be permitted for specific essential uses. In order to minimize negative impacts on the health of humans and the environment, in the case of essential uses manufacturing companies and users should be obliged to establish provisions for monitored recycling, including take-back obligations and aftercare measures.

In the communication published by the EU Commission in April 2024 on its concept of ‘essential uses’ for chemicals, it defines several relevant terms: a harmful substance is deemed essential for a society if, first, its use is necessary for health and safety or critical to the functioning of society and, second, if there are no acceptable alternatives (Europäische Kommission, 2024: 4). Necessary for health means the need to “prevent, monitor or treat illness and similar health conditions, sustain basic conditions for human or animal life and health, manage health crises and emergencies, ensure personal safety or ensure public safety” (Europäische Kommission, 2024: 4). According to the EU Commission, a substance is deemed critical for the functioning of society if it is necessary in order to “provide resources or services that must remain in service for society to function (e.g. ensure the supply of energy and critical raw materials or resilience to supply disruption), manage societal risks and impacts from natural crises and disasters, protect and restore the natural environment, perform scientific research and development, or protect cultural heritage” (Europäische Kommission, 2024: 4 f.).

The EU Commission emphasizes that the process of determining the ‘essential use’ should take the context of use into account. Conditions for minimizing emissions and exposure should be defined for substances with an essential use. The determination of the ‘essential use’ is not static, but can be reviewed on the basis of new findings, contexts of use or alternatives. Deadlines can be set for this (Europäische Kommission, 2024: 6).

The WBGU welcomes this concept. It is essentially in line with the WBGU’s proposal to implement an assessment procedure for ‘essential uses’, which was already presented in the 2023 flagship report based on the provisions in the Montreal Protocol (WBGU, 2023). However, the EU Commission's concept still leaves considerable leeway when it comes to assessment, and this needs to be clarified.

7.1.1.1
New procedures for the assessment of chemicals

In the past, many chemicals were put on the market without adequate identification, consideration, assessment or monitoring of properties such as persistence, bioaccumulation, mobility and toxicity (PBT/PMT) in the aquatic environment. Nor were additive and synergistic effects of substance mixtures and reaction products of chemicals in the environment or the effects of their metabolites in the body tested before they came onto the market.

The EU REACH Regulation provides for the registration of all chemicals with a production volume of one tonne or more per year that are to be placed on the market in the EU. Regulation (EC) No. 1272/2008 on the classification, labelling and packaging of substances and mixtures (CLP), which also regulates chemicals, came into force in 2009.

At the beginning of 2023, the Commission published the Delegated Regulation (EU) 2023/707 amending the CLP regulation with regard to the hazard classes and the criteria for classification, labelling and packaging of substances and mixtures (Box 7.1 1).

Adverse effects on water quality caused by industrial chemicals can be avoided if substances are tested for properties such as persistence, bioaccumulation, mobility and toxicity before they are registered and put on the market. Advance testing by the manufacturing industry enables an ex-ante (precautionary) risk assessment, the introduction of which would make a substantial contribution to implementing the zero-pollution model.

As the hazard classes in the CLP extension are expanded and the hazardous substance classes are extended to include PBT/PMT substances and endocrine disruptors (Box 7.1-1), the need for chemical assessment continues to increase. The new hazard classes could result in a significant improvement in water protection, as hazardous substances could be stigmatized by corresponding labelling. The CLP regulation thus acts as an important lever for protecting human health and aquatic ecosystems from chemicals manufactured in and imported into the EU, including pesticides and other biocides. However, there is a lack of alternative methods for substance assessment that could replace cost-intensive and lengthy animal testing. So-called 'New Approach Methodologies' (NAMs), which include experiments without animal testing on cells (in vitro) and computer modelling (in silico), offer new opportunities to overcome the existing problems in the assessment of chemicals, and to avoid negative effects on humans and the environment right from the substance-design stage (Escher et al., 2023; Schmeisser et al., 2023).

Box 7.1-1

The Delegated Regulation (EU) 2023/707 of the CLP regulation on the classification, labelling and packaging of substances and mixtures

Both the REACH and CLP regulations of the European Union require that data on the intrinsic properties of substances, including physico-chemical, toxicological and ecotoxicological information, be collected and evaluated. The original version of the CLP regulation contains detailed criteria for the classification, labelling and packaging of chemicals covered by REACH as well as for biocides, pesticides and consumer products. To date it has classified physical, health and environmental risks into two hazard classes: chemicals that pollute bodies of water and chemicals that damage the ozone layer. The Delegated Regulation (EU) 2023/707 came into force in April 2023. Since this revision, endocrine disruptors (substances that can interfere with the hormone system) with an effect on the environment, substances and mixtures with PBT and vPvB properties (persistent, bioaccumulative and toxic or very persistent and very bioaccumulative), as well as substances and mixtures with PMT and vPvM properties (persistent, mobile in water and toxic or very persistent and highly mobile in water) must also be labelled. The classification and labelling of substances according to the new hazard classes will be mandatory for new substances from April 2025 and for new mixtures from April 2026. From October 2026 and April 2028 respectively, this will also be mandatory for substances and mixtures already on the market.

The CLP Regulation refers to the use of suitable test methods to assess the properties of chemicals. Experimental data on algae, daphnia and fish toxicity are required for the assessment of environmental hazards. In the classification of hazards to human health, animal testing is almost exclusively required. The exception is the classification for skin damage, where in vitro tests (tests outside living organisms) are accepted. The recommended test methods are based on internationally recognized standards of the Organisation for Economic Co-operation and Development (OECD) and the EU regulation laying down test methods pursuant to the REACH regulation (Regulation (EC) No 440/2008).

7.1.2 Amended EU Urban Wastewater Treatment Directive

The amendment to the EU Urban Wastewater Treatment Directive (91/271/EEC) adopted by the EU Parliament in 2024 is an important milestone for the preservation of water quality in Europe and beyond (Box 7.1-2; Fig. 7.1-2). It further specifies the zero-pollution vision formulated as part of the European Green Deal (WBGU, 2023: 176). The financial participation of the manufacturers of pharmaceuticals and cosmetic products in the implementation and operation of the so-called advanced treatment stage is new (Box 7.1 2). This obligation is in line with the polluter-pays principle, in that the costs of water-damaging behaviour are imposed on the polluter. At the same time, it is an expression of the WBGU principle of 'Valuing water and appreciating the value of water' (Section 5.2.6). It is to be criticized that the manufacturers' cost-sharing scheme is limited to two sectors (pharmaceuticals, cosmetics) and offers little incentive to substitute substances with environmentally friendly chemicals (Section 7.5.1, Section 8.3). Furthermore, concrete approaches for changing consumer behaviour are missing, and the reduction of chemicals with persistent substance properties in the aquatic environment has not been included.

For efficient wastewater treatment, nature-based solutions could also be coupled with integrated, catalytically active media based on new findings in materials science and using modern biomolecular methods. They enable the use of selective and high-performance bacteria ('Coupled Green-Gray Technologies'; CGGT; Castellar et al., 2022). This could include the use of a new generation of innovative biofilters that combine a high disinfectant effect with the efficient transformation of hardly degradable organic trace substances with low energy requirements, without producing problematic residues (Arden and Ma, 2018; Karakurt-Fischer et al., 2020, 2021, 2023).

7.1.3 Global dissemination and reception of EU approaches

In response to the introduction of the approval procedure pursuant to the REACH regulation in the EU, a number of countries outside the EU have brought their national chemicals regimes closer to the European model. They include Australia, Canada, China, India, Japan, Russia, South Korea and the USA. Even if the motivations for the respective states differ, in addition to strategic and economic interests, the EU's pioneering role and the

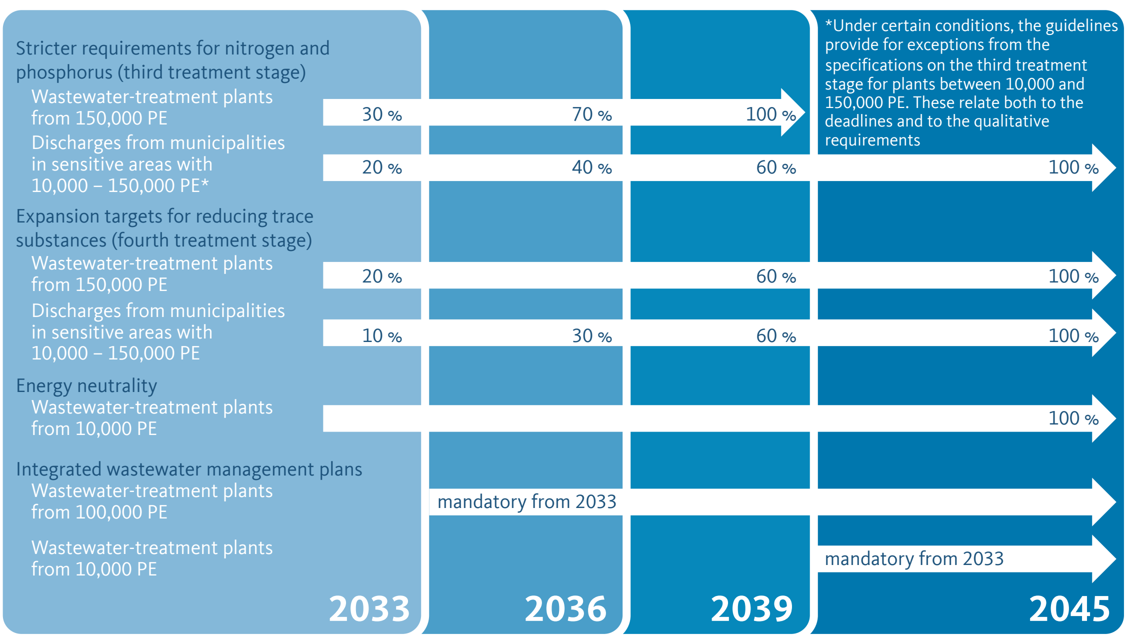


Figure 7.1-2
Contents of the amended EU Urban Wastewater Treatment Directive. New ceilings for the removal of nitrogen, phosphorus and organic trace substances in wastewater-treatment plants will be gradually introduced by 2045. In addition, the energy neutrality of wastewater-treatment plants and the preparation of integrated wastewater-management plans to reduce the discharge of untreated wastewater into surface waters will become mandatory.
Source: WBGU based on Verband Kommunaler Unternehmen, 2024

Box 7.1-2

Contents of the amended EU Urban Wastewater Treatment Directive (91/271/EEC)

In detail, the amended EU Urban Wastewater Treatment Directive – as adopted by the European Parliament in April 2024 (European Parliament, 2024a) – includes the following content (Europäischer Rat, 2024):
Wastewater treatment: For the third treatment stage in wastewater-treatment plants – the removal of nitrogen and phosphorus – the Directive provides for a tightening of the upper and lower limits. The new limits will be mandatory for plants with a population equivalent (PE) of 150,000 or more from 2039 and with 10,000 PE or more for discharges in areas at risk of eutrophication from 2045. What is new is the obligation to set up a so-called advanced treatment stage to remove organic trace substances that pose a risk to human health and the health of ecosystems. They originate, for example, from pharmaceuticals, household chemicals and cosmetic products.

Extended producer responsibility: For the expansion and operation of an advanced treatment stage for the removal of trace substances, the Directive provides for at least 80 % of the costs to be financed by the manufacturers of pharmaceuticals and cosmetic products. This applies to all products available in the EU, irrespective of whether they were produced within or outside the EU. The defrayment of at least 80 % of the operating costs also applies to plants that are already in operation when the Directive comes into force.

Integrated wastewater-management plans: The Directive also provides for the preparation of wastewater-management plans, which will be mandatory for plants with a population equivalent (PE) of 100,000 or more from 2033 and 10,000 or more from 2039. The aim of these plans is to reduce combined sewer overflows, i.e. the discharge of untreated wastewater into surface waters in the event of hydraulic overloading of the sewer network during heavy rainfall. Combined sewer overflows are a risk to the health of humans and ecosystems. This target is to be achieved by the separate collection and treatment of relatively unpolluted rainwater and avoiding rainwater overflows, e.g. by means of a blue-green infrastructure in cities (Section 6.4.3).

Energy neutrality: The Directive also includes the goal of energy neutrality for wastewater-treatment plants with 10,000 PE or more by the end of 2045. The purchase of energy from renewable sources of up to 35 % is permitted in order to achieve this. Energy can be produced both off-site and on the site of the wastewater-treatment plant.

Water reuse: The Directive stipulates that the reuse of further treated wastewater should be promoted by the member states wherever possible. However, there is no obligation for member states to develop national plans, targets and measures for water reuse (Europäischer Rat, 2024).

active dissemination of the REACH idea by EU institutions at the bilateral and international level appear to have been decisive (Lavenex, 2014; Bradford 2020). It would be desirable if the amended EU Urban Wastewater Treatment Directive could serve as a similar role model.

7.1.3.1
Global Framework on Chemicals

In October 2023, the international community adopted a legally non-binding Global Framework on Chemicals. The WBGU welcomes the Framework and its precautionary approach, which it had recommended in its 2023 flagship report (WBGU, 2023). The Global Framework on Chemicals could serve as a basis for further developing regional and national chemicals regimes, honing them towards the zero-pollution target and dovetailing them with each other.

7.1.3.2
Science Policy Panel on Chemicals, Waste and Pollution Prevention

Intergovernmental science-based institutions such as the IPCC are now playing a key role in combating global environmental change, taking political action and developing international environmental law. The WBGU therefore welcomes the decision by the United Nations Environment Assembly (UNEA) in 2022 to establish a Science-Policy Panel (SPP) to contribute to the safe management of chemicals, waste and pollution prevention. In the WBGU's view, this Science-Policy Panel can contribute to the global dissemination and implementation of the zero-pollution and circular economy principles. However, this can only happen if, in addition to describing the risks arising from the use of chemicals, it also addresses the societal and political strategies for dealing with risks in its assessment reports.

Furthermore, the Science-Policy Panel can support global precautionary action if the systematic search for and early identification of new risks (horizon scanning) become part of its functions. The Panel could also provide important findings and data on water quality for the Water Mapping Initiative proposed by the WBGU (Section 8.4.1.3). In the WBGU's view, it should also be enabled to close data gaps and support data-poor regions in collecting relevant data. For a systemic and comprehensive view of chemicals and their effects in water cycles, the adoption of a One Health perspective lends itself to recognizing risks to ecosystem services, ecosystems and humans (WBGU, 2023).

7.2 Diffuse substance inputs into the water cycle

7.2.1 Impairment of water quality by pesticides and nutrients

The diffuse impairment of water quality due to agriculture is widespread, but varies locally. Nutrients and pesticides introduced into the soil are mobilized by environmental influences and often spread via water transport in soils, water bodies and the air. They also have an effect on soil and water organisms as well as humans (Haygarth et al., 2005). The EU's Zero-Pollution Action Plan and Farm-to-Fork Strategy aim to reduce nutrient losses and the use of chemical pesticides by 50 % by 2030 compared to the reference period 2013–2017.

Nutrient and pesticide inputs can be reduced by switching production to alternative systems such as agroforestry, aquaponics, conservation agriculture, precision farming, ploughless farming, root intensification, the use of biofertilisers and targeted financial levies such as a pesticide tax (Section 6.3.2). These measures have been scientifically tested and can make a valuable contribution to the optimization of nutrient cycles and the reduction of biocides in water cycles. For low- and middle-income countries, too, scientists are recommending the implementation of high-yield and resource-conserving agriculture that increasingly uses alternative methods (Adedeji et al., 2020; Adegbeye et al., 2020; Frimpong et al., 2023; Solomon et al., 2016; Tschora and Cherubini, 2020).

Various alternative agricultural measures and production systems were presented and evaluated in the WBGU's flagship report 'Rethinking Land in the Anthropocene' (WBGU, 2020). These are also recommended for the next funding period of the EU's Common Agricultural Policy (CAP) after 2027, which reaffirms measures that are highly relevant for the protection of water quality (Section 7.5.2).

All the measures involve additional costs for farmers, which varies depending on the application. For this reason, compensatory measures, such as financial compensation, and planning reliability must be guaranteed for farms of all sizes (Section 6.5.1.3). In the WBGU's view, a results-orientated form of compensation based on the Augsburg model is desirable (Barataud et al., 2014; Wezel et al., 2016). Within this model, any losses are compensated by equalization payments if the required water quality is maintained on the managed parcels of land. In particularly pollution-sensitive areas, this can be linked to the promotion of organic farming (WBGU, 2020: 153). The German government has partially addressed the excessive input of nutrients with the Fertiliser Ordinance (DüV). The national monitoring programme for nitrogen and phosphorus associated with the DüV should also be extended to other substances such as pesticides and their metabolites.

7.2.2 Adverse effects of pharmaceuticals on water quality

Antimicrobial resistance (AMR) has been detected worldwide in wastewater and process water from livestock farming and animal-processing plants (Box 7.2-1). It is associated with a high risk of infection for staff who have contact with animals (Foyle et al., 2023; WBGU, 2023; Werner et al., 2023; SRU, 2023). In addition, resistant germs can enter soils and water bodies via exhaust air or the spreading of liquid manure (Fig. 7.2-1). The level of antibiotics administration in livestock farming in Germany is high compared to other EU Member States (Tsilimekis, 2023). The EU's Zero Pollution Action Plan

Box 7.2-1

Antimicrobial resistance (AMR)

Bacteria that are resistant to antibiotics can easily transfer the gene sequences responsible for the resistance to other bacteria. As soon as a bacterium is resistant to more than three classes of antibiotics, it is said to be multi-resistant. As all humans and animals harbour intestinal bacteria that can develop resistance, any administration of antibiotics involves the risk of resistance developing. The 2023 Special Report of the German Advisory Council on the Environment discussed the increasing antimicrobial resistance and its risks to humans in detail (SRU, 2023). Vulnerable people in particular are at risk from AMR, but all people can become carriers of multi-resistant germs and fall ill from them after they have spread through the air, water or soil (Westphal-Settele et al., 2018). In the case of an infection with multi-resistant bacteria, treatment options are significantly limited and those affected can often only be treated with reserve antibiotics. If these are also ineffective, a life-threatening situation can develop even for an otherwise healthy person. In order to counteract the increasing development of resistance, the WBGU supports the recommendations of the SRU for its containment (SRU, 2023).

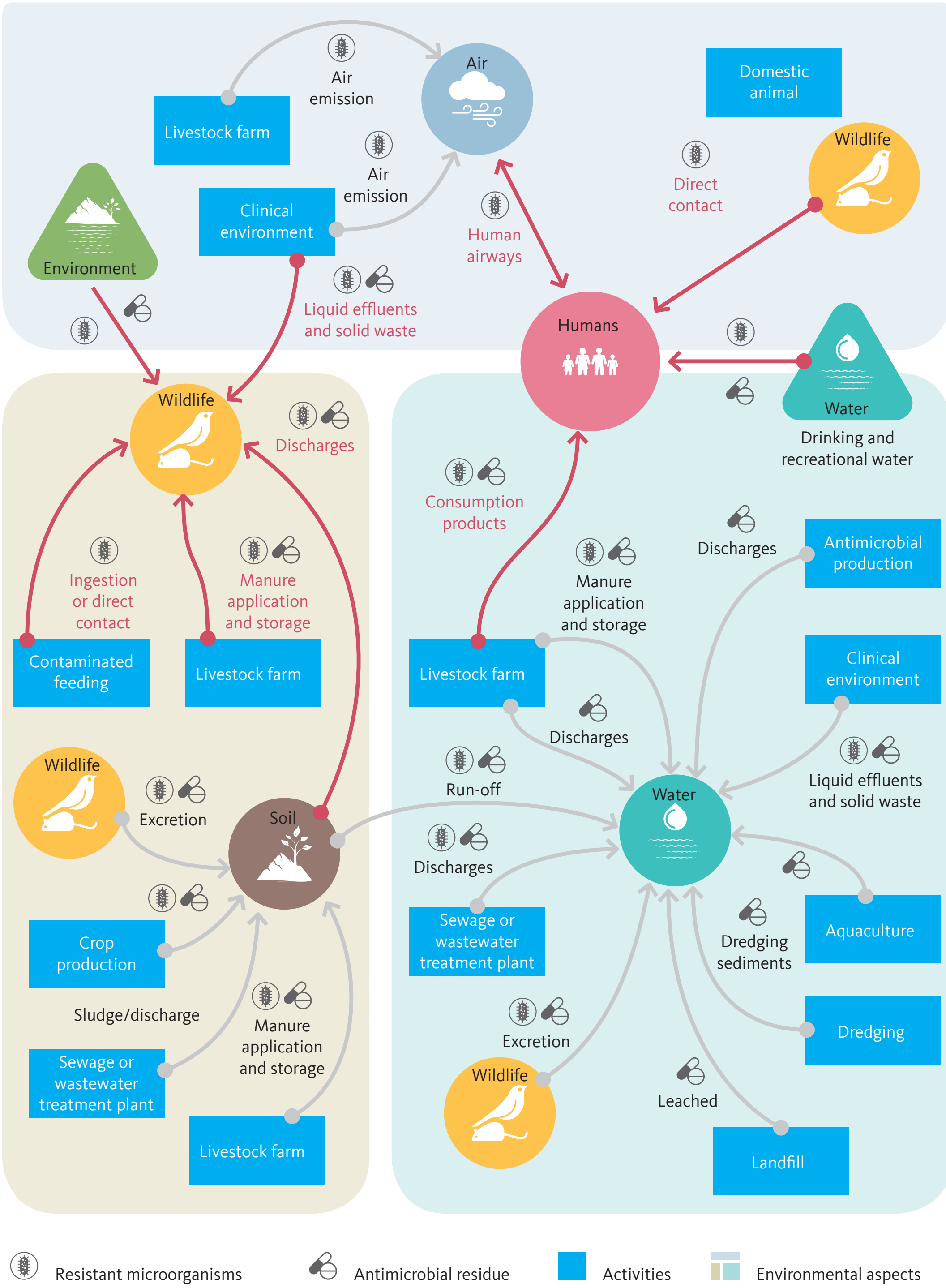


Figure 7.2-1
Transmission and spread of antimicrobial resistance via the environment. The diagram shows the pathways (grey arrows) of antimicrobial resistance and the ways it can be transmitted to animals and humans (red arrows).
Source: UNEP, 2023

envisages a 50 % reduction in the sale of antibiotics intended for livestock and aquaculture by 2030.

Measures against antibiotic residues in wastewater can be easily implemented using centralized, piped wastewater systems in existing wastewater-treatment plants. In decentralized, non-piped wastewater systems, measures may be more expensive and technically more complex to implement. The risk of the diffuse spread of AMR can be higher in decentralized wastewater systems compared to treatment in wastewater-treatment plants, especially if an advanced treatment stage optimized for the removal of AMR is installed (Hiller et al., 2019).

The increasing use of hormones and other veterinary medicinal products in livestock farming worldwide is also playing an ever greater role in the pollution of water bodies from diffuse sources (Section 3.3.2.1). Better forms of livestock farming reduce inputs while at the same time improving animal health. Less meat consumption by humans leads to less pollution of water bodies by resistant pathogens, antibiotics, hormones and other veterinary medicines, with simultaneous benefits for human health (WBGU, 2023).

The German Antimicrobial Resistance Strategy (DART) 2030, the BMBF's support for the Joint Programming Initiative on Antimicrobial Resistance (JPIAMR) and the EU's strategic approaches for pharmaceuticals in the environment and for the prevention of antimicrobial resistance are pioneering approaches for the prevention of AMR. The joint initiatives of the Food and Agriculture Organization (FAO), World Health Organization (WHO), UN Environment Programme (UNEP) and World Organization for Animal Health (WOAH) to contain antimicrobial resistance (AMR) are also exemplary (WBGU, 2023).

7.2.3 Adverse effects of microplastics on water quality

Under the Zero-Pollution Action Plan, the EU aims to reduce the amount of microplastics released into the environment by 30 % by 2030. A step in this direction has already been taken with Regulation (EU) 2023/2055, which came into force in 2023. The regulation amends the REACH regulation to ban the use of synthetic polymer microparticles in cosmetics, sports field granulates, pesticides and pharmaceuticals, among others. The EU's next Euro 7 emissions standard for vehicles will also stipulate limits for brake-pad and tyre abrasion in passenger cars and vans for the first time from 2028. Abrasion is a major cause of diffuse pollution of the air and water by microplastics.

In view of the predicted increase in plastic products and motorized private transport, the EU measures, also in combination with the action plan for the circular economy and the global plastics agreement currently still being negotiated, could turn out to be insufficient (OECD, 2022b; Section 8.1).

The rising use of agricultural films, colour and protective varnishes, as well as wood substitutes made of plastic, means that a further increase in microplastics due to abrasion and UV-induced decomposition, and their entry into water bodies, can be expected in the future – with serious consequences for aquatic organisms and the contamination of drinking water.

7.3 Alternative wastewater-disposal concepts in low- and middle-income countries

7.3.1 Flexible use of centralized and decentralized wastewater systems

The discharge of untreated domestic wastewater is a major cause of pollution of surface waters with pathogens, organic carbon compounds and nutrients in low- and middle-income countries (LMICs), which harms the health of humans and ecosystems (Section 2.3, Section 4.5). Informal settlements are particularly affected. In the context of the various approaches for the concrete implementation of zero pollution (Fig. 7.1-1), treating domestic wastewater is the most effective approach for reducing these substance inputs into surface waters. Historically, international donors and local decision-makers have long favoured the cost-intensive construction of centralized wastewater systems with extensive sewer networks based on the model of high-income countries (Heidler et al., 2023). For many formal and especially informal settlements in low- and middle-income countries, however, centralized wastewater treatment is not appropriate and therefore unsuitable as a universal solution for wastewater disposal (Gambrill et al., 2020; Section 4.5).

Alternative concepts such as Citywide Inclusive Sanitation (CWIS), which focuses on customized solutions and equitable access to drinking water, sanitation and hygiene for all population groups and urban districts (Lüthi et al., 2020), have been gaining in importance for some years now. In CWIS systems, wastewater disposal and treatment are seen as a service concept rather than the pure provision of infrastructure. It comprises a wastewater service chain consisting of collection, emptying, transport, treatment and disposal or reuse (Heidler et al., 2023). Different technical components (such as centralized, piped wastewater systems or decentralized, non-piped wastewater systems with faecal sludge management) can be used flexibly to enable the hygienic handling of wastewater in a locally adapted manner (Narayan et al., 2021). An important characteristic of decentralized, non-pipe-based solutions is that no waterborne sewage system is used in which water transports faeces. As a result, less water is used and the spread of pollutants in the aquatic environment is significantly reduced.

Centralized wastewater systems are also managed by wastewater companies in low- and middle-income countries. In districts that are not connected to central sewage systems (often informal settlements), there are often unsafe, decentralized, non-piped sewage systems involving leaking latrine pits. Furthermore, pits are frequently emptied without hygienic protection and faecal sludge disposed of into surface water (Section 4.5). The informal staff involved in the management of decentralized wastewater systems are exposed to enormous health risks and are often poorly paid and stigmatized (WHO and UNICEF, 2020: 71 f.). In addition, unsafe practices pose a risk to public health and to ecosystems. Following the CWIS concept, the existing decentralized, non-piped sewage systems can be formalized and improved through faecal-sludge management and hygiene measures (Lusaka case study: Section 7.3.2).

Since the first publication of the CWIS principles in 2016, i.a. by the World Bank, the Bill and Melinda Gates Foundation and the University of Leeds, many other actors have taken up the concept, e.g. the International Water Association and the Asian Development Bank (ADB, 2021; Lüthi et al., 2020; IWA, 2022). The African Union has also recognized the complementary roles of conventional centralized, piped sanitation systems and hygienic, decentralized, non-piped systems in its African Sanitation Policy Guidelines (AMCOW, 2021: 39). In Kenya, the government plans to implement a nationwide wastewater-disposal system with 40 % using conventional, centralized wastewater systems and 60 % using decentralized, non-piped systems (World Bank, 2023c: 3).

The WBGU welcomes the initiatives of the various public and private actors to reduce the discharge of pathogenic microorganisms and chemical substances from untreated domestic wastewater into water cycles by the flexible and adapted use of various technologies. This follows the principle of protecting water as a common good for people and nature (Section 5.2.1).

7.3.2
Case study: the Lusaka Sanitation Programme

The following case study illustrates the concrete implementation of flexibly combined centralized and decentralized wastewater-disposal systems using the example of the development of faecal-sludge management (FSM) in Lusaka (Zambia). The example shows that in order to successfully improve decentralized, non-piped wastewater systems, the institutional and organizational framework must be adapted parallel to the development of technical infrastructure. The Lusaka Sanitation Programme can also serve as an example of transformative urban design in terms of climate-resilient urban water management (Section 6.4), focusing on water quality and safe access to clean drinking water and sanitation infrastructure for all city residents. The example also illustrates the requirements for the selection, combination and development of measures in the context of climate-resilient water management. They include, in particular, analysing feasibility in the respective context and taking greater account of possible multiple benefits (Box 6.2-1; Section 6.2.2).

70 % of Lusaka's 2.5 million inhabitants live in informal settlements, which are characterized by high population density, low housing standards and a lack of public infrastructure. 90 % of them use latrine pits, 9 % use centralized, piped sewage systems or septic tanks and 1 % practise open defecation (Simwambi et al., 2023).

Legally, households are responsible for the construction and maintenance of latrine pits and the city administration is responsible for monitoring them. In practice, monitoring is incomplete due to a lack of capacities, which is why the quality of the sanitary facilities varies greatly. Many of the latrine pits are not sealed and therefore pose a risk to the water supply, 60 % of which is fed by groundwater close to the surface. Outbreaks of typhoid, dysentery and cholera regularly occur in Lusaka's informal settlements (Hubbard et al., 2020; Simwambi et al., 2017; Gething et al., 2023).

Until the launch of the FSM projects, the latrine pits were emptied by vacuum trucks or manually and mostly without hygiene protection by household members or informal, unregulated service providers (Simwambi et al., 2017). As there was no treatment option for removed faecal sludge before the FSM projects began, it was buried near the latrine pits or disposed of in nearby ditches and surface waters. Especially during the rainy season, open latrine pits can overflow and the buried faecal sludge can be washed up. In the context of the increase in the number of heavy rainfall events predicted for Lusaka due to climate change, this poses an additional risk to the health of humans and ecosystems (Libanda et al., 2024).

Between 2012 and 2015, the Lusaka Water and Sewerage Company (LWSC), together with the water-supply and wastewater-disposal company of the city of Lusaka, implemented a project to set up FSM in the informal settlements of Kanyama and Chazanga. The project was financed by the NGO Water and Sanitation for the

Urban Poor and implemented by the NGOs Water and Sanitation Association of Zambia and Bremen Overseas Research and Development Association. The project involved the construction of two faecal-sludge-treatment plants with sludge storage tanks, screens for separating solid waste, digesters for biogas production and sludge-drying beds. These treatment plants are owned by the LWSC and under the supervision of the local administration, but operated by organizations of city residents. The latrine pits are emptied and the faecal sludge is transported to the treatment plants by employees of the Water Trust, who were recruited, trained and equipped by the informal service providers (Klinger et al., 2019; Simwambi et al., 2017).

Following the successful pilot project in Kanyama and Chazanga, the LWSC launched the city-wide Lusaka Sanitation Programme in 2015, which will run until 2024. This project is being funded with a total of US$300 million by the World Bank, the African Development Bank, the KfW Bankengruppe and the European Investment Bank and follows the CWIS concept by combining centralized and decentralized wastewater systems (Huang, 2022). The objectives are to expand and improve the sewer network, build sanitary facilities and faecal-sludge-treatment plants for decentralized wastewater systems and improve FSM in peri-urban informal settlements. In addition, the institutional capacity of the LWSC to manage wastewater systems in Lusaka is to be improved (Huang, 2022).

In 2022, two project goals were achieved: 3,500 newly built sanitary facilities for decentralized wastewater systems and the emptying of 13,000 latrine pits. However, the construction of a new plant for the treatment of faecal sludge was only 25 % complete (Huang, 2022). In addition, the original target of providing 90,000 people with improved sanitary conditions was reduced to 75,000 due to rising costs. By 2022, this figure had already reached 68,000 (Huang, 2022).

The institutional and organizational framework of the wastewater system in Lusaka was also adapted in the context of the Lusaka Sanitation Programme. The emptying of latrine pits and the transport of faecal sludge have been assigned to the LWSC, which is also to issue licences to the water trusts and private service providers. These in turn are obliged to report to the LWSC (CWIS, 2021). This was an important step towards the formalization and recognition of existing decentralized wastewater systems (Section 7.5.5). In addition, the Lusaka Sanitation Programme was supported by a project of the German Society for International Cooperation (GIZ) from 2016 to 2020. The aim was to create the conditions for climate-friendly sanitation and FSM in informal settlements through training programmes, coordination between actors, compliance monitoring and improved management practices.

Since the start of the FSM projects to improve decentralized wastewater systems, various favourable factors, limitations and multiple benefits have been identified. For example, the strong involvement of the local population through the water trusts, the capacity development of previously informal service providers, campaigns to raise awareness of health benefits, and the role and services of the water trusts proved to be positive factors influencing the acceptance of the FSM by the local population (Simwambi et al., 2017).

In terms of limitations, it should be mentioned that the latrine pits are sometimes used by the population to dispose of other forms of waste. Accordingly, 22 % of the sludge in the latrine pits consists of solid waste, which makes the use of vacuum trucks difficult, so that emptying has to be done mainly manually (Simwambi et al., 2023; Klinger et al., 2019). Solid waste can also lead to blockages in faecal-sludge-treatment plants. Since the plants were commissioned, there have been several temporary closures due to operational and maintenance problems. It is therefore important to have a motivated and qualified workforce in order to avoid blockages, misuse and downtime (Klinger et al., 2019).

Even with optimized and smooth operation, the maximum intake capacity of the treatment plants is a further limitation. The plant in Kanyama, for example, was only built to collect faecal sludge from 30,000 of the total population of 250,000 (Simwambi et al., 2017). One year after the end of the project period (2016), 11 % of the latrine pits in Kanyama were emptied by Water Trust employees and taken to the treatment plant, while 30 % were emptied by vacuum trucks and 59 % by households or informal service providers (Simwambi et al., 2017). As the treatment plant has reached its capacity limit, it is not possible to increase its share of faeces disposal without expanding it (CWIS, 2021).

As regards the FSM's multiple benefits, dried sludge can now be sold as fertiliser after treatment. However, this has not yet happened in Kanyama and Chazanga (Simwambi et al., 2017). The biogas from the digestion of faecal sludge is also exploitable. The original intention was to sell it to neighbouring households. However, as the building owners did not grant permission for the construction of gas pipes, the biogas is instead used internally by the Water Trust to run the canteen (Simwambi et al., 2017). A further advantage is that the previously informal employees of the Water Trust have benefited from the formalization of their work (combined with the advantages of regular employment, a stable income and secure working conditions) and social empowerment through the upgrading of their work (Simwambi et al., 2017).

An open question concerning FSM concepts in general is the development of a business model that is viable without external financial support. In Kanyama and Chazanga, despite the income from emptying the latrine pits, the FSM has to be subsidized by the Water Trust's income from supplying water in order to keep prices competitive and affordable for the population.

7.4 Effects of energy supply on water quality

The energy sector is the second largest consumer of water worldwide after agriculture; it is responsible for up to 40 % of water consumption in some countries (Lohrmann et al., 2023). A more fluctuating water supply in the future and water-related extreme events could jeopardize energy production (Box 7.4-1). As part of the energy system transformation, the quantity of water consumed in the energy sector is also changing along with the power-plant technologies used (Box 7.4-2).

At the same time, the effects of energy supply on water quality will change if fewer fossil fuels are extracted in the future, or if more and different materials, such as rare earth metals or lithium, are required for energy conversion and storage (Section 7.4.1). The recovery of raw materials from wastewater is becoming even more important in this context (Section 7.4.2).

7.4.1 Effects of power generation on water quality

The energy system transformation is also a resource transition with considerable relevance for water: the conversion and storage of energy have different effects on water quality depending on the technology used. Water pollution occurs during the extraction and processing of energy carriers, the extraction of the raw materials required for the construction of power plants and storage facilities, during their use and during their dismantling and recycling. The following section briefly discusses water pollution during the extraction of fossil fuels. This is followed by an example of water pollution during the extraction of lithium salts, which are necessary for the production of energy-storage systems. Solutions for pollution reduction and avoidance are also introduced to illustrate the challenges to water-quality protection posed by the energy transition, and how they can be met by applying the principles of zero-pollution and the circular economy (Fig. 7.1 1). Part of the solution is the recovery of raw materials (Section 7.5.5).

7.4.1.1 Pollution from fossil fuels

The extraction and processing of fossil fuels generates large quantities of waste, some of which contains toxic substances that can find its way into water bodies. The process wastewater itself is often purified and reused within the extraction process (Kalisz et al., 2022). Heavy pollution of the surrounding water bodies by sulphates, metal ions, etc. was observed, for example, during coal extraction by mountaintop-removal mining. In the USA, around 1.2 million people live in areas where coal is extracted by blasting. In the process, river courses over a total length of around 2,000 miles have been buried by waste material. Effects are predicted to last for decades after extraction (Hendryx et al., 2020).

Underground coal mining, too, has a considerable impact on the quality of water resources. Acid mine

Box 7.4-1

A fluctuating water availability can jeopardize power-plant operation

Stronger fluctuations in precipitation due to climate change and changes in total water volumes and surface runoff (Berga, 2016; Chapter 2; Chapter 3) will influence the quantities of electricity that can be generated in the future. Water shortages and higher water temperatures can limit the capacity of thermal power plants and make temporary shutdowns necessary. Nuclear power plants are particularly affected as they have a high water-withdrawal requirement for safety reasons (Jin et al., 2019b). A study by van Vliet et al. (2016) predicts that the availability of up to 74 % of hydropower plants and 86 % of thermoelectric power plants worldwide could be restricted in the years 2040–2069.

In addition to the expansion of photovoltaic systems and wind energy, adjustments to thermoelectric power plants and hydropower plants can reduce the susceptibility of energy generation to a fluctuating water availability. These include, for example, measures to increase efficiency, the use of alternative cooling systems and a switch from coal to gas with lower cooling requirements (van Vliet et al., 2016). Reduced water supply at catchment-area level and its effect on potential for energy generation, and possible conflicts of use should be given greater consideration in energy and climate policy, spatial planning and the planning of water infrastructure (e.g. by means of strategies for decarbonizing the energy sector, resilience analyses, long-term climate policy strategies; WBGU, 2021).

Power plants are also jeopardized by an oversupply of water and corresponding water-related extreme events. Therefore, threats to the energy infrastructure from water-related extreme events should be strategically considered and risk-minimization measures taken where necessary. Measures for hydropower plants are described, for example, by Wasti et al. (2022).

drainage, which is caused by the ingress of surface water and the oxidation of minerals, is one of the biggest sources of pollution in coal mining. For example, heavy metal ions dissolved by mine water have been detected in neighbouring water resources, e.g. contaminated groundwater in Indian coal basins (Finkelman et al., 2021; Masood et al., 2020).

Furthermore, the combustion of coal has been found to contaminate water and soil with polycyclic hydrocarbons, mercury, arsenic, chromium and other substances. They originate i.a. from the coal ash stored in mining waste tips (Hendryx et al., 2020; Finkelman et al., 2021).

In oil and gas production, the largest amount of waste and a potential source of water pollution comes from the drilling fluids used. Although in some countries, such as the USA, around 90 % of the liquid is reused in the process, harmful substances contained in the liquid, such as toluene, can enter ground and surface water bodies if it is disposed of incorrectly or if there are leaks (Pereira et al., 2022; Kalisz et al., 2022; Allison and Mandler, 2018). The extraction of shale gas using hydraulic processes (fracking) has also been found to contaminate groundwater (DiGulio and Jackson, 2016).

7.4.1.2
Health and environmental risks of material extraction for the energy system transformation

In the course of the urgently needed transformation of the global energy system to renewable energies, the number and quantity of raw materials and materials required for the production of energy-generation plants and energy-storage systems is increasing sharply (Watari et al., 2021; WD, 2023). The growing extraction of e.g. rare earths, copper, graphite and lithium for the production of wind-power and photovoltaic systems, for the expansion of the electricity grid and for lithium-ion batteries and other electrochemical storage systems harbours risks for water quality (Chapter 2; Chapter 3; Northey et al., 2017; Europäische Kommission, 2020; Bogardi et al., 2021; Raabe, 2023). During the extraction of raw materials such as aluminium, copper, lithium or cobalt compounds, surface and groundwater can be polluted with process chemicals, metals and semi-metals such as cobalt or arsenic, which are harmful to the health of humans and ecosystems (Chapter 2; Chapter 3; Madaka et al., 2022; Pesa, 2021; BGR, 2020). In Morocco, for example, arsenic concentrations far above the World Health Organization (WHO) quality standards for drinking water have been detected in rivers and springs whose water is used to irrigate crops. Cobalt mining is assumed to be responsible for this (Blum et al., 2023). With materials such as copper, which are extracted from sulphide ores (metal sulphides), there is a risk of water pollution from acid mine water and the dissolved metal ions it contains (Northey et al., 2017) – similar to coal mining. These risks must be taken into account and suitable solutions to protect water quality must be implemented with foresight. Avoiding pollution during material extraction is important to prevent unintended negative consequences of the energy system transformation.

Example: health and environmental risks of lithium extraction

The light metal lithium is extracted mainly from solid rock or by water-intensive evaporation technology from lithium-rich brine in salt lakes (Halkes et al., 2024). Lithium extraction can pose environmental and health risks – on the one hand due to high water consumption (depending on the process) and on the other to impairments of water quality. Lithium itself and by-products of its extraction can have a toxic effect (Buchert et al., 2020; Bolan et al., 2021). For example, numerous negative effects of high doses of lithium on humans, animals, plants and aquatic systems have been identified, including negative impacts on brain functions, functional disorders and pathological tissue changes of the thyroid gland (WBGU, 2023; Tanveer et al., 2019; Bolan et al., 2021; Sproule, 2002; Adeel et al., 2023, Chevalier et al., 2024). Lithium fulfils the WHO definition of an endocrine disruptor, but there is currently no upper limit for a lithium concentration in drinking water to avoid harm to human health and the environment (Chevalier et al., 2024; Adeel et al., 2023; EPA, 2023; BMJ, 2023; WHO, 2022a). There is an urgent need for research in this area.

There is also a lack of understanding of the interaction between dissolved substances and by-products in the extraction of lithium salts. During the extraction of lithium salts from solid rock, the wastewater produced is channelled into sedimentation tanks and partially reused (Schmidt et al., 2023). With this extraction method, the residues stored in sedimentation tanks are a source of pollution for water bodies. Harmful substances can enter bodies of water through breaches in the sedimentation tanks or through seepage (Buchert et al., 2020). Another risk is posed by process waste that is discharged into rivers (TPI, 2016). There is an urgent need to develop innovative and sustainable process technologies.

The extraction of lithium salts using evaporation technologies also has an impact on water bodies. These technologies require fresh water and are often used in arid regions, for example in the Atacama salt basin (Salar de Atacama) in the Chilean desert (Agusdinata et al., 2018). With this technology, over 90 % of the water from the brine pumped into the surface pools evaporates. Depending on the deposit, 100–800 cubic metres of water are needed to extract one tonne of lithium carbonate (Li_2CO_3), a basic material for lithium-ion batteries (Vera et al., 2023). Further process steps require around 15–33

Box 7.4-2

Water requirements of the energy sector and effects of climate change

The water consumption of different power plants for electricity and heat generation is calculated over their entire life cycle. It includes direct water consumption for operating the power plants and indirect consumption for their construction, the production of the necessary materials and the provision of fuels. Consumption depends heavily on the location and its prevailing climate, the type of power plant, the cooling method, the fuel used, material production and other factors (Jin et al., 2019b; Mekonnen et al., 2015; Meldrum et al., 2013; Flörke et al., 2021).

Comparing individual studies is complicated by the different methods used to determine water demand and the system boundaries used as a basis. This means that studies differ in how and to what extent water demands are included, for example for the production of materials, the construction of power plants or the mining and transport of fuels (Jin et al., 2019b; Pfister et al., 2017).

The studies analysed have in common that they record the consumption of blue water, but do not take into account the pollution of wastewater. Furthermore, not all regions of the world are equally represented in studies (Jin et al., 2019a, b).

The water demand of different power-plant technologies can differ by several orders of magnitude (factor of ten or higher powers of ten), so that despite the differences and uncertainties mentioned, qualitatively robust patterns can be recognized – in this case, based on the meta-analysis by Jin et al. (2019b), which is consistent with the studies cited above (Fig. 7.4-1).

- The water consumption over the entire life cycle of oil, nuclear and coal-fired power plants in relation to the quantities of electricity and heat generated is one or two orders of magnitude higher than for photovoltaics (PV) and wind power; concentrating solar-thermal energy, geothermal energy and natural gas-power plants lie in-between.
- The water demand of storage hydropower plants can be significantly higher than that of oil, coal and nuclear power plants due to a high level of evaporation from reservoirs. This depends largely on the local climate and topography, which determine the surface enlargement during damming (Jin et al., 2019b; Mekonnen et al., 2015). For example, a particularly low evaporation rate was determined for a hydropower plant with a reservoir in Norway (Trollheim) (Bakken et al., 2016).
- The water requirements of bioenergy can be an order of magnitude higher than consumption by hydropower plants. The scale of the difference depends on how much irrigation is used in biomass cultivation and, if residues that can be used to generate energy are produced during food cultivation, what proportion of water consumption is attributed to residues and what to food production (Jin et al., 2019b; Mathioudakis et al., 2017).
- In the case of wind power and PV, most of the water required is used to manufacture and clean the systems.
- In the case of nuclear power plants and fossil-fuelled power plants, most of the demand is for cooling during operation, while in the case of bioenergy power plants the highest demand results from irrigation during fuel production. The operational water consumption of thermal power plants that use carbon capture and storage (CCS) is 30 % to 80 % higher than those without CCS.
- Depending on the cooling method used, water withdrawal (not shown in Fig. 7.4-1) can be significantly higher than the actual water consumption, in the case of nuclear power up to an order of magnitude.

The total water consumption of the energy sector therefore also depends on its composition in relation to the types of power plants. A restructuring of the energy sector to reduce greenhouse-gas emissions can therefore lead to a higher or lower overall water demand, depending on the respective shares of the different technologies installed. This should be given greater consideration when designing scenarios and strategies for the electricity and heating sector (Lohrmann et al., 2023; Flörke et al., 2021; Mekonnen et al., 2016; Payne et al., 2024).

Wind energy and PV may reduce water consumption

Increasing electricity generation from hydropower and bioenergy from wood or cultivated biomass can significantly increase the total water consumption for electricity and heat generation (e.g. Mekonnen et al., 2016). The use of wind energy and PV reduces regional water consumption compared to fossil-fuelled or nuclear power plants, and can help to mitigate or avoid local water crises. The installation of PV modules over canals or floating on the reservoirs of hydropower plants can generate multiple benefits. The modules reduce evaporation and are cooled by the remaining evaporation, making them more efficient. At the same time, the area of land required for PV (Jin et al., 2023) is reduced. The modules can also decrease the growth of harmful algal blooms (Section 3.1.3.2). The power-generation potential of floating PV modules is high. PV systems with a total output equivalent to that of all fossil-fuelled power plants could be installed on just 10 % of the reservoir area of all hydropower plants worldwide (Almeida et al., 2022). However, there are also ecological risks, potential conflicts of use and technical issues that need to be weighed up and resolved (Jin et al., 2023; Almeida et al., 2022).

Electricity generation from hydropower already plays a major role in many parts of the world, especially in China, South America and Africa (Ritchie et al., 2023). In Asia in particular, major expansions are planned or already underway, while there is great untapped technical potential for hydropower especially in Africa. As with bioenergy, however, it is essential to take an overall ecological, social and political view in addition to a climate- and energy-policy perspective. This can prevent, for example, the power supply for industry and urban centres or climate-change-mitigation measures from being accompanied by land consumption and the massive disruption of local water balances at the expense of ecosystems and the population.

Furthermore, there is a change in spatial patterns of water demand, which makes local water supply crucial: PV and wind power require much less water at the point of electricity generation than thermal power plants. Moreover, the water consumption to produce materials and systems for wind turbines and solar modules occurs at different locations from the water required for the extraction, processing and transport of fossil and nuclear fuels.

Take greater account of the value of water for other uses and ecosystems

Future changes in the water availability will create challenges for electricity generation and may exacerbate conflicts of use. At the same time, the functions of water reservoirs beyond electricity generation, which often serves as a source of their finance, are becoming more valuable. They can be used for flood retention, drinking-water supply, as a buffer for irrigation, industrial use and the preservation of ecosystems, e.g.

by ensuring minimum flows while limiting maximum flows and retention during heavy rainfall.

However, the planning, dimensioning, investment and operation of power plants have so far been dominated by aspects of energy economics. Water-economic incentives, for example to take into account their function as water reservoirs for dry periods, are weak. Existing water-management ordinances and regulations generally do not provide power-plant planners and operators with time-resolved information and incentives on scarcities, other needs and alternative uses (opportunity costs), the value of the retention function for flood prevention, etc. The dimensioning and filling of (power-plant) water reservoirs often neglect the increasing uncertainty of precipitation in order to fill the reservoirs in time, as well as the disappearance of base flows from glaciers and permafrost soils in alpine regions.

Increase efforts to incorporate water into planning procedures

In future, the more fluctuating supply and the value of water should be given greater consideration in regulations and in investment and operating decisions for power plants (which have hitherto often been dominated by energy economics). One relevant option here is time-resolved price signals, i.e. time-dependent payments to reservoir operators for the secure provision of water from storage facilities, or time-dependent water prices for the operators of thermal power plants that want to withdraw cooling water. This would ensure that, for example, the multifunctionality of dams is better taken into account when investing in and operating them, that the externalities of water consumption by thermal power plants are fully reflected in their electricity-generation costs, and that conflicts of use caused by the operation of hydrogen plants are better taken into account. Water-economic effects should already be determined during the planning and authorization of hydropower plants, perhaps as an obligation on the part of the applicant, in order to relieve the approval authorities, and should be included in a cost-benefit analysis (Section 6.1.3).

Power-generation technologies with a high demand for water, such as thermoelectric and hydropower plants, should be used above all when substitution by other generation, storage and transmission technologies is hardly possible (e.g. for system stabilization) or when a high additional benefit is to be expected from more consistent water supply or flood protection (which cannot be achieved by nature-based solutions).

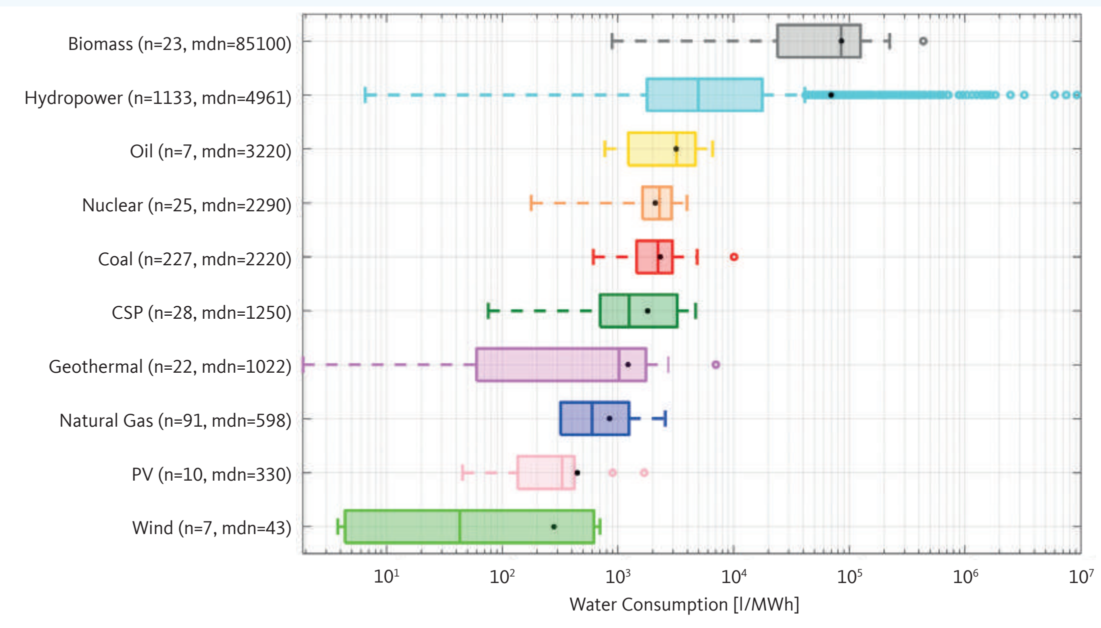


Figure 7.4-1
Consumption of blue water by different types of power plant over their life cycle. The consumption of green water in the cultivation of biomass is not included. n: number of data points taken from different studies. Each represents a specific technical characteristic, local environmental conditions and detailed methodological assumptions; mdn: median value of the water consumption of the respective technology. Dots indicate the respective average value, circles indicate outliers.
CSP: concentrating solar power.
Source: Jin et al., 2019b

m^3 of fresh water per tonne of Li_2CO_3 and 31–50 m^3 of fresh water per tonne of lithium hydroxide (LiOH), another starting material for lithium-ion batteries. A large proportion of the treated water is then reused (Kelly et al., 2021; Dellapenna et al., 2013; Schmidt et al., 2023).

The intrusion of lithium salt extraction into salars can have an impact on the water levels of neighbouring rivers and other water bodies (Vera et al., 2023; Schmidt et al., 2023). The details of the connections are the subject of current research projects. In the Salar de Atacama, the water levels of the surface waters have already fallen (Vera et al., 2023, Gutiérrez et al., 2022). With evaporation technology, process chemicals such as plasticizers are collected in basins, which can enter water bodies if barriers fail (Agusdinata et al., 2018).

Alternative processes for lithium salt extraction are being developed under the heading of Direct Lithium Extraction (DLE), which do not require evaporation basins and are more efficient. These technologies are still at an early stage of development and need to be adapted to the different brine deposits. However, some variants still require fresh water for the process, sometimes even more than evaporation technology (Vera et al., 2023; Halkes et al., 2024).

There are initial indications that direct lithium extraction technologies can be combined with technologies for water reuse and raw-material extraction to protect water quality (Vera et al., 2023; Section 7.4.1.3). The WBGU recommends researching whether and to what extent such integration is possible. The evaporation technology currently used to extract lithium salts, as described in the previous paragraph, already produces potassium chloride as an additional raw material. Direct lithium extraction could also potentially produce substances such as potassium compounds and magnesium compounds as by-products.

Further research is required to assess the potential and possibilities for integrating existing technologies, which are currently at very different stages of development (Vera et al., 2023). One example is the use of ion-exchange resins, where the wastewater can be further treated and reused depending on the quality requirements of the respective process (VCI, 2017).

The treatment of wastewater to extract its metal ions and minerals is an additional benefit in terms of climate-resilient water management (Section 6.1.2) if they are reused as secondary raw materials and extracted while avoiding secondary pollution.

7.4.1.3 Recycling of lithium-based batteries

If lithium-ion batteries are not recycled at the end of their life cycle but disposed of improperly, there is a risk of pollutants being released into the soil and water. Increased lithium concentrations in drinking water and rivers as a result of human activity, i.e. from lithium-ion batteries, have already been detected in Seoul (Choi et al., 2019). In principle, it is possible to recycle batteries; however, the existing industrial recycling capacity is nowhere near the predicted volume of batteries (Neef et al., 2021).

Various recycling processes are available to prevent water pollution and reduce the need for primary raw materials (Nijnens et al., 2023). Water is required for all

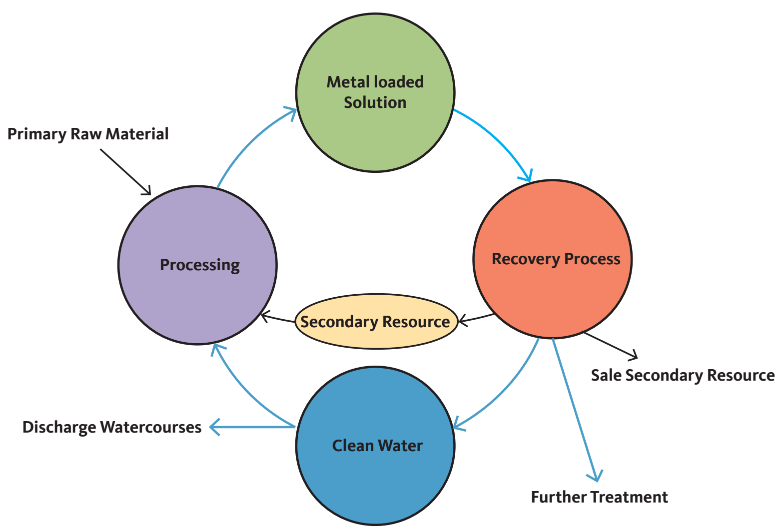


Figure 7.4-2
Raw-material recovery from industrial wastewater. The recovery of raw materials during the production of goods reduces the need for primary raw materials in the production process and enables a reduction in overall costs through their sale. As certain raw materials can have a toxic effect depending on their concentration, raw-material recovery can improve wastewater quality. Depending on the quality standard achieved, the wastewater can be reused in the production process, sent for treatment in wastewater-treatment plants or discharged directly into watercourses.
Source: WBGU

processes, albeit to varying degrees (Fahimi et al., 2022). As processes with comparatively low water consumption have other undesirable effects, the possible advantages and disadvantages with regard to the local water balance and possible other unintended effects should be examined and weighed up when setting up a recycling plant (Wagner-Wenz et al., 2023; Bai et al., 2020). It should also be taken into account that recycling reduces the amounts of primary raw materials that need to be extracted (Section 7.4.2).

Due to the high water requirement in battery recycling, further wastewater treatment with the aim of reusing raw materials makes sense, as this wastewater contains a usable proportion of lithium and can be reused after treatment where appropriate. The water pollution and water consumption associated with the discharge of wastewater would be reduced. Corresponding industrial processes are being developed and would have to be adapted to the recovery of lithium in battery recycling.

7.4.2
Recovery of raw materials from wastewater

One way of protecting water quality and implementing the zero-pollution principle is to recover raw materials such as lithium from wastewater (Fig. 7.4-2). As a valuable resource, wastewater can be used in several ways to close gaps in the circular economy and generate multiple benefits (Section 6.1). On the one hand, wastewater should be further treated and reused depending on the intended use, e.g. for irrigation in agriculture, and depending on the required and given quality. On the other hand, energy can be recovered from sewage sludge during wastewater treatment through biogas production, which is important in the context of the energy neutrality of municipal wastewater-treatment plants aimed for in the amended EU Municipal Wastewater Directive (Section 7.1.2).

In addition, wastewater is a carrier for substances that are under certain circumstances considered harmful, but can also be recovered as valuable secondary raw materials, such as biopolymers, lithium or copper (DuChanois et al., 2023; Schambeck et al., 2020; Paul et al., 2021). As already compulsory for phosphorus in the Sewage Sludge Ordinance in Germany, these substances could also be recovered in the course of wastewater treatment (Section 7.1.2). The National Water Strategy also addresses the recovery of recyclable materials in its vision for water, energy and material cycles, and aims to achieve the necessary sector coupling (BMUV, 2023b). Fig. 7.4-2 shows the relationship between the demand for raw materials for the energy system transformation, the extraction of secondary raw materials and water reuse. In terms of economic efficiency and technical feasibility, however, not all wastewater is equally suitable for recovery. Municipal wastewater is more suitable for recovering organic substances, while industrial wastewater is more suitable for metals (Dutta et al., 2021; DuChanois et al., 2023).

For example, municipal wastewater is a source of polyhydroxyalkanoates, which can replace fossil-based polymers as biodegradable biopolymers. Cellulose can also be recovered from wastewater and used as a binder in building materials or in paper production (Dutta et al., 2021; Schambeck et al., 2020; Paul et al., 2021). Significant concentrations of metal ions are found in industrial wastewater, for example from battery production, and in wastewater from mining. In mining, non-extractable metals washed out of the ore are collected as waste in sedimentation tanks. The first step in recovering metal ions from industrial wastewater is to identify valuable metals. These are generally critical materials such as rare earths, for which there is a high risk of supply disruption to industry, but which are essential for the energy transition, among other things. Further criteria for evaluation include low recycling rates from products, high energy costs in raw-material production and rare geological deposits. The need of new mining areas for the recovered materials could be reduced, the volumes of the sedimentation basins in the mines could be downsized, and the pollution of surrounding waters could be reduced (Section 2; Section 3; Dutta et al., 2021; DuChanois et al., 2023).

The current technologies for recovering raw materials from wastewater (Dutta et al., 2021; DuChanois et al., 2023) are often very energy-intensive and have to be integrated into an existing process. From a financial point of view, it makes sense if the costs of recovery do not exceed the current market price of the raw material. Energy recovery from wastewater-treatment processes can also help here by providing financial support for the implementation of recovery technologies (EEA, 2022). Methods such as biosorption and bioleaching, in which, for example, bacteria are used to extract metals, are promising as low-cost, energy-efficient and environmentally friendly technologies (Adeeyo et al., 2023; Dutta et al., 2021).

7.5 Recommendations for action

7.5-1 Implement the EU Urban Wastewater Treatment Directive in a targeted way

Expand extended producer responsibility and make it incentive-compatible

The amended EU Urban Wastewater Treatment Directive adopted by the EU Parliament in 2024 stipulates that the manufacturers of pharmaceuticals and cosmetic products must finance at least 80 % of the investment and operating costs for the expansion and operation of an advanced wastewater-treatment stage in sewage treatment plants. In the WBGU's view, it should be examined to what extent it is possible to expand extended producer responsibility to cover more pollutant classes, e.g. toxic and persistent household chemicals and pesticides, as well as substance properties such as toxicity and persistence in the aquatic environment. As a result, all manufacturers of water-polluting products would bear the costs of preserving water quality (UBA, 2023a: 8). The structure should be incentive-compatible: companies should be held accountable, depending on the environmental hazards of the substances and products they put into circulation. This would mean lower contributions to the costs or even exemptions for companies that use environmentally friendly, easily degradable substances. Companies that release highly hazardous substances into the environment would contribute more. Article 9 of the amended EU Urban Wastewater Treatment Directive explicitly envisages a scaled corporate contribution according to the environmental danger of the substances they release. According to the Directive, there should also be exemptions for products that contain substances that are proved to be rapidly degradable or leave no organic trace substances at the end of their lifespan. When implementing the EU Urban Wastewater Treatment Directive, these aspects are crucial for creating incentives for reducing emissions of environmentally hazardous substances.

7.5.2 Reduce diffuse discharges from agriculture and forestry

Introduction of a pesticide tax

Integrated soil and water protection could be implemented via a pesticide levy, for example in the form of a tax. In Denmark, a pesticide tax is already levied based on quantity and risk; this has reduced the pollution of soil and water (Nielsen et al., 2023). The tax's underlying principle – 'the more harmful a pesticide is to humans and the environment, the higher the tax' – would be one building block for achieving the goal of reducing pesticide use in the EU by 50 % by 2030, as set out in the EU's Farm-to-Fork Strategy.

Stricter monitoring of nitrogen, phosphorus and pesticide discharges

The WBGU recommends extending the national monitoring programme for nitrogen and phosphorus associated with the Fertiliser Ordinance (DüV) to other substances such as pesticides and degradation products. In addition to reducing the nitrate content in groundwater, the aim of such comprehensive monitoring should also be to protect biodiversity from eutrophication and pesticides.

In addition to the EU target of reducing pesticide use by 50 %, monitoring and effective countermeasures using restrictive action when the regulatory acceptable concentration of a pesticide is exceeded can significantly

Box 7.5-1

Example: the pesticide chlorpyrifos

One example of the export of a pesticide banned in the EU is chlorpyrifos. Until a few years ago, chlorpyrifos was also authorized in Germany, although the chemical was known to have neurotoxic properties. It is particularly harmful to aquatic organisms such as amphibians. It was only after the European Food Safety Agency classified residues of chlorpyrifos as a risk to children's development even before birth due to its neurotoxic effect – and Germany and other EU countries had already banned the pesticide – that an extension of the EU-wide registration was refused in 2020. There had been initial indications of the neurotoxic effect as early as 1998 (Mie et al., 2018). Although German authorities are currently preparing to include the chemical in the Stockholm Convention, chlorpyrifos continues to be exported from the EU to third countries. As a result, residues can still be detected on citrus fruits, tomatoes and olives imported into the EU, posing health risks to consumers. Above all, however, the (aquatic) ecosystems and human health in the areas of cultivation are at risk (EFSA et al., 2024).

improve water quality at local level. As in the determination of nitrate sources, this requires a closely meshed network of monitoring stations.

Development of biological alternatives to pesticides

The renunciation of chemical pesticides could be expedited by developing biological agents, e.g. microbial, botanical or biochemical pesticides, and by the use of natural predators and agriculturally applicable antibiotics (Ayilara et al., 2023; Seenivasagan and Babalola, 2021; Tomar et al., 2024). These alternatives should also be analysed in advance with regard to their effectiveness and possible negative effects on humans and nature. The approaches could be used to develop nature-based solutions that could offer future prospects for farmers, and development and market opportunities for smaller producers. Corresponding projects could be funded via the BMBF's 'Bioeconomy' research line.

Export ban on pesticides banned in the EU

Chemical companies in the EU continue to export pesticides that can no longer be marketed in the EU itself to countries with less stringent rules regarding their authorization and use (Sarkar et al., 2021). The WBGU therefore recommends accelerating the implementation of the already formulated export ban on pesticides that are no longer authorized in the EU. A ban is not only necessary to reduce pollutants in water cycles; it is also morally imperative. In low-income countries, pesticide users usually do not have sufficient protective clothing and machinery for application to protect themselves from the health hazards posed by the products (Boedeker et al., 2020). In addition, persistent pesticides can return to the EU as residues in food (EFSA et al., 2024). The German government should advocate the EU-wide harmonization of the export ban and the abolition and avoidance of double standards. The export ban in France can serve as a model. It has been in force since 1 January 2022 and, in addition to exports, also bans the production and storage of pesticides that are no longer authorized in the EU.

Develop harmonized pesticide standards

The WBGU recommends multilateral processes for the development of harmonized pesticide standards. At the same time, no agricultural products should be imported into the EU from regions where pesticides are used that are classified in the EU as demonstrably harmful to the environment. A tightening of import restrictions would need to be accompanied by projects financed by development cooperation to support transformation processes in the affected production systems, especially if they are located in low-income countries. Conformity with world trade law must also be ensured.

Stop illegal trade in pesticides

In order to curb the illegal trade in pesticides and chemical fertilisers, international cooperation should also contribute to strengthening cross-border cooperation in this field in Africa, Latin America and Asia. Germany and the EU should also do more to support the efforts of the Organisation for Economic Cooperation and Development (OECD) to combat the illegal trade in pesticides (OECD, 2024).

Extend the Stockholm Convention

An extension of the Stockholm Convention on Persistent Organic Pollutants to include carcinogenic and endocrine disruptors should be sought politically in order to prevent their production and release into the environment (WBGU, 2020).

Reduce pesticide use and water consumption in agriculture

Reducing the use of imported pesticides and fertilisers in low- and middle-income countries serves to protect water and health on the one hand, and to achieve financial independence from imports on the other. The WBGU therefore supports the efforts of the German Federal Ministry of Food and Agriculture (BMEL) to work with African partners to develop sustainable and economically viable agriculture in Africa that is adapted to local conditions; this includes funding relevant research. The aim is to increase yields while minimizing water consumption and nutrient inputs. The German Federal Ministry for Economic Cooperation and Development (BMZ) also supports the development of a sustainable agricultural and food industry with corresponding programmes, e.g. in the ASEAN region. Such programmes should be expanded, i.a. with an additional focus on water conservation and the limitation and optimization of fertiliser and pesticide use. Location-adapted measures can often only be implemented with knowledge of traditional agriculture (WBGU, 2020). Indigenous practices are designed to preserve the fertility of fragile soils – e.g. by increasing humus formation with African black earth (chernozem) – and to protect both green and blue water (Solomon et al., 2016).

7.5.3 Curbing water pollution from pharmaceuticals

Restriction of reserve antibiotics in animal fattening

Reserve antibiotics should only be used with official authorization. According to the Federal Institute for Risk Assessment (BfR), reserve antibiotics were used in 41 % of cases in broiler chickens in Germany in 2022 (BfR, 2023).

Promoting animal welfare to improve water quality

An effective lever for improving water quality, which can be used by policy-makers as part of a One Health approach, for example, is the reduction of livestock farming and a higher prioritization of animal welfare – combined with a lower use of antibiotics. Animal ethics also play a role here. This would also serve to protect human health, as effectively preventing the development of antimicrobial resistance and maintaining the effectiveness of reserve antibiotics is necessary to ensure the right to physical integrity. There is an urgent need for action here. To improve animal welfare, the state also has more far-reaching measures at its disposal than those agreed in the German Antibiotic Resistance Strategy DART 2030. More support should be given to implementing the recommendations of the German Nutrition Society to reduce meat consumption (DGE, 2024).

Restriction of the use of veterinary medicinal products

The use of veterinary medicinal products solely to increase yields in livestock farming, as in hormone-controlled reproduction (Section 3.3.2.1), must be prohibited by law. The aim here is both to protect animal welfare and, in line with the zero-pollution approach, to avoid discharges of veterinary preparations and hormones into the soil and water in the EU and, via corresponding supply-chain laws, in non-EU countries.

7.5.4 Promote the use of modern testing methods

Closer monitoring using high-throughput screening methods

The use of modern (bio-)analytical methods should be expanded in the existing monitoring of drinking water, effluents from wastewater-treatment plants and watercourses, as well as in an extended monitoring network in agricultural areas. Methods and procedures to protect water quality should be promoted with corresponding research lines. Modern environmental monitoring and human biomonitoring using novel and cost-effective non-target screening methods and in-vitro methods make it possible to establish early-warning systems and to link them closely together in terms of space and time using high-throughput analytics (Escher et al., 2021; González-Gaya et al., 2021; Paszkiewicz et al., 2022).

Consistent integration of tests, authorization and monitoring

In line with the zero-pollution approach, the aim should be to establish a closely meshed network for the authorization and monitoring of substances to protect the health of humans and ecosystems. Possible negative effects on humans and the environment should already be recognized and avoided at the development stage of new substances using AI models. Many 'new-approach methodologies' (collective term for a broad spectrum of approaches and animal-testing-free methods, e.g. in-vitro and in-silico methods) can be established, standardized and incorporated into substance-approval procedures at low cost. Results with relevance for humans and the environment should be subject to mandatory documentation. If problematic substances are identified, this information should be automatically forwarded to the authorities responsible for substance authorization, who would then examine possible bans and restrictions. With skilful implementation and dovetailing of authorization and monitoring, the new procedures promise a better protection of waterways by prevention and more closely meshed environmental monitoring, while at the same time reducing costs for companies and monitoring authorities. The establishment of uniform standards with cost-effective procedures also promotes competition between certified testing institutes in the service sector.

7.5.5 Promote the use of alternative wastewater-disposal concepts

Promote the use of innovative wastewater systems

In development cooperation in the field of water, sanitation and hygiene (WASH), the German government should prioritize projects that go beyond the construction of piped wastewater systems and focus on the entire wastewater-service chain (Section 7.3.2). From a technological point of view, this means that hygienic, decentralized, non-piped wastewater systems with faecal-sludge management should be regarded as an equivalent solution on a par with centralized wastewater systems. In particular, the focus should be on improving and formalizing hitherto informal, existing decentralized, non-piped wastewater systems. Faecal-sludge volumes, transport routes and costs, as well as disposal or reuse pathways must also be analysed to prevent the incorrect dimensioning of septic tanks and faecal-sludge treatment plants.

Integration of decentralized wastewater systems into training and practice

In order for hygienic decentralized, non-piped wastewater systems to become an equivalent option to conventional, centralized wastewater systems, the training of engineers and technical specialists must be adapted. At present, the curricula cover almost exclusively the planning, construction and operation of centralized wastewater systems. Planning offices, too, tend to focus on conventional solutions without sufficiently checking whether they are suitable for the respective location. Often there is no analysis of whether the costs of operation and maintenance can be afforded, or whether less affluent population groups in low- and middle-income countries are reached by these solutions (Gambrill et al., 2020). There, too, expertise and capacities for planning hygienic, decentralized, non-piped wastewater systems need to be built up.

Assumption of leadership by national governments

Prioritizing water, sanitation and hygiene (WASH) in the political agenda and the assumption of leadership by national governments can make a significant contribution to improving the WASH situation. A positive example is the 'Clean India Mission', which led to a long-term, significant decrease in open defecation (WHO and UNICEF, 2020: 27, Section 4.5). Following India's example, Nigeria has also declared a 'WASH emergency' and launched the 'Clean Nigeria: Use the Toilet' campaign to end open defecation by 2025 (WaterAid, 2024). The German government should provide even greater support to countries in their efforts in these areas via development cooperation.

7.5.6 Advance the recovery of raw materials from wastewater

Promote the recovery of raw materials from wastewater

By reducing the use of fossil fuels, the water pollution caused by their extraction – and particularly by coal combustion – is decreased. The example of lithium shows that the demand for raw materials associated with the energy transition also involves risks to water quality. However, it also shows that consistent, forward-looking implementation of the circular economy principle can significantly minimize these risks. The necessary wastewater treatment particularly affects raw-materials extraction and product-recycling processes. A resource-conserving combination of recovery processes should be considered which includes further wastewater treatment and the reuse of water, as well as the recovery of raw materials and energy in an efficient cycle (EEA, 2022; VCI, 2017). In future, the influences of raw-material use on the water balance must be preventively quantified and avoided by closed-loop recycling and suitable resource-conserving industrial wastewater treatment. Future recycling technologies require suitable direct water treatment for the recovery of all dissolved substances and compounds.

7.6 Research recommendations

Develop new methods for substance design, substance evaluation and monitoring

The WBGU recommends the further development of procedures for the assessment and labelling of chemicals, in particular for the prediction of persistence, toxicity, bioaccumulation and water mobility. Special attention should be paid to 'new approach methodologies' here. They should be specifically promoted by research projects to establish more comprehensive, standardized test procedures. Methods for determining persistence, toxicity, bioaccumulation and water mobility should be combined into easily measurable, two-stage, high-throughput methods. As a first step, substances, mixtures or other environmental samples should be characterized with a comprehensive set of high-throughput in-vitro tests before the substances are subjected to biodegradation, likewise at high throughput. In the second step, the end products are tested again in a comprehensive set of high-throughput in-vitro tests (Escher et al. 2023). In this way, hazard classification can be coupled with the assessment of environmental persistence. AI approaches too, such as machine learning and neural networks, should be further developed and become mandatory in the assessment of substance properties. These approaches, as well as (bio-)analytical methods and procedures for the protection of water quality, should be promoted via corresponding research lines.

Organic trace substances in low- and middle-income countries

Any future amendment to the EU Urban Wastewater Treatment Directive will require the removal of organic trace substances, such as residues from pharmaceuticals and cosmetics, by the so-called advanced purification stage in wastewater-treatment plants in the EU. This is a technologically and financially complex end-of-pipe solution. In low- and middle-income countries, on the other hand, the focus is currently on providing basic public services and ensuring the supply of water of sufficient quality, as well as sanitation and hygiene.

However, organic trace substances from cosmetic products or pharmaceuticals can also be found in domestic wastewater. Research is needed into how these can be removed with limited financial resources and a restricted availability of technologies. In particular, consideration must be given to which cost-effective and simple technical solutions – e.g. near-natural treatment processes or sequential groundwater recharge – can be used to remove trace substances.

Business models for decentralized wastewater systems

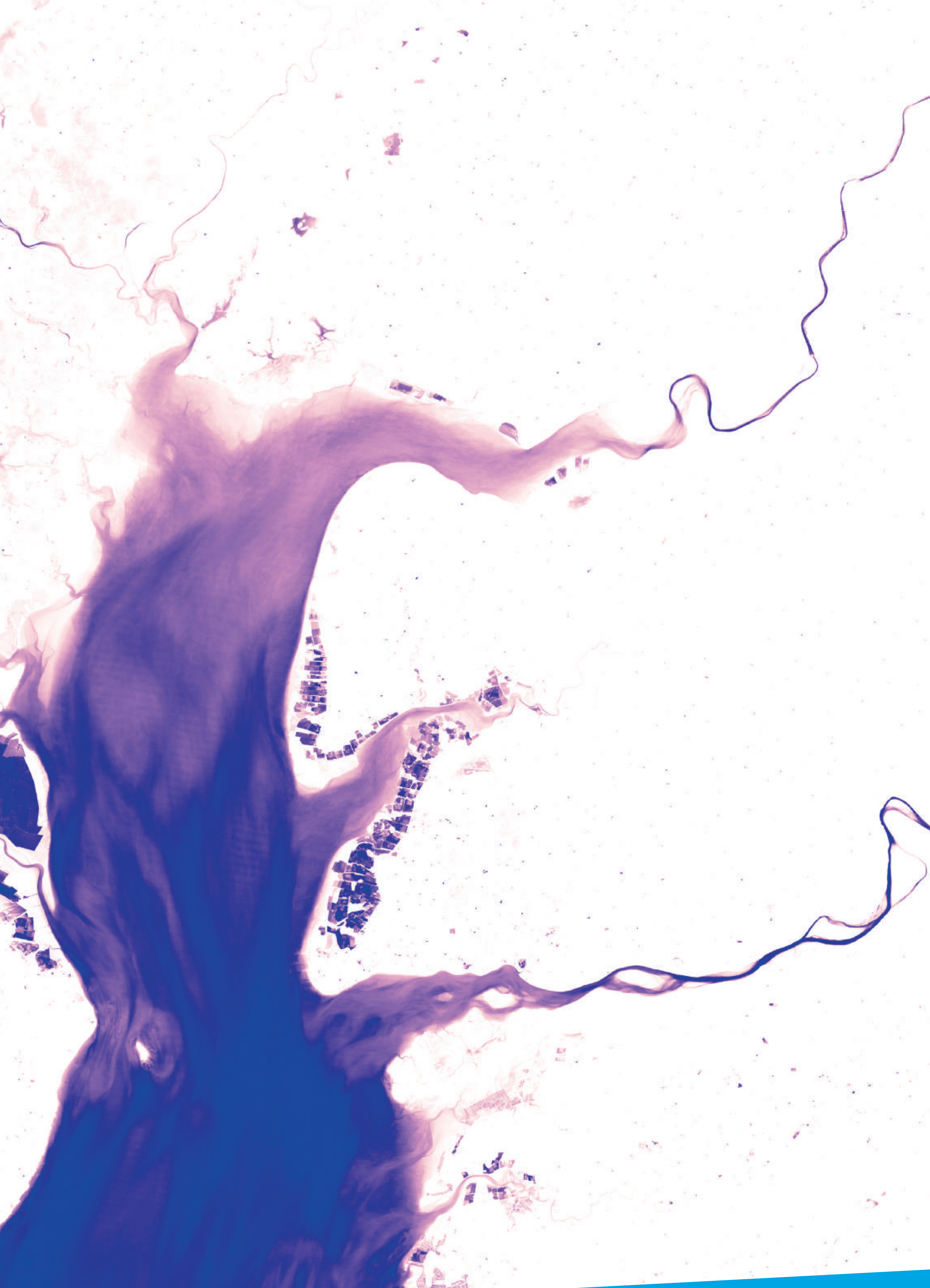
Private service providers are important actors in the provision of universal, safe wastewater disposal via decentralized, non-piped wastewater systems, especially in informal settlements. For example, the World Bank is already promoting projects to identify business models and opportunities for public-private partnerships (PPPs) in all segments of the wastewater service chain (World Bank, 2022). The promotion of PPP models, in which the costs and risks of investments lie with private actors who are supposed to finance them through cost-covering wastewater charges, is sometimes viewed critically (Heidler et al., 2023). It is feared that the mistakes made in the 1990s, when water supply and wastewater disposal were transferred from public services to PPPs, could be repeated with purportedly new PPP models (Heidler et al., 2023). In this context, the WBGU recommends funding research that develops innovative financing and business models for decentralized, non-pipeline-based wastewater systems. Joint research projects with universities and research institutes in low- and middle-income countries are key, as they also serve to build local capacities.

Further development of decentralized wastewater systems

Various technical solutions are used in all segments of the wastewater service chain (containment, emptying, transport, treatment, reuse and disposal) for decentralized, non-piped wastewater systems. In their implementation, the technical solutions known from centralized wastewater systems cannot be transferred without modification – e.g. because the physical, chemical and biological properties of faecal sludge (decentralized systems) and sewage sludge (centralized systems) differ (Michalak et al., 2023). There is therefore a need for research into predicting the characteristics and quantity of faecal sludge produced in decentralized, non-piped wastewater systems, the rapid dehydration of sludge to reduce its volume, and an understanding of the microbiological and physico-chemical processes in septic tanks and latrine pits (Michalak et al., 2023). In addition, research into pathogen inactivation and different options for safe usage is necessary for the safe reuse of treated faecal sludge.

Further development of technologies for recovering raw materials from wastewater

The current technologies still have some disadvantages, resulting in the need for research into the following topics: stability, energy consumption, selectivity and thus flexibility with regard to different materials to be extracted, such as lithium, copper, biopolymers, as well as the avoidance of process-related secondary pollution, e.g. through the further development of technologies based on biological and solar-chemical processes.



Development of climate-resilient water governance

8

An International Water Strategy should be developed as a stimulus for water diplomacy, together with a Water Mapping Initiative for the early detection of impending water emergencies. In the long term, the strategy should lead to an international agreement. The protection of water resources should play a greater role in international economic and trade policy. The interplay between state and self-organized governance and the mobilization of private capital are important. In view of the need to adapt to ongoing changes, science has a key role to play in this context.

Forward-looking, water governance that is able to learn and adapt is needed to avoid future regional water emergencies with a planetary dimension (Chapter 4), to maintain sufficient distance from the limits of controllability (Chapter 5) and to prevent distribution conflicts. To this end, it is important to scientifically determine the global dimension of regional water emergencies and the limits of adaptation, and to emphasize that preventing and combating them is a joint international task. It is therefore important to put climate-resilient water management on the international agenda, make greater use of financing options and strengthen research and education. The international community must be persuaded and motivated – as with the Rio Conventions (UNFCCC, CBD and UNCCD) – to cooperate more closely on the topic of water. It is therefore crucial that science and civil societies around the world take an active role in enabling governmental water cooperation on a scientific basis and incorporating local contexts. They must also be able to offset the consequences of any possible lack of cooperation.

The WBGU recommends that international water governance should be further developed through a new International Water Strategy. In terms of content, the foundations have been laid in the water-related goals formulated in the 2030 Agenda, especially Sustainable Development Goal 6, as well as the references to water in the other 16 goals. Procedurally, further development requires regular, preferably annual, international meetings of the international community, which would be science-informed and further developed based on the current state of research on regional water emergencies with a planetary dimension. The new future International Water Strategy should encourage states to support a well-functioning regional or local self-organization of water management and to develop a national water strategy. The latter requires the organization of a societal process that negotiates which risks can be accepted and which precautionary adaptations and frameworks for transformations are to be made. As far as possible, this process should be scientifically based on existing data and modelling. Furthermore, national water strategies should include climate-resilient and socially balanced water management and short-term crisis-defence mechanisms. Requirements for their establishment and implementation should be developed and interfaces should be identified with other agreements dealing with green and blue water.

In such a dynamically and – despite or precisely because of increasing geopolitical tensions – cooperatively organized framework, existing financing options for the prevention, adaptation and combating of water emergencies should be better used and new ones developed. There is also a need for measures aimed at cross-border trade in water-intensive products.

The strategy's long-term goal should be the adoption of a binding global water agreement by all states, primarily in order to overcome the deficits of the existing

Gulf of Khambhat (India)

water conventions on transboundary freshwater bodies with their focus on regional cooperation and low state participation. Up to now, the focus has been on human use of blue water. A commitment by states to establish green and blue water management for humans and nature would extend this current focus. To achieve this, national and regional strategies, local adaptation measures and crisis-preparedness mechanisms should be democratically negotiated as part of the International Water Strategy (Fig. 8-1).

In the following, the WBGU argues in favour of developing an International Water Strategy (Section 8.1). The strategy should be geared towards the reorganization of international water diplomacy and international water cooperation. The development of the water strategy is intended as a contribution to the UN Water Conferences in 2026 and 2028. This would be followed by an orientation towards the national and sub-national level. Here, the WBGU advocates a proactive state while, at the same time, promoting societal self-organization in water management (Section 8.2). Cooperation with financial and economic actors (Section 8.3), actors from academic disciplines and the education sector (Section 8.4) is at the centre of the second half of the chapter. The concluding sections contain recommendations for action and research (Sections 8.5 and 8.6).

8.1 International responsibility and cooperation

Cross-border water governance should be strengthened at various levels. There is a need for an assumption of responsibility and cooperation at the international level (Section 8.1.1), at the level of the world's regions (Section 8.1.2) and transnationally via economic and trade relations (Section 8.1.3).

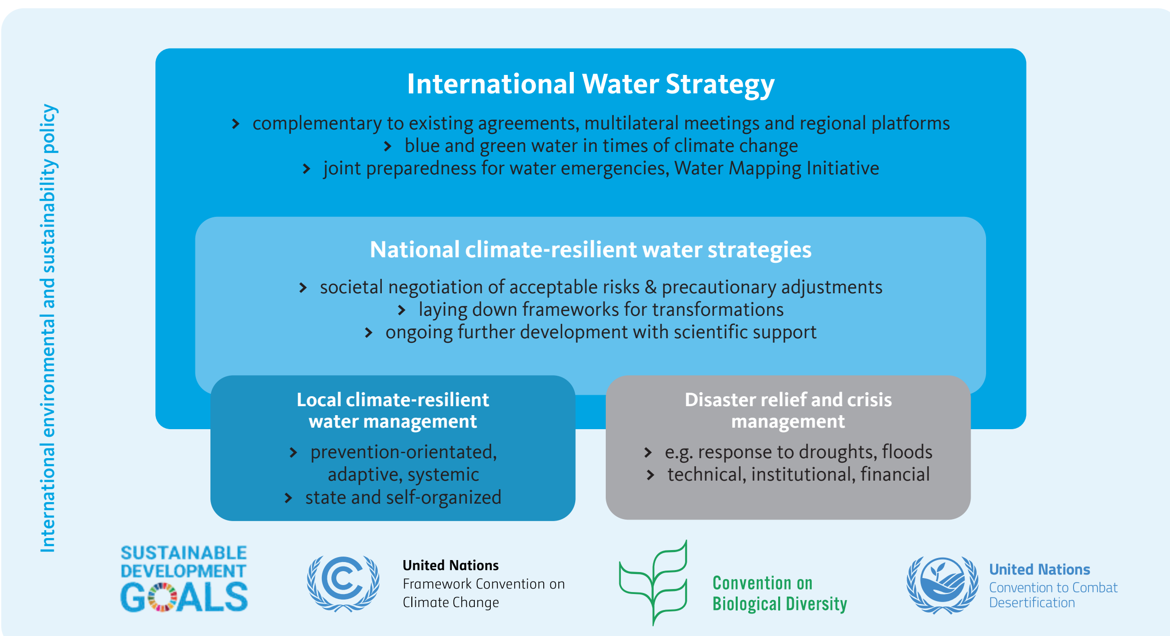


Figure 8-1
Proposal for an International Water Strategy. The International Water Strategy and national water strategies interact with local water management. Local water management involves all relevant actors, including self-organized structures, in addition to municipalities. National water strategies should be formulated coherently with the International Water Strategy. They should initiate local climate-resilient management measures and include emergency aid and crisis management.
Source: WBGU

8.1.1
Strengthen international water governance

Existing international law relating to water has good starting points in terms of content; however, up to now these have hardly targeted overcoming the limits of controllability outlined above, or at combating regional water emergencies with a planetary dimension. Water problems have hitherto been mainly understood and treated as local and regional phenomena (Weiss, 2012). In the following, this section therefore explains how international water diplomacy can be reorganized to effectively meet these challenges (Section 8.1.1). At the same time, more responsibility and coordination are required at the regional and multilateral level. Regional organizations, such as the African Union or regional development communities, lack coordination mechanisms and instruments for enforcing the law vis-à-vis the member states. This applies to regional actors such as the Economic Community of West African States (ECOWAS), the East African Community (EAC), the Southern African Development Community (SADC), the Association of Southeast Asian Nations (ASEAN) and the Latin American MERCOSUR organization. Yet they could play an important role in implementing the goals of the International Water Strategy proposed by the WBGU (Section 8.3.2). After all, responsibility in the sense of the new guiding principle of water as a common concern of humankind should also be assumed by paying more attention to the goals and contents of an International Water Strategy in economic and trade relations. To this end, water should be better integrated into economic decisions at an international level, and international economic relations and trade policy should be aligned with the goals of an International Water Strategy. Low- and middle-income countries should be supported in this endeavour via close cooperation (Section 8.3.3).

8.1.1.1
The 2030 Agenda as a normative basis for international water cooperation

Water plays a key role in achieving the Sustainable Development Goals (SDGs) of the 2030 Agenda. In addition to the key SDG 6 'Clean drinking water and sanitation for all', access to water, its supply and quality, are prerequisites for achieving many other SDGs. It should therefore be considered in all policy areas. Although important progress has been made in terms of water quality and access to water, the mid-term review of the 2030 Agenda shows that the efforts made so far are not enough.

The fact that the percentage of people worldwide with access to safe drinking water rose from 69 % to 73 % between 2015 and 2022 can be seen as a success. An additional 687 million people now have access to safe drinking water. The trends in the areas of sanitation and hygiene are also positive: the number of people with access to safe sanitation rose by 911 million and to basic hygiene services by 637 million (UN, 2023c). Nevertheless, in 2022, 2.2 billion people still had no access to quality-assured drinking water and 3.5 billion lacked access to safely managed sanitation facilities. In addition, two billion people had no opportunity to wash their hands with soap (UN, 2023c). The efficiency of water use increased by 9 %, but water stress and water scarcity remain a problem. In 2020, 2.4 billion people lived in countries affected by water stress. Ecosystems and species are also under pressure. 81 % of the species that depend on inland wetlands have declined since 1970. As far as transboundary governance is concerned, only 32 out of 135 countries affected have concluded operational agreements covering the majority (over 90 %) of their transboundary waters (UN, 2023c).

Figure 8.1-1 shows the global status of implementation of SDG 6. Progress is being made globally, but it varies greatly from country to country. For example, an evaluation of progress at the half-way mark in September 2023 confirms that Germany has achieved the progress it had set itself for SDG 6 (SDSN, 2023). At the same time, this report has highlighted an urgent global need to expand transboundary water cooperation and to shape the necessary structural change for sustainable water management in line with the goals formulated in the 2030 Agenda. An integrated management of water resources at all levels by 2030 has not yet been realized (UN, 2023c). Overall, high-income countries must become more ambitious and implement national indicators in the fields of water protection, reducing water stress and transboundary effects. Here, too, none of these targets will be achieved by 2030 if progress continues at the same pace (SDSN, 2023).

Against this background and in view of the extensively documented scientific fact of increasing global water stress (Chapter 4), it is of key importance to position water as an issue alongside the implementation of the 2030 Agenda in the emerging discussions on a possible post-2030 Agenda:

1. Because of the interconnectedness and interactions of water management and the breadth of climatic, ecological, social, (geo-)political and economic challenges worldwide, an international assumption of responsibility for water supply and quality is still of key importance. It should also be possible, perhaps after 2030, to adopt an agenda jointly drafted by the international community that takes into account the entire range of global challenges and thus shapes a universally applicable policy for the future.
2. The central positioning of climate-resilient and socially responsible management of green and blue water

is essential here. This should already be considered now in the development of models for alternative ways of measuring prosperity (instead of gross domestic product, GDP) and should be integrated into them where possible (Dixson-Declève et al., 2022; Lima de Miranda and Snower, 2020). This realization should also be reflected in a post-2030 Agenda. It is important here to consider the particular impact and burden on women and other marginalized groups in connection with water (fetching water, use of water in connection with care work, period hygiene) and to ensure gender equality.

3. In addition to this formulation of goals to create orientation, the foundations for successful implementation should also be laid. A post-2030 Agenda should incorporate key goal conflicts and synergies in connection with water; it should also outline examples of systemic water policies that are appropriate for each specific context. At the same time, the further development of the policies and their adaptation to the different local contexts should be encouraged.

4. A post-2030 Agenda should also take into account the spillover effects that arise in relation to water. This should already be introduced today into economic-, trade-, environmental- and social-policy instruments as well as into the indicators to be developed for a post-2030 Agenda (Section 8.3.3.1).

For Europe and Germany, it should be borne in mind in these preparatory processes that the EU assumed a pivotal, formative and globally integrating role in the negotiation of the 2030 Agenda in the years leading up to its adoption in 2015. Without the EU's global opinion leadership in this process, the 2030 Agenda would most likely not have been possible. Today – after a global pandemic followed by a debt crisis and a global crisis of confidence, wars in Europe, the Middle East and sub-Saharan Africa – the 2030 Agenda has lost a significant amount of political influence and traction, despite its reaffirmation in New York in 2023. The discussions on the Agenda are dominated by its inadequate implementation, not by the progress it has made possible. The 'Political Guidelines for the next European Commission

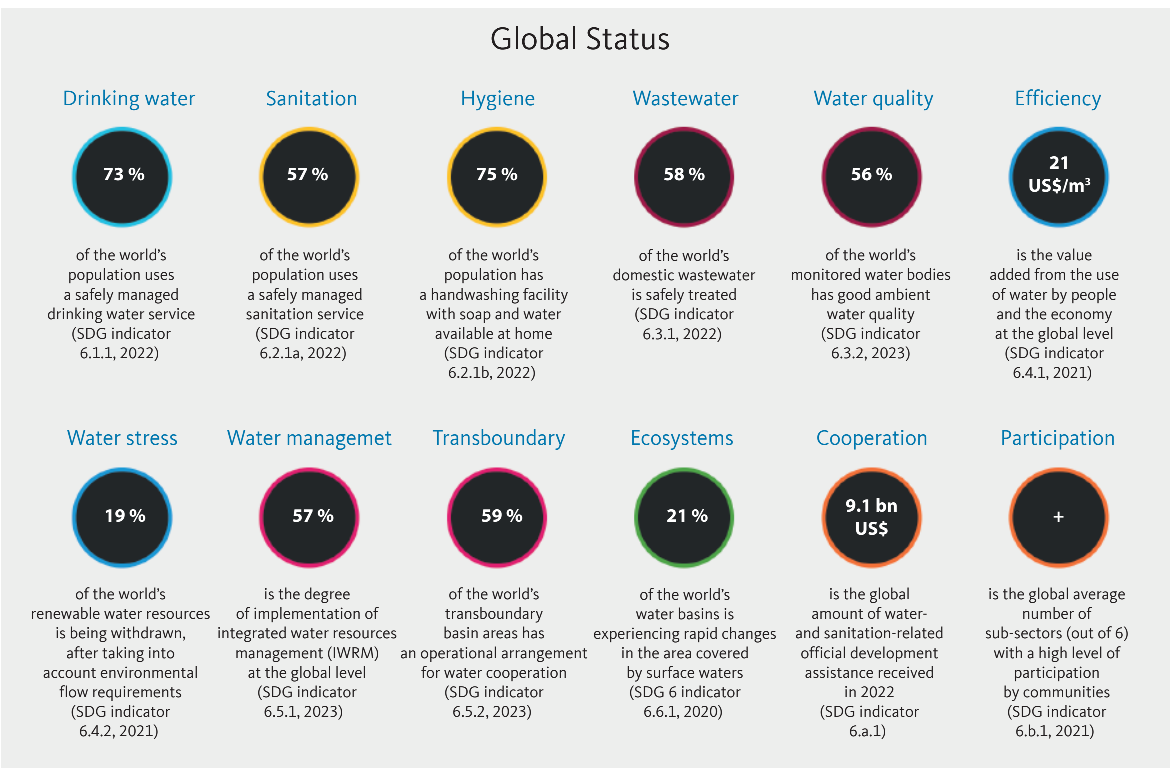


Figure 8.1-1
Global status of SDG 6 target achievement. The global estimates are based on data from individual countries compiled and verified by the relevant United Nations organizations, and supplemented in part by data from other sources. There are 11 indicators for determining SDG 6 target achievement. For some indicators, however, there was not enough data a vailable to make an estimate at a global level.
Source: UN, 2024

2024–29' presented by EU Commission President Ursula von der Leyen do not mention the 2030 Agenda or the Sustainable Development Goals at all. However, especially against the background of the expansion of the BRICS+ community of states in January 2024, the gradual 'de-dollarization' of global trade flows and the ever-advancing expansion of the Shanghai Cooperation Organisation, this appears to be too short-sighted in terms of geopolitical strategy. Instead of relying merely on a Green Deal and Global Gateway, perceived in parts of Southern Africa as 'green colonialism', in its response to China's Belt and Road Initiative in its external relations, Europe and Germany should be focus more on the significance of global opinion leadership for sustainable development and the future. It is about nothing less than ensuring a future worth living within planetary ecological, societal, economic and political borderlines for people worldwide by further shaping the 2030 Agenda and expanding the discourse structures for a post-2030 Agenda. This requires a global cooperation agenda for the future. It also needs progressive alliances that are sought and developed in and from Europe with like-minded forces on all continents. The aim is to find sustainable answers to social polarization, autocratization and geopoliticization, which are diametrically opposed to a joint and cooperative approach to global ecological and economic challenges.

Suitable entry points are needed to enable the transformation intended by a possible post-2030 Agenda. The Global Sustainable Development Report 2023 makes six recommendations in this regard (UN, 2023a). These are integrated and transformative measures – also known as 'transformative shifts' – which are intended to accelerate target achievement on the basis of scenario research and which are also relevant for a possible post-2030 Agenda: (1) human well-being and capabilities, (2) sustainable and just economies, (3) sustainable food systems and healthy nutrition, (4) energy decarbonization with universal access, (5) urban and peri-urban development and (6) the global environmental commons. For the water sector, this means that transformative changes and progress towards achieving progress in the area of 'human well-being and capabilities' will require, among other things, increased investment in water and sanitation infrastructure in order to ensure universal access to piped water and halve the amount of untreated wastewater. For transformative changes and progress in the protection and conservation of 'global environmental commons', among other things water consumption by households, farms and industry must be reduced (UN, 2023a: XXII f.).

8.1.1.2 Windows of opportunity and interfaces at the global level

International water policy is currently in the midst of an unusually active phase (Fig. 8.1-2).

The UN Water Conference in March 2023 led to an in-depth transnational dialogue and new approaches to global water governance. The Water Action Agenda, which resulted from the 2023 conference, contains over 700 voluntary commitments. However, the outcome of the UN Water Conference is relativized by the non-binding nature of the commitments. Furthermore, numerous reform proposals for global water governance were not formalized in a joint, binding decision. Only 28 % of the commitments mention clear sources of funding,

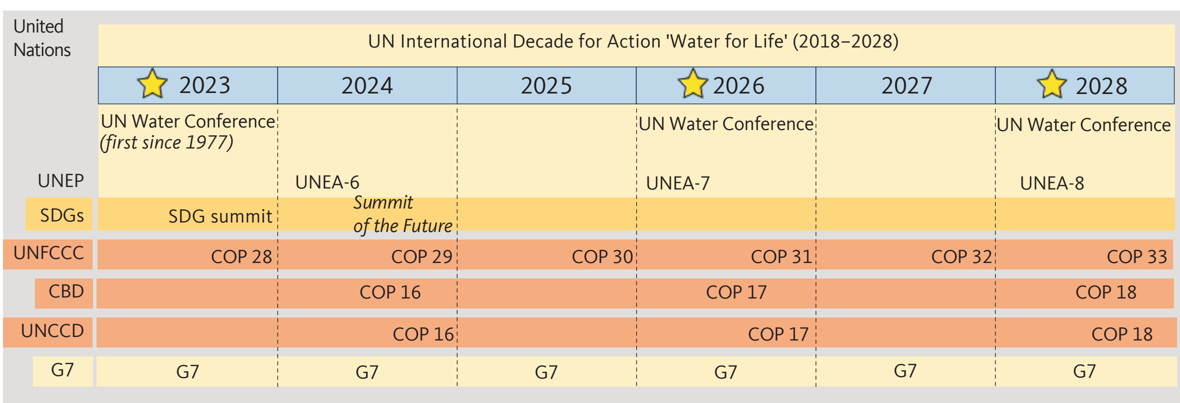


Figure 8.1-2
Processes of water governance 2023–2028. The time line shows the chronological sequence of various water-policy governance processes: meetings of the United Nations Environment Programme (UNEP), international conferences on Sustainable Development Goals (SDGs), climate (UNFCC), biodiversity (CBD), desertification and land degradation (UNCCD), and anticipated meetings of the G7 Water Coalition. The UN Water Conferences are marked with a star.
Source: WBGU

and only 22 % of the commitments submitted up to the end of March 2023 include quantitative targets for results (Iceland and Black, 2023). The planned UN Water Conferences in 2026 and 2028 (UNGA, 2023) are of key importance for the further development of international water governance. The WBGU believes these should be used as a basis for further developing and enriching the existing positive approaches and translating them into an International Water Strategy. It is possible to build on the water-related multilateral activities which are largely based on the 2030 Agenda (Section 8.1.1) and, where applicable, on the 'Pact for the Future' which results from the Summit of the Future in New York in September 2024.

Water-specific issues are also negotiated at the regular Conferences of the Parties to combat climate change (UNFCCC), protect biodiversity (CBD) and combat desertification (UNCCD; Section 8.1.1.3). In addition, G7 countries founded a 'G7 Water Coalition' in 2024 to coordinate common goals and strategies to tackle the global water crisis (G7, 2024).

8.1.1.3
Strengthen international water diplomacy

Water diplomacy comprises negotiation processes that are initiated internationally for dealing with water at all levels (Grech-Madin et al., 2018). In addition to multi-level governance, the policy field of water is characterized by its cross-border dimension and diverse interfaces with other governance processes. In the WBGU's view, an International Water Strategy should be harmonized with the policy areas of sustainable development, climate, biodiversity and land degradation (Fig. 8.1-3). This mainstreaming approach requires close cooperation between the various departments on the political and administrative levels. While the integration of water governance within related policy processes remains important, a specific process for an International Water Strategy in addition should be strengthened and institutionally expanded. Actors who are already working at interfaces should be able to play an active role in shaping this process.

Green water and blue water should be integrated into the processes of the three Rio Conventions (climate, biodiversity, land degradation) as a separate dimension and made more visible, e.g. with regard to water supply and quality for humans and nature, as well as goals for adaptation to the new threats. In other words, they and their indicators should be integrated into the national implementation mechanisms of the Paris Agreement, the Kunming-Montreal Global Biodiversity Framework and the strategic framework of the UNCCD, and become more visible (Table 8.1-1).

Climate governance interface

The interface with climate governance is highly relevant, since climate-change mitigation can have considerable effects on water, both positive and negative. In addition to the goal of limiting the temperature increase to 1.5 °C if possible, but certainly to well below 2 °C, the Paris Agreement also has a global adaptation target "of enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change, with a view to contributing to sustainable development" (Art. 7). At COP28, numerous actors in the water sector called for water-related adaptation goals and indicators to be firmly integrated into the global goal on adaptation (Water for Climate Pavilion, 2024). Negotiations will begin in 2024 on a New Collective Quantified Goal on Climate Finance (NCQG), which is highly relevant for both mitigation and climate adaptation, and thus for water governance and cooperation (UNFCCC, 2024b).

The Paris Agreement is implemented by means of Nationally Determined Contributions (NDCs), which are reviewed on the basis of a mandatory Pledge and Review Mechanism. While some countries formulate adaptation goals and measures in their NDCs, about 50 countries have also submitted National Adaptation Plans (NAPs). The trend is rising: a total of 142 countries have already signalled their interest in an NAP process (UNFCCC, 2023c). The development of NAPs is regarded as a strategic process enabling countries to identify and address their medium and long-term priorities for adapting to climate change (NAP Global Network, 2020). The Green Climate Fund (GCF) plays a key role in supporting the implementation of NAPs (UNFCCC, 2023a). The Loss and Damage Mechanism was set up as part of the Paris Agreement for reconstruction following extreme climate-related events. It received financial commitments for the first time in 2023 and has been hosted on an interim basis by the World Bank.

The mechanism is intended to provide funds for climate-change-related losses and damage following extreme weather events (e.g. droughts or floods) and for the consequences of slow-onset effects of climate change such as sea-level rise, desertification or glacial melting (UNFCCC, 2024a). In addition to climate adaptation, the reduction of greenhouse-gas emissions and thus the energy transition are also of great importance for water and its management (UNESCO, 2024: 65). This includes the choice of technologies for reducing emissions in the energy sector, as well as alternative land-use practices. For example, the increased use of hydropower and other water-intensive technologies involves the risk of increasing the demand for water (Chapter 7; UNESCO, 2024: 69). Operating power plants with carbon-capture and storage (CCS) is very energy- and water-intensive. According to a study, "the widespread deployment of CCS to

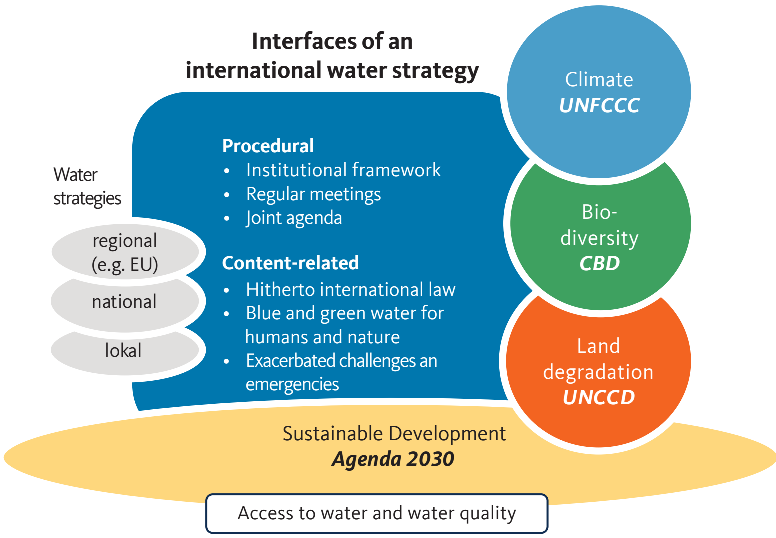


Figure 8.1-3
Proposal for a climate-resilient International Water Strategy. Up to now, the 2030 Agenda has formed the basis for most water-related policy processes. In the WBGU's view, the three most relevant interfaces at the global level relate to the following areas: climate (UNFCCC), biodiversity (CBD) and desertification and land degradation (UNCCD). Regional, national and local water strategies, such as the German National Water Strategy, can open up further interfaces.
Source: WBGU

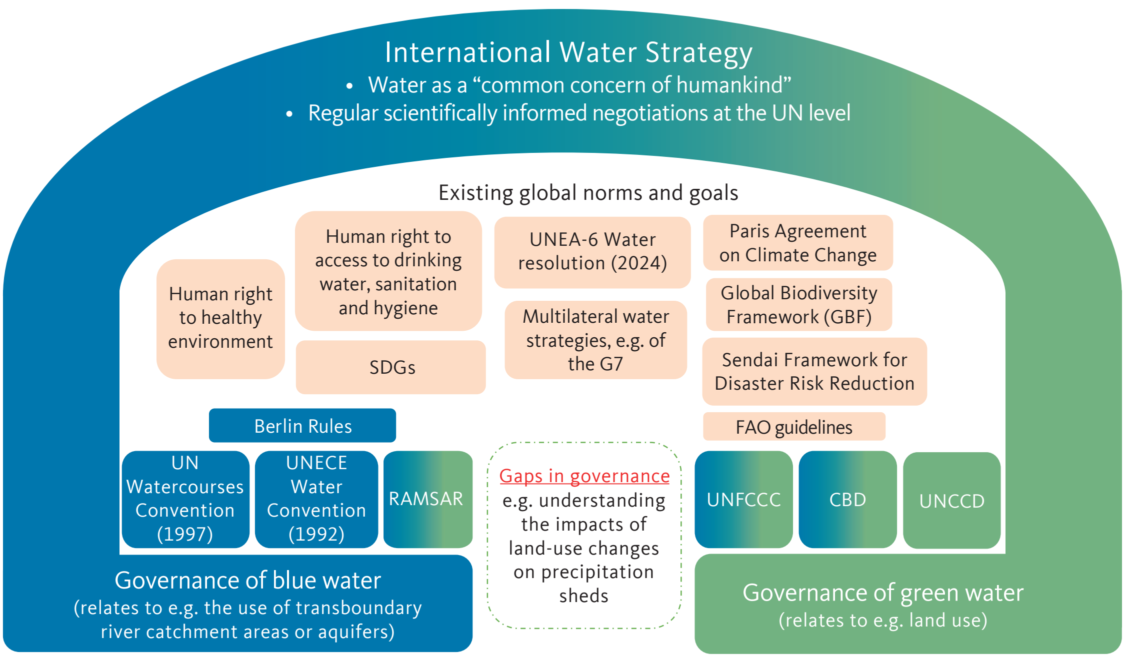


Figure 8.1-4
Proposal for an International Water Strategy with governance on blue and green water. Procedurally, the International Water Strategy provides an institutional framework for this. In terms of content, it should refer to existing conventions and global standards. Such an International Water Strategy would offer the international community an opportunity to move from a hitherto fragmented water governance to one that is as coherent as possible (Herrfahrdt-Pähle et al., 2019: 9).
Source: WBGU

Table 8.1-1
Interfaces between water governance and ongoing processes of international environmental policy. In the WBGU's view, the most relevant interfaces at international level are the 2030 Agenda for Sustainable Development and the processes of the three Rio Conventions on climate change, biodiversity and desertification/land degradation.
Source: WBGU

2030 Agenda on Sustainable Development	Paris Agreement on Climate Change under UNFCCC	Kunming-Montreal Global Biodiversity Framework (GBF) under the CBD	UNCCD Strategy Framework 2018–30. Goal: neutrality of land degradation
› SDG 6 as the main interface, › water affects all goals of the 2030 Agenda, › development financing	› Climate adaptation, › mitigation, › loss and damage, › climate financing	› Biodiversity conservation and ecosystem restoration, › sustainable use › access and equitable distribution of benefits, › biodiversity financing	› Combating land degradation & drought impacts, › restoration of land areas, › funding i.a. via a global mechanism
Respective strategies at state level as potential interfaces for water governance			
› National Sustainable Development Strategies (NSDS)	› Nationally Determined Contributions (NDCs); › National Adaptation Plans (NAPs)	› National Biodiversity Strategies and Action Plans (NBSAPsd Action Plans, NBSAPs)	› National action programmes and their review on the basis of the › Performance Review and Assessment of Implementation System (PRAIS)

meet the 1.5°C climate target would almost double the anthropogenic water footprint" (Rosa et al., 2021: 1).

Biodiversity interface

In addition to the above-mentioned negotiations on the post-2030 Agenda (Section 8.1.1.1), biodiversity governance offers another window of opportunity for the further development of water-related biodiversity targets. The Kunming-Montreal Global Biodiversity Framework, adopted in 2022, is implemented through national strategies and action plans, which are currently being revised in many countries. In this context, integrated landscape and mosaic approaches can facilitate the integration of water (Section 8.5).

The Global Biodiversity Framework (GBF) sets four long-term targets up to 2050 and 23 action-oriented global targets to be achieved by 2030 in order to halt biodiversity loss and conserve biodiversity. The first three targets of the GBF address anthropogenic area use on land and at sea, one of the main causes of the loss of water-related ecosystems. However, the realization of the other targets is also essential for the conservation of water-related ecosystems and ecosystem services (CBD, 2023). This includes, for example, the sustainable use of biodiversity and sustainable production in agriculture, fisheries and forestry, and sustainable consumption decisions (Targets 10 and 16); the reduction of ecosystem pollution (Target 7); the expansion of green-blue infrastructure in urban areas (Target 12), the management of invasive species (Target 6) and the use of synergies between climate protection and biodiversity conservation (Target 8).

Interface with desertification and land degradation

The prevention of land degradation, the restoration of degraded land and the management of drought impacts through sustainable land use are enshrined in the UN Convention to Combat Desertification (UNCCD). This makes the UNCCD a key component in safeguarding the water-storage capacity of soils and preserving green water. The Convention's scope extends beyond drylands. With the inclusion of the goal of Land Degradation Neutrality (LDN) in the list of SDGs, the target of achieving a "land-degradation-neutral world" by 2030 was agreed in 2015 (SDG 15 and 15.3). Land degradation should be compensated, for example, by restoration measures so that no further degradation occurs overall and the net effect in terms of land degradation is zero (Wunder et al., 2018). These goals are also set out in the UNCCD's Strategic Framework 2018–2030, which forms the basis for implementing the Convention's goals at the national level.

Interim conclusion: make the most of windows of opportunity in the coming years

The WBGU is convinced that a new impetus is needed for international water governance, which to date has been too fragmented and ineffective to recognize and adequately take into account the limits of controllability and the regional water emergencies with a planetary dimension. The international windows of opportunity will open in the coming years. This impetus should result in an international strategy that can build on the results of the UN Summit of the Future. In particular, the new impetus should also inform the UN Water Conference planned for 2026.

8.1.1.4 Design of an International Water Strategy

Like the Global Biodiversity Framework (GBF), which supplements the Convention on Biological Diversity as soft law for the target horizon up to 2030, international water governance also requires long-term policy planning at least up to 2030 that takes the 2030 Agenda into account. International water governance can build on existing targets, content and measures of international water law, but it must also go further. By analogy with the GBF, which is accepted by the international community, this soft-law strategy could be called the International Water Strategy. It has its starting point in the recognition of the protection of water resources as a common concern of humankind, which is flanked by a universal human right to water (Box 8.1-1).

The proposed soft-law process follows on directly from the UN General Assembly resolution, which stated the intention to "consider further ways to actively engage governments, civil society, the private sector, the United Nations system and other actors to drive progress and support the realization of internationally agreed water-related goals and targets [...]" (UNGA, 2023, para. 3).

It is important to emphasize here that the main purpose of an International Water Strategy is initially to provide an exchange platform for states and other relevant actors to agree on non-binding standards of water governance. As illustrated by the low ratification figures for the two international treaties – UN Watercourses Convention and the UNECE Water Convention (Section 2.4.2.1) – there is a lack of consensus among states on key issues relating to the transboundary regulation of blue water; in the case of green water, there is even a lack of data and empirical knowledge in some cases. The International Water Strategy therefore consists of both a process and key points of content (Section 8.1.1). On the one hand, the aim is to avoid parallel structures, on the other to institutionalize current processes. Since, as shown, several discussion and dialogue forums on water already exist, the International Water Strategy should therefore provide a platform for exchange and coordination, but also go beyond this and, as an international, coherent strategy, develop concrete regulations – albeit not reinforced by sanctions – as well as goals and principles. These include procedural rules such as reporting obligations on voluntary commitments, like those made as part of the Water Action Agenda at the 2023 World Water Conference. Quantifiable targets and reporting obligations make it possible to monitor compliance with the commitments. Due to the lack of binding force, a failure to meet the target would not be subject to sanctions, but comparisons between states would be possible and 'naming and shaming' would be available as a soft enforcement mechanism (von Bogdandy and Goldmann, 2009). At the same time, countries should be given incentives to participate in the international strategy. This could be achieved through a mechanism that provides scientific and technical expertise, offers additional water-specific cooperation opportunities and financing options for the implementation of common goals, and promotes mutual learning and new networks.

A further advantage of this soft-law approach is that non-binding standards serve as a trailblazer and catalyst for subsequent binding regulations (Gurreck, 2023). In addition, the non-binding mode of action makes a higher degree of flexibility and reversibility possible, so that regulations can initially be trialled and, if necessary, adapted by mutual learning (Chinkin, 2000).

The International Water Strategy should initially address the least controversial issues so that a sense of identification and ownership can be established. Subsequently, issues that are the subject of conflict should also be addressed step by step and, in the longer term, the binding character of the agreements reached under the International Water Strategy should be increased. After 2030, this process should lead to a more legally binding framework for international water governance, similar to the CBD on biodiversity or the Paris Agreement on climate change.

In addition to the interfaces with sustainable development, climate, biodiversity and land degradation, there are also numerous discussion and dialogue forums on water within the United Nations, but up to now their coordination and effectiveness has been insufficient. The landscape of actors is highly fragmented: there are over 30 UN organizations whose mandate includes water. UN-Water is a technical coordination mechanism between 35 UN institutions that is intended to counteract fragmentation, but has not yet been able to do so effectively. As an inter-institutional mechanism, UN-Water also supports the Water Action Decade process and the monitoring of SDG 6.

The UN General Assembly adopted a resolution in 2023 that sets an important course for the development of better coordinated cooperation between UN agencies in the field of water (UNGA, 2023). UN-Water was mandated to develop a new "system-wide UN strategy for water and sanitation" in coordination with the member states, and aims to have an integrative effect in the hitherto fragmented UN system. The strategy was published in July 2024 (UN, 2024).

8.1.1.5
Institutional framework for UN water conferences

In order to strengthen UN water governance institutionally, the WBGU recommends a partial reorganization. A dedicated secretariat at UN level should be established, supported by a scientific Expert Panel that is part of a Water Mapping Initiative (Section 8.4). The proposed UN Water Secretariat should prepare the international conferences (2026, 2028 and beyond). The aim here is to draw on scientific expertise from the Expert Panel, which is made up of scientists from all regions of the world and various specialist disciplines. The composition of the scientific committee should be as diverse as possible; this would offer an opportunity to communicate and explain climate-resilient water governance – which is yet to be developed – to the respective regional and national actors, thereby increasing their level of ownership. In addition, the many different perspectives from different regional and institutional contexts with which the experts are in dialogue could enrich the consultations.

Box 8.1-1

The human right to water as part of the human right to a healthy environment

To date, international treaty law does not explicitly mention a general human right to water, i.e. one that is not restricted to specific groups of people. However, it is sometimes assumed that such a right can be derived from the International Covenant on Economic, Social and Cultural Rights (UN Social Covenant) of 1966 (Cullet and Koonan, 2017; Laskowski, 2010). The UN Social Covenant has been ratified by 172 states, although but not by the USA. Under the UN Social Covenant, the human right to water includes a right to "sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic use" (UN, 2002, para. 2). The amount of water should be sufficient "to prevent death from dehydration, reduce the risk of water-related diseases and provide for consumption, cooking, personal and domestic hygiene requirements" (UN, 2002, para. 2). The right includes appropriate and non-discriminatory access to water. According to the Committee on Economic, Social and Cultural Rights, adequacy means supply (at least 20 litres per person per day according to WHO recommendations), quality (freedom from micro-organisms, chemical substances and radiological hazards in quantities hazardous to health) and accessibility (physical and economic accessibility, non-discrimination and access to information on water issues; UN, 2002). The right to water in the UN Social Covenant is seen holistically, i.e. it includes not only the right to drinking water but also to sanitation and wastewater disposal. Water is seen as an essential resource that is relevant not only for the supply of drinking water but also for personal use in the household and for addressing health aspects (Laskowski, 2010).

The law contains rights to freedom and benefits. The former include access to existing supply systems, especially the water infrastructure, and protect against interventions such as arbitrary interruption or contamination of the water supply. The latter grant an entitlement to the establishment of supply schemes (UN, 2002), such as drinking fountains and an adequate wastewater infrastructure. The core obligations of the states also include the adoption of national planning instruments such as strategies or plans to implement the right to water. In addition, indicators must be defined, and monitoring of compliance with the obligations must be ensured. Furthermore, the states should also provide water-related environmental information and introduce legal protection options in the event of violations of the right to water (UN, 2002). Since the states must therefore create and maintain a sufficient framework that makes it possible for the right to be exercised, the human right also has an objective-legal dimension of protection (Kirschner, 2020).

General Comment No. 15 of the Committee on Economic, Social and Cultural Rights from 2002 was a significant further development of the law. The hitherto rather general statements on what the right entails are specified here as the right to adequate and non-discriminatory access to water for personal and domestic use. The fact that this right is implicitly contained in the UN Social Covenant can be deduced from an interpretation of Articles 11 and 12 of the UN Social Covenant. Article 11 guarantees the right to an adequate standard of living, including food, Article 12 the right to health (UN, 2002).

Although General Comment No. 15, as a legal commentary by a panel of experts, is not binding, the General Comments have a considerable influence on state practice. Moreover, General Comment No. 15 has not been contradicted (Kirschner, 2020). Its influence is particularly visible in the fact that national courts refer to it (High Court of South Africa, 2008), and the right to water has been subsequently included in several national constitutions (Thielbörger, 2014). Several resolutions of the UN General Assembly also recognize a human right to water and refer to General Comment No. 15 (UNGA, 2010, 2013, 2015b). The same applies to the UN Human Rights Council (UN, 2010), which also led to the appointment of a UN Special Rapporteur on access to safe drinking water and sanitation (UN, 2008, 2011).

Neither the resolutions of the Human Rights Council nor those of the UN General Assembly are legally binding. Whether a human right to water exists under general international law, i.e. under customary international law and also outside the UN Social Covenant, is therefore controversial. This presupposes (1) general execution in state practice, which (2) is supported by a corresponding legal opinion (Art. 38 para. 1b, ICJ Statute). The process of normative consolidation, which has now been ongoing for decades, may indicate a growing international consensus, i.e. the existence of the second condition. However, the existence of general execution in state practice in relation to the existence of a human right to water under customary law is less clear, especially since the right is indeed often not guaranteed (Kirschner, 2020; Laskowski, 2010; Thielbörger, 2014).

For almost two decades, Germany and Spain in particular have been key supporters of recognizing the human right to water under international law, although the German Basic Law itself does not contain a fundamental right to water. The WBGU also advocates recognition of a general human right to water, which includes not only access to clean drinking water but also the participation of civil society in water-related decision-making processes and access to environmental information and legal protection. This recognition should also make it clear that the human right to water is a manifestation of the human right to a healthy environment, which is not yet codified either (WBGU, 2023). This right was recognized by the UN General Assembly in 2022 in a non-binding resolution, which in particular calls for the inclusion of this human right in national constitutions (UNGA, 2022). As a rights-based enforcement mechanism, this is more than just a symbol and should be enshrined in constitutional law and catalogues of human rights with enforcement mechanisms, particularly in the Basic Law and the EU Charter of Fundamental Rights. This could close substantive and procedural gaps: in substantive terms, the recognition of a claim strengthens the interests of environmental protection in governmental deliberation processes via health protection. Procedurally, the human right makes it possible for individuals to exercise environmental rights before the courts and to assert them for themselves and the environment (WBGU, 2023).

Box 8.1-2

FAO process on water tenure

Global water-related 'soft norms' include the FAO initiative on water tenure, which is supported by the German government. Water tenure is defined as "the relationship, whether legally or customarily defined, between people, as individuals or groups, with respect to water resources" (FAO, 2020b: 3) and responds to the fact that over 70 % of the world's freshwater is used by agriculture. The FAO has founded a practice-based community on this topic. On behalf of the FAO Committee on Agriculture and the FAO Council, the FAO has committed itself to organizing a global dialogue on water rights with the member states and partners from civil society, academia and the private sector (FAO, 2024a). In the FAO project entitled 'Knowing Water Better – KnowWat', successful consultations on water tenure have been carried out in pilot projects in Sri Lanka, Rwanda and Senegal with the involvement of interest groups from various sectors and state institutions (UNESCO, 2023). Building on the water-tenure approach, in 2012, the Committee on World Food Security adopted the Voluntary Guidelines for the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security (FAO, 2022a). The Voluntary Guidelines on the Responsible Governance of Tenure (VGGT) are an international soft-law instrument dealing with the tenure of land and natural resources (FAO, 2020b). Discussions are being held on extending these land-related guidelines to water tenure (Heck et al., 2022). On the one hand, this would address the issue of access to water and region-specific distribution issues. On the other hand, it would pick up on the inseparability of the land-water nexus. Traditional concepts of property rights are only partially suited to understanding the complex interrelationships involved in access to and the use of natural resources. This applies especially to water, whose dynamics are even more complex due to the relationship between water and land (Srigiri et al., o.J.). In addition, there is the idea of extending the VGGT to green water or rainwater, and including rainwater as part of water tenure.

Since the issue of water-use rights links various SDGs, it has the potential to promote the implementation of the 2030 Agenda. This would increase the protection of vulnerable groups by improving access to water, increasing water security and improving climate resilience (FAO, 2024a). For example, water-use rights are an important field of action in relation to food security (Srigiri et al., o.J.). The relationship between formal and informal water allocation also plays a role in this context (Section 2.4.3); it could influence food security and aggravate inequality; it is exacerbated by climate change. Taking water tenure into consideration could support the integration of formal and informal relationships, e.g. in the context of integrated water resource management (IWRM; Section 8.2; FAO, 2024a).

The Secretariat and the Expert Panel could also continuously review whether jointly agreed water-policy goals resulting from the UN Conferences in 2026 and 2028 are being achieved and the measures submitted for this purpose implemented.

In order to design and implement this future international water governance, greater use should be made of forecast and real-time data based on climate modelling and models of the water balance, as well as on the collection of current data on water availability and demand. Artificial intelligence (AI) and digital methods should be increasingly used in the implementation and evaluation of intended impacts. The use of big data and AI must be accompanied at all levels by measures for data protection, data security, freedom from manipulation and informational self-determination, as well as for ensuring data quality. The protection of privacy and the democratic public sphere in the digital age should therefore be systematically taken into account in the implementation of the SDGs, and firmly established in a post-2030 process (WBGU, 2019).

Intensifying cross-border cooperation to strengthen resilience is essential. A lack of cross-sectoral coordination on water issues and operational agreements in international cooperation jeopardizes the achievement of targets for food, energy, health, climate, life on land and under water, and peace (UN, 2023c). Germany and other high-income countries should support lower-income countries in water management.

8.1.1.6
Strengthen water conventions: integrate green water, dovetail water-related conventions and encourage states to join them

The UN Water Convention and the UNECE Water Convention have sustainability- and precaution-oriented objectives and a set of instruments that focuses in particular on regional cooperation (Section 2.4.2.1). Up to now, however, these conventions have only been ratified by about a quarter of all states (UN Water Convention: 38 ratifications; UNECE Water Convention: 52 ratifications). An International Water Strategy, as proposed by the WBGU, could motivate states to accede to the water conventions under international law, for example by providing a platform for clarifying the controversial issue of the relationship between the rules on reasonable and prudent use on the one hand and the prohibition of harm on the other. This could then result in the adoption of an interpretation guideline for the conventions in which the different interests are reflected.

What the UN Water Convention and the UNECE Water Convention also lack is a focus on green water in addition to blue water. In future, the scope of application should be extended to include the regulation of green water. This is because local interventions in the water balance can also lead to quantifiable negative transboundary changes in the form of fundamental disruptions to precipitation and evaporation patterns. There are also various dependencies between states and regions, which is why action must also be taken between states. For example, evaporation over Central Africa is responsible for two thirds of the rainfall in Nigeria; Egypt's water supply is dependent on use by the upper-Nile riparian states of Sudan, South Sudan, Egypt and Uganda; Argentina is dependent on atmospheric water transport from updraft areas, especially in Brazil (Rockström et al., 2023b: 795; Section 2.2.1). Trade, particularly international trade in agricultural products and the associated virtual (green and blue) water flows, also creates interdependencies between countries and regions that offer opportunities for water-scarce regions, but can also exacerbate problems such as water overuse (Section 2.3.1; Chapter 3).

The maxims of the principles under international law of fair and reasonable use and the prohibition of harm – that the use of a shared resource obliges states to weigh up the interests of all user states and that the use of one's own territory must not lead to any significant impairment of foreign territory – can be applied to atmospheric water transport. However, the interactions between land-use changes and precipitation are much more complex than in the case of transboundary rivers, for example. Further research is therefore needed to regulate the use of green and atmospheric water appropriately (te Wierik et al., 2020). An International Water Strategy can offer a forum for regular information exchange to promote corresponding scientific cooperation with a view to subsequent appropriate regulation. Legal control of the handling of green and atmospheric water could – as soon as sufficient knowledge is available – take the form of information, consultation and approval obligations for projects such as extensive land-use changes that have a significant impact on transboundary water transport (te Wierik et al., 2020). Finally, there is also a need for dovetailing with other treaties under international law, treaties that also affect green water, at least indirectly, such as the Convention on Biological Diversity (Fig. 8.1-4). These interlinkages should be strengthened through appropriate dialogue forums in order to avoid contradictions and increase the coherence and effectiveness of water governance.

In order to take account of the fundamental importance of water for life and health on Earth (as regards supply and quality), the protection of water as a resource should be internationally recognized as a common concern of humankind. This concept is based on the finding that the protection and use of the resource concerned cannot be achieved by individual states alone, but that it requires joint efforts and is in the common interest of the international community (Cottier et al., 2014: 296). This does not lead to the loss or modification of the sovereign rights of states, nor can binding rights and obligations be derived from it. Rather, it serves as a guiding principle, promotes cooperation, favours a fair distribution of benefits and burdens (UNEP, 1991: 254), and can thus influence the interpretation of norms under international law, such as world trade law (Strank, 2019: 435).

In this respect, it is possible to build on the conventions in the climate and biodiversity sector, which categorize the protection of the climate and biodiversity as a common concern of humankind (UNFCCC, 1st Preamble; CBD, 3rd Preamble). Water scarcity and pollution, like biodiversity loss, have the most direct impact locally, so that protective measures must also be taken mainly locally. By way of contrast to the principle of the common heritage of mankind (e.g. 'the Area' in the deep seabed regime, Article 136 of UNCLOS), the common concern of humankind principle applies to matters within the territory of sovereign states (Brunnée, 2007: 552 f.), which would be another parallel to the Convention on Biological Diversity and the Framework Convention on Climate Change.

Overall, there is a need for institutional changes, not only to ensure long-term and continuous globally representative monitoring by an international institution, but also to guarantee a long-term and continuous framework, intergovernmental cooperation and dispute settlement. The precise organization of this should be one of the goals of an International Water Strategy. It is also conceivable that UN-Water could be given a stronger mandate to help determine the programmatic direction of UN organizations.

8.1.1.7
Consideration of the International Water Strategy in UN processes and outside of UN bodies

Not only the implementation of voluntary state commitments under the Water Action Agenda (UN, 2023b: 21) but also the proposed International Water Strategy should be followed up in future at the annual High-Level Political Forum on Sustainable Development, and through further follow-up and review processes in intergovernmental, private-sector and non-governmental forums. In this context, the UN Special Envoy for Water can take on a hinge function and contribute to the necessary integration of different policy areas.

However, institutions outside the UN system should also be involved in order to promote this integration with other international organizations and processes. How important is the reorganization of the World Bank, International Monetary Fund, New Development Bank and Asian Infrastructure Investment Bank, for example? What role do regional banks play in financing water policies in their implementation?

8.1.1.8
Create policy coherence internally and externally

As part of their international political actions, Germany and the EU should establish policy coherence between the various external policy fields relating to water as well as between the external and internal fields. This is particularly important for Europe's and Germany's credibility and ability to act internationally, which depend on the expansion of strategic alliances with countries on all continents and from all income groups. In the context of their international relations, Germany and the EU pursue a wide range of goals that result, on the one hand, from international agreements on climate and environmental policy and, on the other, are made up of economic interests or geopolitical strategic interests and values. Political measures to promote these goals must be checked for compatibility and coherence. This can affect a wide variety of water-related areas, e.g. securing Germany's energy requirements (e.g. gas extraction in Senegal and hydrogen production in Namibia), agricultural subsidies that are incompatible with the protection of water resources, or the impact of investment agreements on sustainable water use and management. Particularly against the background of geopolitical power shifts, the importance of trusting partnerships and ensuring Germany's credibility in its own political actions is increasingly moving to the centre of attention of political considerations. Also in preparation for the upcoming processes to negotiate a new post-2030 Agenda, the promotion of European and German credibility in the eyes of strategic partner countries worldwide is also of key importance.

8.1.2
Promote regional assumption of responsibility and coordination

Alongside the international and national assumption of responsibility, there is above all a lack of accountability and coordination at the regional level (Box 8.1-4): although the EU's water-legislation instruments (Water Framework Directive and its daughter directives) provide good legal regulations, there is a lack of adequate implementation by the member states. However, the EU Commission can secure redress for non-implementation before the ECJ by instigating infringement proceedings.

The growing relevance of a European, climate-resilient water policy has been increasingly evident since 2023. The European Economic and Social Committee (EESC) proposed a Blue Deal in 2023, quoting 15 principles to emphasize the urgency of a cross-sectoral, sustainable European water policy (EESC, 2023). The proposal was supported by members of the European Parliament from the 'MEP Water Group' (MEP Water Group and EESC, 2023). The European Commission announced a water-resilience initiative in 2024, which has so far only resulted in informal discussions and has not yet led to the development of a European water strategy (Canas, 2024; Europäisches Parlament, 2024b). In addition, existing EU legislation, such as the EU Water Framework Directive and the EU Urban Waste Water Directive, which aims to protect water quality, should be effectively implemented in the member states (Section 7.5.1).

Regional organizations such as the African Union, ASEAN and MERCOSUR lack the kind of comparable coordination mechanisms and law-enforcement instruments vis-à-vis the member states that are characteristic of a supranational organization such as the EU.

Institutionally, international water governance should be organized through intergovernmental meetings at both global and regional level. Regional governance platforms have proved their worth in the Sendai Agreement on Disaster Risk Reduction (Box 8.1-3), where they regularly assess implementation progress and share approaches and knowledge, e.g. on policies, programmes or investments. Similar to the water sector, achieving the Sendai goals requires improving the implementation capacity and capability of low- and middle-income countries, especially the least developed countries (LDCs), small island states and African countries, since they face special challenges. Regional platforms are well suited for

Box 8.1-3

Example of regional governance platforms: Sendai Framework for Disaster Risk Reduction

The experience of the Sendai Framework can serve as a model for the water community to translate the regional and global dimension of water into an appropriate governance architecture. The Sendai Framework (2015–2030) was adopted in Sendai, Japan, in 2015 and pursues the overarching goal of reducing the scale of disasters and associated risks, and improving public preparedness (Sendai Framework, para. 17). The Sendai Framework is coordinated by the United Nations Office for Disaster Risk Reduction (UNDRR), which is an office of the United Nations Secretariat and headed by a Special Representative of the United Nations Secretary-General for Disaster Risk Reduction.

The Sendai Framework builds on the positive experiences made with combining global and regional governance levels. It has a global platform as well as regional platforms for Africa, North and South America, the Arab countries, Asia-Pacific and Europe-Central Asia (UNDRR, 2024b). The regional intergovernmental organizations are expected to play an important role here. The EU's role in the regional platform for Europe-Central Asia shows that this can be achieved (UNDRR, 2024a, Sendai Framework, 2019, German version, para. 28c). Regional platforms can act as an interface for development and climate issues and promote integration into other sectors (Sendai Framework 2019, German version, para. 28c).

highlighting regional differences. They make it possible for affected countries to develop their own regional strategies on which to base implementation measures.

Multilateral cooperation communities can serve as a bridge between the different levels of governance (WBGU, 2020: 277). They can bring together 'coalitions of the willing', both globally and regionally, to exchange ideas on effective solutions and provide mutual support.

8.1.3
Use the opportunities of economic and trade relations

In line with the new guiding principle described in the proposed International Water Strategy, water should be understood as a common concern of humankind and taken into account accordingly in economic and trade relations. The overarching goal should be to use and strengthen the potential for the protection of water resources, growth, development and food security, and to avoid negative effects such as pollution, overuse and the associated environmental impacts.

Trade and economic relations are drivers of growth and development, employment and poverty reduction (Engel et al., 2021; Europäische Kommission, 2016). Trade can contribute to food security (Section 2.3.1). Trade and economic relations can also have a positive impact on environmental protection and resource conservation. Experience shows, for example, that traded agricultural goods can be produced where they require less water, and that trade thus leads to water savings from a global perspective (d'Odorico et al., 2019; Section 2.3.1). Trade can contribute nationally to the protection of the environment and resources, for example by favouring the spread of technologies, products or management practices that enable more efficient water use or a reduction in pollution. Trade can also offer incentives to adopt stricter environmental standards, which in turn encourage the development of cleaner production processes and technologies (OECD, 2019b; WTO, 2023). Moreover, trade can lead to the adoption of water-saving technologies and thus to improved water-use efficiency and water savings (Kagohashi et al., 2015; Dang and Konar, 2018).

International trade also harbours risks, e.g. for food security and for environmental and resource protection, including the supply and quality of water resources (Section 2.3.1). For example, the EU imports water-intensive products such as animal feed, alcohol and tobacco, vegetables, soya and coffee, as well as meat and other animal products, from the Mercosur countries of Argentina, Brazil, Paraguay and Uruguay, with potentially negative spillover effects on water resources in the exporting countries.

The positive effects described above are therefore neither automatic nor do they necessarily apply to all trade flows. In order to maximize the positive potential of trade and economic relations for climate-resilient water management, water scarcity needs to be adequately reflected in economic decisions. Furthermore, the design of trade and economic relations is crucial.

8.1.3.1
Increase the integration of water into economic decisions at the international level

Integrating the protection of water resources into economic decisions is highly relevant. A basic prerequisite for this is recording the impacts of economic activities on water resources and making water-related risks transparent for actors and investors, e.g. due to changes in water supply as a result of climate change (Section 8.2).

In recognition of an International Water Strategy, states should therefore work towards strengthening and further developing this transparency within the framework of corporate reporting and disclosure obligations, both nationally and internationally. Germany is already

Box 8.1-4

Positive example: the Mekong Agreement

The Mekong Agreement between Cambodia, Laos, Thailand and Vietnam is a positive example of regional cooperation. It came into force in 1995 and serves as a legal framework for cooperation between the signatory states to achieve, among other things, optimal use of the Mekong as well as environmental protection, especially the maintenance of the ecological balance in the river basin and the optimization of multifunctionality. Article 3 obliges signatory states to protect the environment, natural resources, aquatic life and the ecological balance of the river from pollution or other adverse effects resulting from development plans and the use of water and related resources in the river basin. Thanks to these regulations, the Mekong Agreement is regarded as the most progressive treaty for the management of a transboundary water body (Bearden, 2010).

The Mekong River Commission (MRC, Art. 11–33), with a Council (ministerial level), Joint Committee (technical working level) and Secretariat, is responsible for reifying these general treaty objectives and obligations. One of the responsibilities of the Council, which meets regularly, is to decide on plans for the river's sustainable development. The Council's current planning instruments, the Basin Development Strategy 2021–2030 and the Strategic Plan 2021–2025, which reifies this, also name environmental protection and climate adaptation as two out of five priorities. The plans also explicitly serve to implement the SDGs (MRC, 2021b; 2021–2030). Furthermore, the Mekong River Commission has to prepare status reports and monitor the measures adopted.

International water law is determined by the tension between the two central rules of international law – the appropriate and reasonable use of the water resources and the prohibition of causing significant damage to foreign territory through this use (Section 2.4.2.1). The interests of upstream and downstream riparians are usually diametrically opposed. In this context, Article 5 of the Mekong Agreement includes several notification, consultation and consent obligations. According to Article 7, a state must make every effort to avoid, minimize and mitigate adverse effects on the environment, particularly on the quantity and quality of water, the aquatic ecosystem and the ecological balance of the river system, which could result from the development and use of the Mekong's water resources or the discharge of wastewater. In addition, use must be immediately discontinued if another state can provide sufficient evidence that another state is causing substantial damage to one or more riparians. In this case, the signatory states concerned are to clarify the facts of the case and address any damage suffered in accordance with the general rules of international law on state responsibility. Disputes are to be settled at the level of the Joint Committee wherever possible (Art. 34 f.).

There are sometimes tensions within the Mekong River Commission, particularly in connection with dams and hydropower plants, which are not always effectively addressed by the planning instruments (Paisley et al., 2016). The effectiveness of the Mekong River Commission is diminished by the fact that China and Myanmar, as upstream riparians, have not ratified the Mekong Treaty (Chakravarty, 2023; Kinna and Rieu-Clarke, 2017). The lack of participation by local and Indigenous population groups is also in need of reform.

Nevertheless, it can be assumed that the Mekong River Commission has an overall positive influence on the governance of the Mekong, i.e. it contributes to a form of integrated water-resource management that is sustainable, and it facilitates a fair balance of interests among the signatory states. The reasons for this are the functioning data exchange, for example on water quality, flow rates and flood forecasts, and the more detailed organization of the rights and obligations of the signatory states (Schmeier, 2013). The Mekong Agreement is therefore also seen as a model for other transboundary rivers such as the Brahmaputra – the most water-rich river in Asia (Chakravarty, 2023). The fact that the Agreement explicitly delegates the reification of Agreement standards to the Council and the Joint Committee in Articles 5, 6, 18 and 26 has made a significant contribution to this. This includes the appropriate and reasonable use of water resources, the regulation of flow rates, including a time schedule for the dry and rainy seasons, monitoring, joint activities and projects, and environmental protection. One of these arrangements is the Water Utilisation Programme, which was drafted by the Joint Committee and adopted by the Council. Among other things, it specified the procedures for the notification, consultation and agreement of projects, and created a framework for decisions by the signatory states on the basis of precise scientific and socio-economic data, for example through modelling and mutual experimental learning (Paisley et al., 2016). Furthermore, various aspects – such as the procedure for data exchange (MRC, 2001), transboundary environmental impact assessments (MRC, 2023) and water quality (MRC, 2021a) – have been successfully reified in guidelines. Although these are not legally binding, they nevertheless make an important contribution to effective cooperation. In addition, the dovetailing of the MRC Secretariat with the national bodies, the National Mekong Committees, promotes the implementation of the measures adopted in the signatory states (Kinna and Rieu-Clarke, 2017).

taking up this goal in its National Water Strategy and emphasizes the need to strengthen the concept of the water footprint and to take the water footprint and water risks into consideration in production using global supply chains and in the consumption of products (BMUV, 2023b). Private and municipal companies should "voluntarily review their global production sites, supply and production chains for sustainability criteria, their water footprint and water risks and disclose the results in sustainability reports" (BMUV, 2023b: 73 f.). As concrete actions for implementing the strategy, Germany's Federal Government proposes a further development of the concept of the water footprint and an examination of other concepts, e.g. water risks, as well more inclusion of water use and water risks in EU sustainability reporting (BMUV, 2023b, Actions 72 and 74). The further development of the water footprint concept aims to "develop national resource indicators for the water footprint, taking supply chains into account, and to provide product-related data on water use (differentiated according to green/blue/grey water or water-scarcity-weighted) as uniform labelling for relevant products and services" (BMUV, 2023b, Action 72). Environmental labels that explicitly display this information could create incentives for a more sustainable use of water in supply chains.

The WBGU welcomes these approaches by the German government. Water-related indicators from supply chains can not only encourage more sustainable imports and consumption in Germany, but also inform exporting countries about the water-related implications of their economic activities. The information obtained can furthermore be combined with data on regional water shortages and the expected future effects of climate change and used explicitly to create the right conditions for climate-resilient water management. Supply-chain-based indicators are furthermore an important basis for better understanding the effects of trade activities on other countries, also in the water context (so-called spillover effects), and for integrating them into economic decisions, for example on trade agreements.

The annual Sustainable Development Report published by the Sustainable Development Solutions Network (SDSN) records progress made towards achieving the SDGs as well as international spillover effects that could jeopardize achievement of the SDGs in other countries. Specifically in the context of water, the report recognizes that most European countries, as well as North America and Australia, still face major challenges in avoiding the consumption of scarce water resources via imported goods and services.

However, appropriate global efforts and standardised procedures for reporting obligations are required to prevent the addressing of spillovers (by policy-makers or due to the costs of disclosure requirements) from merely leading to exports being diverted to countries with lower requirements (Weko and Lahn, 2024). Cooperation with and support for exporting countries is also essential to improve the documentation of spillovers and the implementation of monitoring (SDSN, 2023; Section 8.3.3.3).

8.1.3.2
Align economic relations and trade policy with the objectives of the International Water Strategy

International economic relations and trade policy should promote sustainable water use and not exacerbate water scarcity in regions suffering from water stress (GCEW, 2023b). Current practice, in which, for example, agricultural subsidies that are incompatible with the protection of water resources lead to distortions in international trade flows, is often not in accord with this principle. A further challenge here is that the effects of trade or investment agreements on water use and management (spillover) are not taken into account in the context of trade agreements (Section 8.2.3.1). Yet, fundamentally different ways of improving the integration of water-related impacts and risks in international trade policy are conceivable, for example within the framework of the World Trade Organization (WTO), regional trade agreements or investment-protection agreements.

World Trade Organization

In the World Trade Organization (WTO), the protection of the environment and resources is currently anchored not so much proactively but primarily in the definition of exceptions (Art. XX, GATT; Zengerling, 2020). Article XX of the General Agreement on Tariffs and Trade (GATT) authorizes WTO members to adopt policies and measures, even if they violate WTO principles, as long as they are necessary to protect human, animal and plant life and health (Art. XX (b), GATT) and/or to protect exhaustible natural resources (Art. XX (g), GATT). Countries must demonstrate that the measures they choose fall into one of these categories and that they are not applied in such a way as to constitute arbitrary or unjustifiable discrimination between countries or a disguised restriction on international trade. Water is not explicitly mentioned. It is often difficult for member states to assess whether a measure will ultimately be categorized as compliant or non-compliant. This lack of legal certainty can have a deterrent effect on the planned introduction of measures (Zengerling, 2020). Several WTO agreements also permit the adoption of measures to protect the environment under certain conditions, e.g. the Agreement on Technical Barriers to Trade. Trade and the environment are also addressed at the institutional level in the WTO through the Committee on Trade and Environment. Among other things, it is responsible for negotiating the relationship between WTO law and potentially conflicting provisions of multilateral environmental agreements such as the CBD, and maintains collaborations with their secretariats. The WTO also cooperates with UNEP (Zengerling, 2020).

WTO negotiations with the aim of removing barriers to trade in environmental goods (Environmental Goods Agreement) – thus facilitating, for example, the spread of drought-resistant crops or technologies to improve use efficiency or wastewater treatment – were interrupted in 2016 and not resumed (Zengerling, 2020). The Trade and Environmental Sustainability Structured Discussions, which have been ongoing since 2021, could work towards a better integration of water in the WTO. The aim is to define and coordinate Best Practices in environmental and trade policies (Weko and Lahn, 2024) – although water is not one of the core topics, but rather has the role of a cross-cutting issue.

Regional trade agreements

Regional free-trade agreements sometimes contain more extensive regulations on environmental protection than WTO law and also address issues on which the WTO has been unable to reach agreement or which have not been negotiated at the WTO (Zengerling, 2020). These include agreements to promote trade in environmental goods and services (e.g. EU-Georgia or New Zealand-Taiwan; Morin, 2019) or the application of environmental safeguards (e.g. EFTA, Article 112 (1); Morin, 2019). However, regional environmental agreements also show the dangers that a lack of integration of water-related spillover effects can have on participating countries. Examples are effects of the North American Free Trade Agreement NAFTA on groundwater supplies in parts of northern Mexico (Gladstone et al., 2021) and the reduction of tariffs on water-intensive agricultural products as part of the Andean Trade Preference Act on water scarcity in Peru (Weko and Lahn, 2024).

The Trade and Environmental Database of the German Development Institute and the University of Laval, Canada, lists about 300 different environmental regulations in 775 trade agreements worldwide (Berger et al., 2017). However, very few of them are explicitly related to water as a resource and its protection, use and management. Many regulations are also rather weakly formulated and their effectiveness is therefore questionable (Zengerling, 2020).

Investment-protection agreements

Foreign direct investment has great potential for supporting climate-resilient development, for example through investment and knowledge transfer in water management, but also in agriculture or urban planning. However, attempts to protect these investments by intergovernmental agreements and clauses in regional trade agreements can also have the opposite effect if, for example, states are sued for high damages because they enforce environmental law (Zengerling, 2020). Regulations on environmental protection have only recently been included in investment-protection agreements, but have so far been rather weak (Zengerling, 2020). The integration of commitments for the protection of water resources and sustainable water management on the part of investors could increase direct investment. However, the role of the International Centre for the Settlement of Investment Disputes (ICSID) should also be re-evaluated, especially its relationship to national jurisdiction. Of around 950 investor-state arbitration proceedings documented at ICSID and other arbitration tribunals up to the end of 2018, almost 400 were related to the environment or resources (Zengerling, 2020).

To sum up, it seems necessary to anchor the protection of water resources more firmly in existing agreements. If possible, this should be done under WTO law in order to achieve coherent regulations for a maximum group of countries – but also in bilateral and multilateral agreements, since reforming WTO law is likely to be difficult in the short and medium term (Zengerling, 2020; Section 8.5.1.3).

8.1.3.3 Strengthen cooperation with low- and middle-income countries

When implementing the measures mentioned (Sections 8.3.3.1, 8.3.3.2), the special situation of low- and middle-income countries must be taken into account, as the protection of water resources should be compatible with their other growth and development goals. Overall, the water sector accounted for only around 4–5 % of development cooperation funding in OECD countries between 2002 and 2018 (OECD, 2022a: 43). Closer cooperation on water-related issues through development cooperation, but also subnationally and at company level, can help low- and middle-income countries to achieve their development goals as well as a more sustainable use of water, and to avoid negative impacts of economic and trade relations on the availability, supply or quality of water. Support is particularly relevant for countries whose vulnerability to water scarcity, water pollution and water-related extreme events makes it especially difficult to guarantee a human right to water and achieve the goals of an International Water Strategy. Support can be provided not only in the form of financial assistance, but also in particular via partnerships for the development and implementation of new technologies or for capacity building. Depending on the context, objectives could include improving water-use efficiency in water-intensive economic sectors such as irrigated agriculture, e.g. by changing irrigation and cultivation methods, preventing pollution, developing alternatives to products and services with a large water footprint for export, or by strengthening local and regional markets and marketing systems. At the same time, effects on water resources – for example in the expansion of renewable energies and the promotion of green hydrogen – should also be considered. It may prove useful to build on existing formats and to develop them further. The following formats can be used, for example:

- The World Bank's Global Water Security and Sanitation Partnership (GWSP), which promotes technical expertise and capacity building to support the water-related Sustainable Development Goals.
- The WTO's Aid for Trade Initiative: Germany could generate impetus here as one of the countries that could provide a large proportion of the pledged EU contributions to Aid for Trade (Europäische Kommission, 2023a; WTO, 2024).

- Bi- and multilateral cooperation in development cooperation: the BMZ already maintains climate and development partnerships, e.g. with countries in the MENA region.
- Water partnerships and Just Water Partnerships: following the example of energy partnerships and Just Energy Transition Partnerships, support could be provided to countries where it seems particularly difficult to guarantee a human right to water or to achieve the goals of an International Water Strategy (GCEW, 2023b: 23 f.).
- Collaborations based on regional policies and measures such as the African Union's Common Agricultural Policy, which regards the expansion of areas under sustainable land and water management as one of its priorities.
- Financial institutions (e.g. regional or multilateral development banks): these can promote multilateral sustainable water regulation and supply, and include them in funding instruments.
- The expansion of cooperation at sub-national and company level is also important for increasing knowledge and capacities as well as developing technologies. The key factor here is that the cooperation should pay off for both sides. There are already a number of existing initiatives in this area:
- The WWF's Water Stewardship Approach (WWF, 2020): with the support of the WWF, companies can identify water risks for their business activities as well as their financial impact, and have countermeasures explained, which they can implement on their own or with local partners.
- The United Nations' Global Water Operators' Partnership (GWOPA): the aim here is to bring together water-infrastructure operators from high- and low-income countries. GWOPA's activities include the mobilization of financial resources, advocacy, capacity development and support for monitoring, documentation and research.
- In Germany, the German Water Partnership (GWP) promotes international partnerships between operators, as well as professional and trade associations. It also devotes itself to developing solution strategies and best-practice examples for various water-related issues worldwide – from agricultural irrigation to urban resilience. The GWP endeavours to open up new markets and improve market access for its members, thus offering them an incentive to join the network. The Federal Ministries for Economic Affairs, Development, the Environment, Research and Foreign Affairs are among the founding members of GWP.
- 'Export Initiative Environmental Protection': since 2016, the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) has been supporting German Green Tech companies in the international dissemination of green innovations, products and services, primarily in low- and middle-income countries with a large requirement for technologies and services in the fields of environmental and resource efficiency (BMUV, 2024). The initiative is also supported by the German Water Partnership GWP, for example.

8.2 Proactive state and promoting self-organization in climate-resilient water management

The interaction between a proactive state and self-organized structures and units offers an opportunity to effectively implement climate-resilient and socially balanced water management (WBGU, 2011). According to the subsidiarity principle, local organizations are to be supported and prepared for regional water emergencies with a planetary dimension. The following section uses various examples to show how this can be achieved.

8.2.1 Self-organized water governance in the context of a proactive state

States have the international and national function of being the main guardians of water supply and quality, and of guaranteeing the provision of public services. They have the obligation to adequately regulate water as a common good, i.a. by establishing instruments based on the precautionary principle and the polluter-pays principle. Examples include producer responsibility, zero-pollutant regulation and a corresponding form of water management targeting the health of humans, animals and ecosystems (Box 8.2-1).

Water governance – and in particular its practical implementation in the form of climate-resilient and socially balanced water management – is always an interaction between political assertiveness and practical water management, dependent on technical infrastructures as well as personnel and control capacities. In other words, water governance always involves an interaction between top-down and bottom-up governance. If the local infrastructures, personnel capacities and local implementation potential are not fully taken into account in the planning of allocation and distribution, there will be friction in the management process – or even misallocations and, for example, distribution patterns that disadvantage certain societal groups, usually at the expense of the quality of water management (Chapter 7) and with it the sustainability of the management of the resource.

Box 8.2-1

UNECE Water Convention: Protocol on Water and Health

The Water and Health Protocol of the UNECE Water Convention – which obliges the contracting parties to take measures to prevent, control and reduce water-related diseases on the basis of the polluter-pays principle and the precautionary principle – can serve as a model for linking water and health (UNECE, 1999). The Protocol requires states to set national and local targets for drinking-water quality and the quality of discharges, as well as for water-supply and wastewater-treatment services. Furthermore, they are to guarantee non-discriminatory access to drinking water and sanitation. This also represents a contribution to granting the human right to water (Box 8.1-1). However, the fact that the protocol has been ratified by fewer than 30 states to date also shows that the proposed soft-law process is needed before a binding regulation can be accepted by a significant number of states (Section 8.1.1.4).

The interaction between state and self-organized water governance – i.e. a combination of top-down and bottom-up approaches in the planning and implementation of water management that corresponds to the societal, infrastructural and ecological realities on the ground – is of key importance for the sustainable management of the resource (Pulido-Velazquez et al., 2022; Girard et al., 2015; Klassen and Evans, 2020; Hornidge et al., 2011).

The role of the state in this context should always be that of a proactive state. The WBGU argues that, in the field of water governance, retreating to a moderating and after-care role is not an option for the state. This is because self-organized non-state actors, complementing and interacting with state actors, can only exploit their potential if the state actively shapes the interaction with self-organized water governance (Section 2.4). An adequate integration of lived, in some cases traditional practices of water management into the formal structures can be ensured in this way. At the same time, however, it is also possible to prevent a situation where, because inadequate state and formalized control structures are cushioned within the framework of self-organization, this contributes to reform needs of the state not being remedied (since they are informally compensated), with the result that 'systems of scarcity management' (Müller, 2000) are perpetuated instead of successively bringing about systemic change (Box 8.2-2).

The example of Uzbekistan is quoted here to illustrate what non-state self-organization can look like in the context of state and hierarchical (top-down) governance. It is not a best-practice example, but it shows that the interplay between a proactive state and self-organization must be set up in a context-specific manner. If the interface and framework between the duties and responsibilities of the proactive state and the dynamics of self-organization are missing, the latter may remain merely a gap-filler of state tasks or, conversely, informal, non-state-organized water governance may run counter to the goals of the common good and equitable distribution.

As in other areas of the transformation to a sustainable society, the WBGU is therefore also in favour of the model of a proactive state in climate-resilient water governance (WBGU, 2011: 203). This is defined as a state that takes active, targeted and participatory measures to promote sustainable development and manage global environmental change. Although civil society and companies sometimes take on key tasks of water governance, especially in situations where water management by the public sector is inadequate (Chapter 2), the state must fulfil its responsibility to guarantee the provision of water, sanitation and disaster risk management.

To this end, it can act as a service provider itself or as a regulator that leaves the water supply to companies or civil-society organizations and other non-governmental institutions within a legal framework with ultimate state responsibility. The example of water user associations in India (Box 8.2-3) shows what such hybrid governance can look like, with the state acting as regulator.

8.2.2
Hybrid governance in dealing with exacerbated risks – national practical examples

The hybrid interlocking of state and self-organized water governance exists in high-, middle- and low-income countries, as well as in all types of societies and regimes. At the same time, the degrees of state and self-organized governance differ, depending on the societal penetration of state control systems. The following examples of existing hybrid governance formats show the extent to which state and self-organized formats can complement each other. They are therefore neither purely examples of best practice nor one-sidedly negative examples. Rather, the aim here is to provide insights into the context-specific organization of hybridity. A future climate-resilient water-management regime requires controlled and planned interaction between the proactive state with all its framework-giving responsibility (top-down) and historically evolved self-organization (bottom-up) in water management, which is already practised in some cases; this kind of governance does not arise out of necessity

Box 8.2-2

Water management in Uzbekistan's agricultures

As part of a BMBF-funded ten-year research project in the 'Integrated Water Resources Management' funding line under Research for Sustainability, it has been empirically documented over a period of years how, in times of severe water scarcity, water users and farmers ensure the conservation of water for their fields not only through legally prescribed channels but also through other channels which, although strategically effective, run contrary to formal institutions and guidelines.

Post-Soviet irrigation farming in Central Asia is still characterized today by the division into centrally controlled large farms and individually managed small farming units. The production systems, which largely stand side by side – in the isolation of the respective laws determining them – represent two self-contained units in the sense of parallel agricultural worlds (Oberkircher and Hornidge, 2011; Veldwisch, 2008). While the centrally controlled, large-scale production of cotton, wine and wheat is regulated by the state via agricultural production plans and generates high yields, smallholder production is largely subject to individual decision-making and creativity (Boboyorov et al., 2009; Herbers, 2006). However, both production systems are dependent on water and therefore on a functioning irrigation infrastructure and water governance (Tischbein et al., 2013).

Since historic times, the two main tributaries of the Aral Sea, the Amu Darya and the Syr Darya, have supplied the water needed to create large irrigation landscapes throughout Central Asia. On the territory of the former Central Asian Soviet republics, the irrigated area supplied by the Aral Sea tributaries was drastically expanded from 4.5 million hectares in 1960 to 7.6 million hectares in 1990 and 8.1 million hectares in 2004 (SIC-ICWC, 2010). For example, in the province of Khorezm, which uses this water directly, the water is channelled to the fields via a complex network of irrigation canals with a length of 16,000 km. Some 275,000 hectares are equipped with irrigation and drainage infrastructure. Around 265,000 hectares of this is used when sufficient water is available (Tischbein et al., 2013). In total, irrigated agriculture accounts for around 95 % of water abstraction.

Agricultural production is dependent on centralized administrations, due to the legacy of the Soviet era and many years of centralized farming with extensive irrigation and drainage systems. The provision of irrigation water is formally the responsibility of state administrative hierarchies, which are responsible for the allocation and distribution of water from the Amu Darya to the transfer points of the water user associations (WUAs). Allocation is the term used for determining limit values for the units and sub-units of the irrigation system.

The first step is to determine the required amounts depending on the size of the area, the soil and the groundwater situation on the basis of static norms. Based on information from the water users, these demand figures are determined via the levels of the WUA, the Sub-Basin Irrigation System Authority (UIS), the Lower Amu Darya Basin Irrigation System Authority (BUIS) and aggregated up to the level of the national Ministry of Agriculture and Water Resources (MAWR). The MAWR defines limit values to determine the quantities of water allocated to the respective system units in a second step from the national to the WUA level (Martius et al., 2009). In the international catchment area of the Amu Darya, it is necessary to harmonize the limits with the water-sharing agreements in the Interstate Commission for Water Coordination of Central Asia (ICWC) between Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan.

In Khorezm – as in the whole of Uzbekistan – there are serious deviations between the official water allocation and the actual quantities of water provided, which in real-life irrigation operations not only depend on the limit values, but are also subject to the influence of a variety of factors (Bekchanov et al., 2010; Hornidge et al., 2011). Individual claims are met using technical aids and social connections, leading to strategic practices that bypass state water management. At least for socially influential actors, this makes it possible to effectively compensate for the limited human, technical and infrastructural capacities of formal water organizations (Hornidge et al., 2013; Oberkircher and Hornidge, 2011; Veldwisch, 2008). The authors argue that this breaking of the rules laid down by the state is socially enabled – by being discursively embedded in the locally accepted political narratives of natural resource management.

but from the opportunity for improved water governance, which can accelerate the implementation of the goals of climate-resilient water management.

Bottom-up or self-managed water organization in Europe – as in many other countries in Asia, Africa or the Americas – often takes place in cooperatives or in forms of municipal co-management. Cooperatives in particular have a long tradition in many European countries and have been widespread there since the beginning of the 19th century (Deane, 2021; Box 8.2-4). There are water cooperatives in Europe, for example in Austria, Finland, Denmark, Germany, Ireland and Spain, for example, especially in rural areas. Water cooperatives are characterized by the fact that the owners are both responsible for and the beneficiaries of the water supply and are not profit-oriented. They have charitable status and are based on the principles of solidarity-based cooperation (OÖ Wasser, 2024a).

Water cooperatives in Austria and Finland, for example, show that a self-managed water supply can be successful, especially in rural areas (Box 8.2-4). In Germany, the multi-actor platform Emschergenossenschaft (Emscher cooperative) is an example of successful water-resource management.

Apart from cooperatives, self-organized water governance can be observed in many countries in situations where the state structures of water management have reached their limits due to insufficient implementation capacity or historically evolved societal scepticism towards state actors and large companies.

One of the fundamental problems in Europe, for example, is pollution from agriculture, mining and residential

Box 8.2-3

Water user associations in India

Agricultural irrigation management in India offers an example of water management by self-organization. For a long time, it was centralized in state hands and generally regarded as inefficient. The main deficits were seen in the insufficient involvement of farmers, which is why a participatory approach has increasingly been pursued since the late 1980s and especially since the early 2000s (Upadhyay, 2006). To this end, the task of irrigation management was transferred to water user associations (WUAs) in line with the concept of integrated water resource management (IWRM; Mollinga et al., 2006; Meran et al., 2021a). Their tasks generally include promoting and ensuring the distribution of water among users, guaranteeing the maintenance of the irrigation system, ensuring the efficient and economical use of water to optimize agricultural production, and guaranteeing environmental protection and ecological balance. One example is the Andhra Pradesh Farmers' Management of Irrigation Systems Act of 1997; Chapter III. Another task is to settle disputes between WUA members and to provide further training in the field of irrigation.

The legal basis for the work of water user associations can be found in the laws of India's individual federal states and varies accordingly from case to case. The same applies to the agro-ecological and agro-economic conditions and evolved structures in various parts of India. The ultimate responsibility for water management always lies with the competent authorities. These can determine the spatial scope of the WUAs' powers and divide or combine them (Cullet and Koonan, 2017). The state supports the WUAs' work financially, at least immediately after they are founded.

One of the strengths of this form of self-organization is that it involves the farmers, thus encouraging them to take responsibility for the irrigation system and to accept the management measures. In this respect, this type of water-management decentralization can be seen as progress compared to the centralized state control previously practised (Madhav, 2009). It has led to more effective and efficient irrigation management in parts of India and helped to minimize conflicts over water distribution (Bassi et al., 2010). An important prerequisite for this is trust between the WUA members and their leadership (Keremane and Mckay, 2007).

On the other hand, various deficits can be observed in the precise organization of WUAs and their institutional process capacities, as well as in their infrastructural equipment. These include insufficient WUA involvement in the decision-making structures of village self-administration (Panchayat Raj) and the integration of constitutional principles, e.g. the granting of special rights to members of particularly disadvantaged castes, the so-called Scheduled Castes (Cullet and Koonan, 2017). At the same time, however, inadequate means of transport (cars or bicycles) repeatedly lead to a limited capacity for practical water management in geographically extensive irrigation systems. In addition, WUA users and members are exclusively landowners or land leaseholders who practise agriculture. Although, under formal law, these can also be women, women are often de facto not recognized as members due to traditional role perceptions (Meinzen-Dick and Zwarteveen, 1998). Occasionally, cases of misappropriation of funds and other forms of a possible abuse of power have been observed as a result of insufficient transparency and accountability obligations (Madhav, 2009).

The Indian WUAs thus illustrate the ambivalence inherent in forms of self-organization. They are not always preferable to top-down state regulation, and their design must be adapted to the respective socio-economic contexts in order to guarantee minimum requirements under the rule of law (Keremane and Mckay, 2007). If there is appropriate regulation and perhaps also state financial support, self-organization can increase the effectiveness and efficiency of water management, as well as its acceptance.

buildings that are not connected to a sewage system. In 2017, around 11 % of the EU population was not connected to the wastewater-collection system (Grebot et al., 2019). In remote regions and in the centre of Europe, for example, water is extracted from the groundwater by households for private and agricultural use. Wastewater is also collected in a similar way and disposed of on site (e.g. in a slurry pit) or channelled into rivers (Grebot et al., 2019). In Spain, where surface water is over-allocated in river catchment areas, groundwater resources are overexploited in many water-scarce regions. To remedy the water shortage, Law 46/1999 introduced water markets into Spanish law, allowing farmers to exchange public water and conclude trading agreements. These two mechanisms have been used sporadically, especially in times of drought (De Stefano et al., 2016).

Current research on socio-technical innovations in urban areas in low- and middle-income countries indicates that universal access to drinking water and wastewater disposal can best be achieved not through centralized, large-scale infrastructure but through a small-scale, self-organized water supply (Blomkvist et al., 2020: 1). The example of Nairobi shows that the formal urban water-supply system is increasingly incorporating practices for water supply in informal settlements. Water users are reached through adaptive innovations, such as vending machines for water, and not – as in the traditional way – via vertical integration and expansion of the official water system (Blomkvist et al., 2020: 10). State and self-organized water infrastructures and practices complement each other here. In Dar es Salaam in Tanzania, local water-supply practices in settlements on the outskirts of the city are replacing the centralized, dysfunctional water system – in practice, there is no clear dividing line between the two systems (Dakyaga et al., 2021: 112). A study on water supply and sanitation provision in Zimbabwe further shows how the involvement of society in planning and designing the water infrastructure can enable the social embedding of this infrastructure and thus also its sustainable use and maintenance (Box 8.2-5).

Box 8.2-4

Forms of self-administration in water management in Europe

Austria, with approx. 6,000 cooperatives, is the country with the most water cooperatives in the EU (data from 2024); about 30 new cooperatives are founded every year (OÖ Wasser, 2024a). The Gramastetten water cooperative is an example of a decentralized, democratically organized water supplier (Hachfeld et al., 2009). It was founded in 1947 and, with 728 members, it is one of the largest water cooperatives in Austria (data from 2023; WGG, 2024). The cooperative's infrastructure is fed from 21 springs in four headwaters (OÖ Wasser, 2024b). Members have access to all relevant information, e.g. on water quality or planned projects, and make important decisions jointly at the general meeting. The fact that it is based on voluntary work results in low administrative costs, enabling low prices for the water supply. The water quality is good and the tariffs are lower than average (Hachfeld et al., 2009).

There are around 1,500 water cooperatives in Finland, and they supply 13 % of the population with water. They operate primarily in rural, sparsely populated areas that were not covered by the networks of urban companies due to a lack of profitability (Luukkonen, 2013, Pietilä et al., 2020). Most Finnish water cooperatives are small and have only a few active members. However, there are also a number of larger, very well organized water cooperatives that are comparable to municipal utilities (Pietilä et al., 2020). The water cooperatives in Finland are very diverse and vary depending on local conditions and requirements (Arvonen, 2017). Many small cooperatives in Finland are facing the challenge of ageing active members and an imminent generational change. There is a risk that undocumented knowledge will be lost, e.g. the knowledge of older active members about the exact position of the supply networks (Pietilä et al., 2020). Small Finnish cooperatives usually have no access to low-threshold counselling services. The structures in Denmark are exemplary in this field. In 2015, the Danish water cooperatives founded an association of 15 experts to advise the cooperatives (Danske Vandværker, 2024; Pietilä et al., 2020).

While cooperatives have been founded mainly in rural areas, in cities there have been positive experiences with other organizational forms such as participatory co-management. One example is the water supplier in Córdoba, Andalusia. Since 1969, the water supply in Córdoba has been provided by the public utility EMACSA, whose services are considered to be of high quality and whose prices are low.

EMACSA's structure is that of a public company that is wholly owned by the municipality. Since 1979, the company has developed a widely accepted and well-functioning structure of participatory co-management. Irrespective of the municipal election results, each party nominates two representatives to the board. The two major trade union groups also nominate two representatives each, and civil-society movements nominate one person. According to surveys, there is a high level of satisfaction with the utility company (Hachfeld et al., 2009; Di Marco, 2023).

Against the background of exacerbated water-related challenges (Chapter 3) with negative impacts on water supply and distribution, the need to consider state and self-organized water governance together in a targeted manner is increasing significantly. The urgently needed, accelerated implementation of forward-looking and sustainable water governance should therefore be understood not only as a top-down promoted measure but also as a targeted and bottom-up hybrid interaction of state and self-organized water governance. Guided by the principle of a proactive state, the WBGU advocates the targeted promotion of the systemic interlocking of both forms of governance. This can also particularly involve states providing financial support for self-organization units. The WBGU refers to this as hybrid implementation governance for climate-resilient water management (Chapter 7).

Dialogue forums with deliberative elements are proposed below as an instrument for shaping successful hybrid governance (Box 8.2-6). Recommendations are then made regarding scientifically informed dialogue forums at all levels.

8.2.3 Dialogue forums with deliberative elements as instruments of hybrid, climate-resilient water governance

With regard to the global water crisis and possible adaptation options, there is a need for a scientifically informed, inclusive discourse on the limits of controllability in the face of regional water emergencies with a planetary dimension (Chapter 4). Participatory dialogue platforms – or a structure of forums at multiple levels – can provide the framework for such a discourse. This requires the inclusion of specialist and scientific expertise and the administration's knowledge, and the integration of diverse societal perspectives and multiple lifeworlds. The forums should be as inclusive and have a composition that is as balanced as possible.

The experience gained with the two-year water dialogue in the run-up to the German water strategy can serve as a model. In structured discussion forums, actors from the water industry and other sectors together discussed the challenges and strategic goals, and developed initial ideas for solutions (Fleischmann and Dworak, 2022). Furthermore, randomly selected citizens from various regions of Germany were included, and their recommendations were taken up in the National Water

Box 8.2-5

Water supply and sanitation provision in Zimbabwe

In many low- and middle-income countries, traditional gender roles mean that women continue to bear the brunt of water activities: they are the ones who collect, transport and use water. They also usually bear the main responsibility for health and childcare, are responsible for the water supply in the household, and promote domestic and municipal water, sanitation and hygiene provision (WASH) (Chihanga, 2019). However, women are often prevented from contributing their points of view and interests politically, e.g. due to a lack of participation in decision-making bodies.

Among other things, the We-Care programme (Davies, 2017) for women's empowerment has studied changes in the water sector in local communities. A key finding was that technical measures alone are not enough, but that technical measures to achieve sustainable-development goals should go hand in hand with social improvements as well as counselling and training services. In the project, the women primarily identified measures that they could implement themselves in the village community, such as opportunities to be trained as pump operators. Many of the once extensively installed pumps in Zimbabwe are defective. Extensive WASH programmes have reduced the percentage of defective pumps from 75 % (out of 47,000) to 30 % (Chihanga, 2019; UNICEF, 2018). Functioning pumps are an important time saver for the women in their daily work – time that can be better used on different tasks; it also protects them from the uncertainties and dangers of fetching water. Functioning pumps give women more choice in how they organize their time and more opportunities to claim their rights and get involved in social, personal, economic and political activities.

As a result, some changes are already becoming apparent in the municipalities analysed: men and boys are now getting actively involved in looking after the village drinking-water and sanitation facilities, which is seen as a first sign that social norms in the communities are changing. Novel approaches could contribute to the empowerment not only of women but also of entire village communities and, at the same time, lead to better and more sustainable implementation and maintenance of the necessary infrastructure. In order to better understand the role of women as pioneers of change, behavioural research (e.g. on social and behavioural change) should be promoted. Another study from Zimbabwe shows that the implementation of measures for drinking-water and sanitation provision (WASH) in a refugee camp without the participation of women as the main actors fails to achieve its goals in implementation and, in addition, women's sanitation and protection needs are ignored (Sibanda et al., 2023).

Strategy (BMUV, 2023b: 6). The evaluation of the water dialogue suggests a multi-phase procedure for future dialogue processes. Initially, small, highly specialized groups could explain activities and challenges in the field of water and prepare the content. A second phase could consist of a variety of inclusive forums in which these proposals are discussed on a broad basis (Fleischmann and Dworak, 2022: 46). Selected actors and randomly selected citizens could participate in this. Representatives of the younger generation, who will be particularly affected by regional water emergencies in the future, could be invited in larger numbers (BMUV, 2024).

It would make sense to link the dialogues conducted at the national level via an interface with the regional governance platforms (Section 8.1.2). Elected delegates from the forums could contribute their experience, exchange ideas and develop joint positions.

Scientifically informed dialogue forums could be established at all levels as an instrument of sustainable hybrid governance (Table 8.2-1). In order to draw attention to the planetary dimension of regional water emergencies (Chapter 4), the topic and negotiation of (water-) adaptation measures should be placed on the national, regional and international agendas. Dialogue forums with deliberative elements at all levels should be institutionally set up and interlinked. In this way, different actors from all areas of society can be motivated and spurred into action to actively contribute in a context-related way to the search for solutions and effective implementation.

The G20 dialogues on sustainable and resilient water management already exist at the intergovernmental regional level, enabling countries to share experience (G20 Water Platform, 2024).

The successes in sustainable, integrated, climate-resilient and socially balanced water management in recent decades – in some cases following the concept of integrated water resource management (IWRM), the water-food-energy nexus or polycentric water-governance approaches (Chapter 2), in others following the 2030 Agenda and the recently launched UN water process – repeatedly point to the fact that sustainable water management that meets today's mutually exacerbating challenges of climate change and geopolitical power shifts, social inequalities and major financial shortages (e.g. debt crises) requires close interaction, coordination and harmonization between top-down and bottom-up water governance. This also means close interaction between state water governance and practised – but also explicitly promoted – self-organization of water management. The precise details of this interlocking of different approaches in different regions of the world and socio-political contexts varies greatly (Chapter 4; Boxes 8.2-2–8.2.5). Governments, civil society and the private sector are called upon to work together closely to shape implementation governance, i.e. to tackle the exacerbated challenges in the water sector by means

Box 8.2-6

Citizen participation and the promotion of self-organization

A democratic culture of participation, both through parties and elected representatives and through innovative, inclusive dialogue processes, is fundamental to the sustainability of political change. Participation reduces the potential for conflict between different actor groups and in this way defuses conflicts of use that can arise, for example, when water is scarce (Kittikhoun and Staubli, 2018; Markowska et al., 2020). The water-specific dialogues should facilitate understanding-oriented discussions on as equal a footing as possible, and support decision-making and self-organization. The more varied the living environments and perspectives of those involved, the greater the potential for understanding and learning. The dialogues should be scientifically informed and can enable social learning in both directions via direct exchange between scientists and citizens (Blum, 2024).

A successful deliberation leads to an experience of political self-efficacy among the majority of participants. The introduction of experience-based attitudes and values by means of argumentation makes it possible for ethical aspects to be included in the discussion. A greater awareness of water as a resource can be developed here through deliberative dialogue forums and a public discourse (Große Hüttmann, 2020; Habermas, 1992), which could trigger a public discourse on a new water ethic (Gerten, 2018; Kowarsch, 2012; Meisch, 2019).

One of the strengths of deliberation is its flexibility. Participation procedures can be adapted to a wide variety of issues and contexts as required (Blum et al., 2022). Depending on the regional problem situation and initial question, either non-affected interested citizens or affected actors, e.g. different water users, can be invited to a dialogue forum. Mixed procedures with randomly selected individuals and organized actors are also possible, as shown by the example of the municipal development councils (Pannke et al., 2024). Dialogue-oriented participation differs from traditional stakeholder participation in that it follows a logic based on understanding rather than interests. The arguments presented are usually developed by the participants in moderated small groups during several workshops, then jointly developed into recommendations. The dialogue forums have an advisory function vis-à-vis the administration and politicians. At the beginning, there needs to be clarity about how the results will be used in the further course of the project.

Dialogue-oriented participation processes can have different orientations – for example in the composition of those involved, who seek a path that works for everyone – usually in iterative processes. Citizens of small, sometimes informal settlements can develop solutions in workshops that can be implemented directly on site, as shown by the example of improving the drinking-water and sanitation situation in Zimbabwe (Chihanga, 2019). Furthermore, interest groups and local-government associations can be involved, as shown by the examples from Brandenburg and Schleswig-Holstein.

Participatory procedures involving voluntary working groups in Schleswig-Holstein under the European Water Framework Directive are a good example of how organized actors with different perspectives can enter into a dialogue. The example also illustrates that power asymmetries and conflicting goals in the water sector have occurred time and time again, and that these should be better understood and researched. An active role, e.g. as 'guardians of green water, water bodies and groundwater' (Blackstock et al., 2010; McGonigle et al., 2012), could turn them into ambassadors and active players in a water transition that pays off both economically and ecologically.

Article 14 of the European Water Framework Directive calls on the member states to already promote active public participation during the planning process. However, the member states must ensure that comprehensive information is made publicly available for the river basin districts and that everyone is given an opportunity to comment. This does not mean that the possibility of active participation is necessarily exhausted with a statement.

A report by the Helmholtz Centre for Environmental Research (UFZ) on the participatory process in Schleswig-Holstein outlines how all decisions made by the working groups were reached by consensus and thus supported by all those entitled to vote (Petersen and Klauer, 2014). "The participants considered it essential that an atmosphere of mutual respect and trust should prevail in the working groups" (Petersen and Klauer, 2014: 12). However, the responsible Ministry of Agriculture, Environment and Rural Areas reserved the right to make a decision independently if no viable solution or consensus could be found, but did not have the right to vote during the process itself. As a rule, the recommendations of the working groups were then implemented unaltered by the ministries (Petersen and Klauer, 2014). The working groups, made up of representatives of regional authorities, corporate entities and associations, had already come together in advance to assess the status quo of the water bodies before the measures were taken. According to the UFZ report, this initiated an early familiarization with the water bodies and the EU directive, and enabled the actors to get to know each other personally. With the incentive of offering the chair of the working groups, Schleswig-Holstein succeeded in actively involving the water and land associations in the implementation of the Water Framework Directive and committing them to compliance with the agreed objectives. This can be seen as a success insofar as the water and land associations mainly pursue economic interests, such as the drainage of agricultural land. However, the UFZ report also emphasizes that this has led to a devaluation of the objectives of the European Water Framework Directive. This can often be observed in participation processes: compromises based on differing interests often lead to a reduction in the environmental requirements down to the minimum consensus.

Table 8.2-1
Dialogue forums on regional water emergencies with a planetary dimension. Proposal on the structure of dialogue forums for dealing with water emergencies and possible limits of controllability at different levels.
Source: WBGU

Level	Focus	Issue	Actors
Local level, cities, municipalities, districts	Discussion of implementation options	What do the limits of controllability mean for our landscape, our village or our city?	› Scientists › Farmers › Randomly selected citizens › Nature conservation › Industry › Provider
Sub-state level	Discussion of options for (construction) planning of infrastructure and adaptation strategies	What do the limits of controllability mean for our federal state?	› Scientists › Administration › Municipalities › Associations › Randomly selected citizens
State level	Discussion on options for preparedness, disaster prevention and early-warning systems	What do the limits of controllability mean for our region of the world?	› Scientists › Administration › Municipalities › Associations › Randomly selected citizens
Regional level	Discussion on options for preparedness, disaster prevention and early-warning systems	What do the limits of controllability mean for our region of the world?	› Scientists › Delegates from the EU/ Asia/ North Africa/ › Americas/etc.
Global level	Discussion of global adaptation goals and adaptation financing, as well as IWRM, with as many countries as possible	What do the limits of controllability mean for our world?	› Scientists › Delegates from state and regional forums › Scientists › SDG actors › UNFCCC actors › CBD actors › UNCCD actors

of the hybrid interaction of state control and practical, everyday water management. In doing so, they should be guided by the goal of ensuring climate-resilient and socially balanced water management.

8.3 Mobilize and organize funding – also for local approaches

The protection of water resources, resilient water infrastructures and the safe provision of water and sanitation need more – and more effective – investments worldwide in order to achieve (far greater) positive effects such as avoided harm, better health, economic development and higher environmental quality. While the public sector continues to play the decisive role, private capital should also be mobilized to a greater extent. Apart from developing the skills and capacities of primarily public companies and regulators, this requires greater transparency about water-related risks in financial markets, a stabilization of revenue sources in the water sector and for water-related projects, and better mediation between water actors and financial actors.

The investment requirement, also in view of socio-economic trends and climate change, is estimated at US$ 6,700 billion and US$22,600 billion by 2030 and 2050 respectively (Khemka et al., 2023, based on widely varying estimates: WWC and OECD, 2015). Although the proportion of the world's population with safe access to drinking water rose from 61 % to 73 % and with safe sanitation facilities from 32 % to 57 % between

2000 and 2022 (UN Water, 2024), even today 2.2 and 3.5 billion people respectively still have to live without these services (UNESCO, 2024). In 2016, it was estimated that in 140 countries with a low provision of WASH services, a tripling of annual investments to US$114 billion would be required in order to achieve SDGs 6.1 and 6.2 by 2030 (Hutton and Varughese, 2016). Water-related investments come mainly from the public sector (Alaerts, 2019). At US$9.1 billion, global official development assistance (ODA) for the water sector in 2022 was more than 4 % below its 2018 maximum (UN Water, 2024). Private actors invest little in the water sector compared to other infrastructure sectors (Alaerts, 2019), partly due to the perceived low creditworthiness and poor efficiency of water suppliers (Khemka et al., 2023; Section 2.5.1). This applies even more in low-income countries, where, for example, the percentage of the water and sanitation sector in private funding leveraged with official development assistance (ODA) was only 1.4 % between 2012 and 2017 (compared to 26 % for the energy sector and 29 % for banking and financial services, for example; OECD, 2019a). The public share is also particularly high for nature-based approaches: in 2017, it accounted for 99 % of all watershed investments in Europe, for example (Bennett et al., 2017). In Germany, some important activities of the National Water Strategy, such as the planned funding programme called 'Climate-related measures in the water sector and watercourse development', are financed from the Action Plan on Nature-based Solutions for Climate and Biodiversity (ANK; BMUV, 2023a). This is one of more than 20 measures linked to funding by the ANK, which runs from 2023 to 2026 and has a budget of €3.5 billion following budget cuts (NABU, 2024). An earlier draft of the water strategy included a separate "immediate action programme for water development and the adaptation of water management to climate change" with a volume of €1 billion over ten years (BMU, 2021).

This is despite the fact that such investments in basic public services pay off several times over: thanks to better health, educational opportunities and higher employment, the global average benefit-cost ratio is 3.4 and 6.8 for drinking-water supply in urban and rural areas respectively, and 2.5 and 5.2 for basic sanitation provision (UNESCO, 2024). In 2019, safe drinking-water, sanitation and hygiene provision could have prevented 1.4 million deaths worldwide from diarrhoea, respiratory diseases, worm infections and malnutrition (Wolf et al., 2023). For example, cholera is transmitted through water and spreads especially quickly under poor hygienic conditions, which are exacerbated during periods of drought. The World Economic Forum (WEF, 2024) estimates that cholera alone will cost global healthcare systems US$51 billion between 2023 and 2050. Investments in early-warning systems, climate-resilient infrastructure, dryland farming, mangrove protection and more resilient water resource management totalling US$1,800 billion by 2030 to avoid water-related risks of climate change could yield benefits of US$7,100 billion i.a. in the form of avoided harm, productivity gains, social benefits and ecosystem services – a ratio of 1:3.9 (GCA, 2019). Nature-based solutions such as wetland restoration often require less investment than technical solutions (but need regular maintenance and corresponding skills; Caretta et al., 2022: 652). In low-income countries, early-warning systems costing US$800 million could prevent losses of US$3–16 billion per year; an advanced-warning time of just 24 hours before an event could reduce longer-term losses by 30 % (UN Water, 2023).

In order to close the investment gap, many strategies emphasize a combination of public and private approaches, for example the World Bank's strategy for scaling up investment in the water sector (Khemka et al., 2023). Also in the current programme to reform the World Bank as a whole, strengthening cooperation with the private sector in order to mobilize investment for sustainable development is one of the cornerstones (BMZ, 2024). This is in line with the Addis Ababa Action Agenda on Financing for Development (UNGA, 2015a). The core idea here is to increase the impact of public funds by attracting additional private investment, e.g. with hybrid financing instruments. To date, the water sector in many countries has been perceived by private investors as less attractive and water companies as less creditworthy, partly due to technical inefficiencies, governance deficits and political, market and currency risks (Alaerts, 2019; Money, 2022; Khemka et al., 2023). As a key prerequisite for greater involvement by private investors, the World Bank (Khemka et al., 2023), Germany with the Urban Water Catalyst Initiative (UWCI, 2024) and others are therefore supporting low- and middle-income countries to build the skills and capacities of public companies and institutions for efficient planning, investment management and operation, supervision, regulation and, for example, the enforcement of water prices. These efforts remain important and also form the basis for investment in climate-resilient water management (Fig. 8.3-1).

However, because of the described exacerbated water-related challenges, regional water emergencies with a planetary dimension (Chapters 3, 4) and the resulting need for change (Chapters 6, 7), the following priorities should be added, and this chapter focuses on these (Fig. 8.3-1): First, greater transparency about water-related risks is needed for companies (in the water sector and outside), municipalities and national economies in order to mobilize and steer investments (Section 8.3.1). Second, more should be invested in locally adapted projects with systemic, often nature-based approaches that

Figure 8.3-1
Selected fields of action in the financing of water-related investments. The focus of the chapter is on the top three areas of action.
Source: WBGU

also have an impact outside the water sector. This means smaller projects – with higher transaction costs from the point of view of large investors – whose returns are also more dependent on political decisions due to multiple benefits that are more difficult to 'monetize' (e.g. government remuneration for the conservation of ecosystem services). Sources of income, especially for sustainable water-related projects and measures or business models, must therefore be stabilized as a whole (Section 8.3.2). Furthermore, better intermediation is necessary between water-related investment projects on the one hand and potential investors on the other – from international and public donors to large water consumers and the private capital market – as well as structured financing models in each case (Section 8.3.3).

8.3.1
Make water-related risks transparent in order to mobilize and steer investments

Many companies are directly affected by water-related risks as water consumers or through water-related extreme events, but also indirectly through supply chains; conversely, they influence the water balance and quality themselves. In addition to water utilities and agriculture (Section 6.3), this also applies to electricity generation (Box 7.4-2) and industry. Many of these companies (and their respective financiers) have reasons to adjust their production, investment and financing decisions, and to invest in the conservation and sustainable use of water resources and disaster-risk reduction. This can be done independently or by participating in joint solutions, e.g. as part of local water funds or international climate adaptation funds (Section 8.1). However, for this capital to be sufficiently mobilized and used efficiently, financial risks – for example from water-related extremes or the effects of economic activities on the water cycle – must be sufficiently known and transparent ('double materiality'). The latter cause costs for the general public, which in turn can lead e.g. to public resistance or stricter regulations, so that taking them into account is also in the interests of the company (Table 8.3-1). In a similar way, the public sector must also be informed about risks, e.g. in infrastructure planning and tendering processes or large aggregated economic risks.

The potential damage caused by water-related risks is significant. At company level, in a study by CDP (formerly the Carbon Disclosure Project) and Planet Tracker, 69 % of the participating listed companies stated that they were affected by water-related risks – involving economic losses of up to US$225 billion (CDP and Planet Tracker, 2022). Together, the water-related impacts of climate change can lead to significant reductions in economic output, potentially exceeding 10 % in some regions of the world (Chapter 3; World Bank, 2016b). This also leads to risks for financial institutions, but only a third of these institutions recorded and assessed these risks in 2021 (CDP and Planet Tracker, 2022). The European Central Bank (ECB), for example, estimates that 10.6 % of bank loans to non-financial companies across the EU are subject to increased flood risk, and 11.2 % and 12.2 % to heat and water-stress risk respectively, which, furthermore, may be concentrated in a small number of banks (ECB, 2021). Since then, a rethink by financial institutions in the EU can be seen, but, even in 2022, none of them comprehensively recorded their climate and environmental risks, and 55 % did not effectively implement formulated targets and plans (ECB, 2022). Yet it is also true for companies that a reduction in risk is often economically worthwhile. For example, a survey by CDP (2021) of 357 companies showed that water risks of US$300 billion compared with reduction or avoidance costs of US$55 billion.

In view of the high investment requirements and the interest of companies, investors and local authorities in minimizing water risks and preserving water bodies, a new market for the private financing of water-related economic activities has emerged worldwide in recent years. The issue volume of 'blue' bonds most recently grew strongly to US$6 billion in 2023, also due to low-income countries such as Uzbekistan, where the

Table 8.3-1
Water-related risk factors that can lead to losses in company values and even turn them into burdens.
Source: CDP and Planet Tracker, 2022

Physical risks	Flooding, drought, declining water quality, ecosystem vulnerability, increased water scarcity and/or stress, and inadequate infrastructure.
Regulatory risks	More stringent water withdrawals and/or discharge permits, mandatory water efficiency, recycling, conservation, or process standards, regulatory uncertainty, and higher water prices.
Reputational & markets risk	Community opposition, increased stakeholder concern or negative stakeholder feedback, litigation, and changing consumer behavior.
Technological risks	Data access/availability, transition to water-efficient and low-water intensity technologies and products – where companies may be left behind if not adopting these new technologies – and unsuccessful investment in new technologies.

government issued a sustainability-related bond totalling US$348 million in 2023 to finance sanitation and the conservation of water resources and water management. However, despite high demand for financing, 'blue' financing instruments still represent a niche market (CBI, 2024; Morgan Stanley, 2023). In order to mobilize private capital even better, improved information on water-related risks and a strengthening of reporting obligations for companies are necessary.

8.3.1.1 Improve available information on water-risk assessment

A good information base is crucial to enable private actors (such as companies, banks, institutional and other investors, auditors, insurance companies) and public actors to correctly assess water-related risks and, in response, become more active and invest in the water sector themselves. There is room for improvement here. For example, an analysis by ECB Banking Supervision found that fewer than 10 % of EU financial institutions use sufficiently detailed and forward-looking information on climate-related and environmental risks (ECB, 2022). This is partly due to a lack of effort. However, it is questionable whether data with sufficient spatial and temporal resolution on water availability, abstraction and storage would be available across the board. Since fluctuations in the water balance are becoming more frequent and more pronounced due to climate change, exceeding limits observed over many years, and there are still major local uncertainties even with mean values (Caretta et al., 2022; Milly et al., 2008; Chapter 3), better and finer-resolution projections and corresponding modelling capacities and scenarios are required, which very few private and public actors are able to develop.

The German Federal Government should therefore improve the collection and collation of daily updated data and long-term projections on local water volumes and water use – and ensure access to such data – as well as the knowledge of local actors on interregional or intersectoral linkages, and also support other countries in this endeavour. Local conditions and the needs of affected and involved actors should also be taken into account. This includes site data, projections on water consumption and pollution in supply chains and production networks, as well as sufficient expertise to analyse and use this information. Corresponding climatological, meteorological and hydrological public services and research institutions may need to be strengthened, networked and their offerings improved for local actors. One possible platform for such data at the European level is the European Single Access Point (ESAP; EU, 2023), which the EU aims to set up in 2027 so that private individuals and potential donors will in future be able to view sustainability information disclosed by companies free of charge, centrally and in machine-readable form, better recognize the potential risks of vulnerable water infrastructures and take advantage of opportunities for water-saving economic activities. At the national level, the improved information on water-related risks and the risk assessments by companies (Section 8.3.1.2) and municipalities should be used to better recognize systemic risks in the context of stress tests.

8.3.1.2 Strengthen sustainability reporting on water-related impacts, risks and opportunities

Companies and investors can assess water-related risks on the basis of information that is already available today – and will be improved in the future. Increasingly, this information is also requested. The EU has been engaged in a comprehensive transparency initiative since 2018, which includes the Taxonomy Regulation (Box 8.3-1), the Corporate Sustainable Reporting Directive (CSRD) and the Sustainable Finance Disclosure Regulation (SFDR), which are all part of the EU Action Plan on Sustainable Finance (Europäische Kommission, 2018). The CSRD aims to comprehensively increase the availability of information on the sustainability of corporate activities, and the SFDR is intended to increase the provision of information to investors. The EU taxonomy is to operate at the interface between the financial markets and the real economy with a common classification system for sustainable 'green' economic activities and, at the same time, eliminate ambiguities in the assessment of sustainable economic activities. The EU's overarching aim is to involve private investors more in the financing of sustainable economic activities, i.a. in relation to water and marine resources (Europäische Kommission, 2021a).

At the same time, there are areas where there is need for improvement: initial experience with the application of the new reporting standards indicate practical implementation hurdles in data collection, verifiability, coverage and international compatibility (Arnold et al., 2023; PSF, 2024; Lötters-Viehof et al., 2023). Due to the internationally patchy and fragmented landscape of reporting standards (Box 8.3-1) and the effort involved in using several standards, investment projects are more difficult to access for international investors, and networked capital markets cannot be used optimally. Efforts are already being made to harmonize climate-change-related standards internationally, for example through initiatives such as the International Platform on Sustainable Finance (IPSF) and the International Sustainability Standards Board (ISSB). The recommendations on climate reporting adopted by the Task Force on Climate-related Financial Disclosures (TCFD) in 2017 now form the basis of numerous climate-related standards in Europe (as part of ESRS E1; EFRAG, 2022) and internationally (e.g. as part of IFRS S2; IFRS, 2023). Similarly, legal sustainability standards relating to water should be harmonized internationally, and Germany and the EU should commit to this.

Box 8.3-1

EU taxonomy for sustainable economic activities related to water and marine resources

The EU Taxonomy Regulation (EU, 2020) is a core component of the EU Action Plan on sustainable finance, which aims to involve the financial markets more closely in the financing of long-term environmental and water targets as part of the EU Green Deal (Europäische Kommission, 2021a). The EU taxonomy enables companies to better communicate their sustainability ambitions to external financiers, and enables financial institutions to assess the sustainability of economic activities and projects and launch suitable financing instruments.

The EU taxonomy follows the principles of uniformity, transparency and bindingness. For an economic activity to be considered taxonomy-compatible (with regard to water and marine resources), it must (a) make a significant contribution to the sustainable use and protection of water and marine resources according to technical criteria, (b) not significantly impair any other environmental objective, and (c) meet minimum social standards. After the EU Taxonomy Regulation came into force in 2018, the EU Commission issued a delegated legal act on taxonomy-eligible economic activities (Europäische Kommission, 2023b). This includes activities such as the manufacture and installation of technologies for leakage control in water-supply systems, construction, expansion or modernization measures for municipal wastewater infrastructure – such as wastewater-treatment plants, sewerage systems or rainwater-management systems – and planning, construction or expansion measures for nature-based flood and drought management and the restoration of coastal or inland water ecosystems (Europäische Kommission, 2023b).

In future, the EU Sustainability Reporting Directive will oblige up to 50,000 EU companies to analyse the materiality of water-related risks for their business model, and thereby report on the taxonomy-eligible and -compatible shares of their turnover as well as their capital and operating expenses. These companies include all large corporations in certain sectors with more than 250 employees, more than €50 million turnover and a balance sheet total of more than €25 million, whereby two of the three criteria must be met. In addition, the regulation also applies to public corporations if they are also obliged to report as large corporations in accordance with country-specific regulations. The reporting obligation will therefore also apply to many water-management companies in Germany and Europe.

Sustainability taxonomies have been launched by many governments in recent years, including in China, South Africa, Japan and Colombia, in order to establish standardized legal regimes with regard to the impact of economic activities on water cycles alongside various voluntary standards (IPSF, 2023). In some cases, such as in South Africa, the EU taxonomy served as a template (Lötters-Viehof et al., 2023). While EU taxonomy reporting will also cover non-European companies in certain cases in the future, there is currently no basis for mutual recognition between different legal classification regimes.

In order to lower the entry barriers to debt financing, especially for companies, and to make nature-based investments more attractive for investors, initial or voluntary reporting could be made easier for small and medium-sized enterprises (SMEs). For example, in 2024 the Singapore government announced grants to cover the costs of initial sustainability reporting in line with new mandatory standards, up to 30 % for large companies and up to 70 % for SMEs (Segal, 2024).

Germany can also share experience on support programmes and capacity-building measures with other EU countries. For example, Denmark provides open-source software, the Czech Republic offers support and appoints ‘administrative experts’, and Poland offers training and information programmes (Europäische Kommission, 2024b).

8.3.2 Make the water sector more attractive via more stable sources of revenue

Investments by private, commercial actors in water-related projects require reliable revenue inflows that can be used to cover operating and maintenance costs and pay investors a return. In view of tight budgets, stable sources of income are also important for public actors. This also applies to – and is often particularly difficult for – locally adapted and nature-based solutions that take particular account of the multifunctionality of water and the importance of green water, and yield ecological, social and economic multiple benefits, which are difficult to record. The following three levers seem particularly promising for stabilizing revenue inflows. The first two in particular generate income for the public sector, which can be invested in the water sector, e.g. in nature-based solutions. The third lever is aimed at rewarding measures with externalized multiple benefits for private actors.

8.3.2.1 Polluters and users must share more of the costs

According to the German Federal Government’s National Water Strategy (BMUV, 2023b: 62), ″greater user and polluter responsibility″ for costs ″can help relieve the financial burden and ensure that the state fulfils its duties adequately for the long term″ and have a steering effect. The polluter-pays principle should for example play a bigger role in covering the costs of operating the water-supply and -disposal infrastructure and of pollution control. This also seems necessary in view of the often limited creditworthiness of infrastructure operators (Khemka et al., 2023). Greater user and polluter responsibility for costs can be achieved through the following measures, among others:

Differentiated tariff structures for drinking-water supply and wastewater disposal: Water and wastewater tariffs based on usage volume with higher prices for large consumers generate revenue and offer an incentive to reduce high consumption. Consumption-based subsidies can ensure that poor households too can afford water-supply and wastewater-disposal services (e.g. many water suppliers in California offer ‘lifeline rates’, i.e. low prices for consumption volumes corresponding to basic needs). However, studies show that such subsidies do not always reach poor households in many low- and middle-income countries. One reason for this is that poor households are often not connected to the water mains (Komives et al., 2005; Abramovsky et al., 2020). Alternatives for reaching households without a connection or water meter are, for example, low basic charges for the water connection or non-consumption-related grants to households to help them pay water and wastewater charges (Komives et al., 2005; Pierce et al., 2020), e.g. with funds from development cooperation.

Appropriate charges for water abstraction, also for large consumers: Water-abstraction charges can also be used to systematically involve large consumers in the costs of measures for water protection, for example, if revenues are earmarked accordingly. The prerequisite, however, is that exemptions for water-intensive industries such as mining and agriculture are abolished; these still exist extensively in many German federal states and OECD countries (Section 2.5.2). In its National Water Strategy, the German government plans to examine the harmonization of abstraction fees charged by the federal states and, if necessary, to introduce uniform federal regulations (BMUV, 2023b). However, it is unclear to what extent this will also reduce exemptions. One problem with the reform of abstraction charges is the partial lack of water-use documentation, e.g. in agriculture. A reform must therefore go hand in hand with improved documentation of abstractions and with demand management.

Charges on water-polluting products and substances: Producers and distributors of water-polluting products and substances should bear a greater share of the costs associated with their disposal and the conservation of water bodies. One important example is levies on pesticides in industrial agriculture. Denmark, for example, has introduced a quantity- and risk-based pesticide tax. According to Möckel et al. (2021), the legal basis for an EU-wide introduction of a pesticide levy is in place. However, water is not only at risk from pesticides and chemicals but also from climate change. Climate-change levies should be set at a level that includes water-related damage. Accordingly, revenue from climate-change levies could be used proportionately to finance the water sector.

Tax revenues from environmental taxes (excluding climate-change levies) accounted for 2.2 % of gross domestic product and 5.5 % of total government revenues from taxes and social contributions in the EU in 2021; of this, only 3.6 % is attributable to taxes on pollution and resources, which also includes the above-mentioned Danish pesticide tax. Germany reported no taxes that fell into the latter category in 2021, and had one of the lowest shares of revenue from environmental taxes relative to total government revenue EU-wide (EuroStat, 2023).

Extended producer responsibility: One way of making those responsible for water pollution contribute to the costs of cleaning is through extended producer responsibility. The reform of the EU Urban Wastewater Treatment Directive provides, among other things, for extended producer responsibility for pharmaceutical and cosmetics manufacturers (Sections 2.4.2.3, 7.1.2). Depending on the quantity of substances they put into circulation and their toxicity, they are to participate in the financing of a fourth purification stage and new monitoring measures. How exactly this participation is realized – whether through taxes, contributions or levies of another kind – is left to the member states. The German Water Strategy (BMUV, 2023b), too, mentions extended producer responsibility for manufacturers and distributors of water-polluting substances and products as an objective to be pursued at EU level.

Benefit-based cost sharing in the financing of public goods: Many measures in the water sector have the character of public goods. This means, among other things, that users can enjoy the benefits of these goods even if they do not contribute to the costs. Examples include technical water- and flood-protection measures such as the construction of dykes and dams, retention basins or infiltration systems, as well as nature-based measures such as the creation of urban green spaces for the retention and evaporation of rainwater. Different actors benefit to different degrees from such measures and should share in the costs in accordance with the benefits they derive. Differentiated levies (Toxopeus and Polzin, 2021) offer one possibility for this. These could, for example, be used to finance flood-prevention measures such as the maintenance and strengthening of dykes and dams, and place a greater burden on property owners who benefit directly from the structures. In Germany, for example, the renovation and construction of dykes is partly financed by differentiated membership fees to dyke associations (e.g. section 79 of the North Rhine-Westphalia Water Act).

Positive side effects of the provision of public goods that can be measured in monetary terms could also be skimmed off via heterogeneous levies (e.g. property tax, service connection charges) and used for financing, e.g. increases in the value of land and property in the vicinity of newly created green spaces (Toxopeus and Polzin, 2021). However, there are often limits to the powers of cities and municipalities to levy charges (Section 8.3.2.2).

8.3.2.2 Strengthen the ability to raise and use funds at the local level

One barrier to the financing of water-related local public goods is the often limited competences of local government and administrative levels to collect their own revenues and decide freely on their use. In order for them to be able to contribute to climate-resilient water management, it seems necessary to strengthen their options in raising funds and in decision-making authority regarding fund use (Section 8.3.4).

Cities and municipalities often have little leeway to levy their own taxes, either because taxes are generally levied centrally or because, in federal countries such as Germany or the USA, the same things may only be taxed once and this is already done by higher levels, or also because tax rates may not be set decentrally in order to avoid differences between municipalities (Droste et al., 2017). In Germany, for example, the municipalities enjoy financial autonomy (Article 28, para. 2, p. 3 of the Basic Law). However, this only applies within the scope of their right to local self-government, i.e. it must concern matters of the local community, and is limited by federal and state laws, such as the municipal tax laws of the federal states (WD, 2022). An example of such a limitation in Germany is the property tax. Although the location of properties is included in the calculation of property tax, e.g. via standard land values, local authorities cannot influence these values and therefore cannot use them to specifically allocate the costs of providing local public goods. It is similarly not possible via the assessment rates, as they must be standardized for properties and agricultural and forestry businesses located within a municipality (Section 25 (4) of the Property Tax Act; Petersen, 2024).

The example of the Cloudburst Plan in Copenhagen (Section 6.4.1) shows that it may be necessary to adapt local or national ordinances and regulations to enable the allocation of costs. With an amendment to the Water Sector Act 2012, Denmark created the conditions at national level for wastewater companies, e.g. in Copenhagen, to invest in measures to adapt to climate change and to include the costs for this in wastewater charges (The City of Copenhagen, 2012; TFCCA, 2012).

In general, the use of revenue at local level is restricted in many countries by the fact that a large proportion of revenue is already tied up in a number of mandatory public tasks. Local administrations then only have limited funds available for free use (Droste et al., 2017). Revenues, e.g. from pesticide taxes or extended producer responsibility, can provide relief if they flow at least proportionately to cities and municipalities for the implementation of local measures (Section 8.3.2.1).

Low-income countries often face particular challenges in the collection and efficient use of government revenue, not only at local level. This is shown, for example, in a study by the World Bank for 28 countries with the lowest incomes worldwide (World Bank, 2023a). Between 2011 and 2019, government revenue accounted for only 18 % of gross domestic product, compared to 39 % in high-income countries. Deficits were particularly evident in tax revenues, especially taxes on goods and services, but also income and corporate taxes. According to the World Bank, the reasons for this include the size of the informal sector and the associated limited tax base, as well as institutional and structural weaknesses such as a lack of capacities and corruption, which make it difficult to collect taxes. The collection of taxes linked to land ownership is also more difficult in low-income countries, as land rights are often unclear or uncertain. This also limits, for example, the options for financially supporting the provision of water-related ecosystem services (WBGU, 2020). At the same time, institutional and structural weaknesses also lead to a comparatively inefficient use of tax revenues (World Bank, 2023a).

8.3.2.3
Make use of multiple benefits and remunerate private actors better

Taking multiple benefits into consideration, also beyond the water sector, can open up additional sources of income for public and private actors. However, one problem with private actors implementing and financing water-related measures with multiple benefits is that potential multiple benefits often materialize as social and ecological benefits, and also as indirect economic benefits, which are not – or not fully – taken into account by private actors in their cost-benefit assessments. Projects like nature-based solutions are then less attractive for private actors. Up to now, private investment has thus represented only a small proportion of the financing of nature-based solutions. According to UNEP estimates, around 86 % of nature-based solutions are publicly funded globally (UNEP, 2021). According to an EIB study, only 3 % of the 1,364 projects surveyed across Europe reported private participation covering more than 50 % of the costs (EIB, 2023a).

The integration of multiple benefits into private-sector decisions can increase the willingness to invest. The aim here is not to crowd out state involvement in the area of basic public services, but to open up new sources of funding for supplementary financing under clear political and legal framework conditions, and to support and guide private-sector investment towards measures with multiple benefits.

Use of monetizable multiple benefits: Potential for multiple benefits that can be used to generate revenue arises in the water sector but also in other sectors such as energy or food. Consideration of the 'water-energy-food ecosystem nexus' can help to identify and use these benefits. For example, wastewater-treatment plants could use wastewater and digester gas as renewable energy sources to generate heat, and feed this energy into the grid. Facilities that already process heat from wastewater in this way exist in Switzerland, e.g. in Zurich, but there are only a few in Germany, e.g. in Lemgo. A study of the potential in Baden-Württemberg shows that this kind of use is economically interesting, but requires the expansion of local and district heating networks (Blömer et al., 2023). In general, there is still little knowledge about the possibilities and potential in Germany. Legal issues also need to be clarified, e.g. levying charges for wastewater use (UBA, 2023c). With regard to sewage gas, the UBA (2018a) refers to the possibilities of using the gas in the energy sector, in transport or for heating and refrigeration, over and above the production of electricity by sewage-treatment plants themselves. It goes on to say that policy-makers must further develop the technical, legal and economic framework conditions so that local authorities can use them.

Rewarding measures with multiple benefits that are difficult for private actors to monetize: Many measures that can increase climate resilience, such as nature-based solutions, do not have easily monetizable benefits in the form of yields or avoided costs. In other cases, the monetizable benefits are too small to cover investment costs and make them attractive for private actors. In this case, the public sector can step in and support projects, e.g. by co-financing projects or with public-private partnerships with blended finance (Calliari et al., 2022; Section 8.3.3).

An alternative way to finance measures with multiple benefits such as nature-based solutions is to pay for the provision of ecosystem services (EIB, 2023a). This can be achieved, for example, through targeted payments from the public sector, which could be financed by a subsidy reform or the sources of revenue mentioned in Section 8.3.2.1. For example, the EIB recommends reforming the CAP in the EU from 2028 so that it promotes nature-based measures in agriculture more strongly and does not create harmful incentives for the expansion of agricultural activities into marginal agricultural areas (EIB, 2023a). Particular attention should be paid to measures that benefit the conservation of water resources. The EIB regards the financial resources of the CAP as sufficient on the whole to finance a significant expansion of nature-based solutions in the EU (EIB, 2023a).

Alongside payments by the public sector, measures with multiple societal and environmental benefits can be made attractive relative to other approaches by means of tax relief and reductions in charges (Toxopeus and Polzin, 2021; EIB, 2023a). For example, the city of Hamburg promotes the installation of green roofs via public subsidies and a reduction in the rainwater charge (BUKEA, 2024).

Debt swaps (WBGU, 2023, 2024), which could be specifically linked to water-related measures, could also be a way of providing funds to promote measures with multiple benefits in low- and middle-income countries. The lender – often, but not always, a state – waives repayment of a loan that has been granted. In return, the borrowing state agrees to use a predetermined sum to finance a domestic development project to protect water resources or implement climate-resilient water management. Water-related debt swaps could be an option in cooperation with countries whose governance systems fulfil the necessary requirements in terms of accountability, transparency and issue-oriented management (WBGU, 2024).

However, compensation for multiple benefits that are difficult to monetize is not necessarily linked to payments from the public sector, even though it often results from state regulation: nature-based solutions and ecosystem services could, for example, be financed via *water funds* to which private actors contribute. This can happen on a voluntary basis if appropriate incentives exist, for example because water suppliers benefit when landowners take measures that contribute to the protection of water resources (Section 8.3.3), or it can be enforced by means of regulation.

Another option for establishing payments for water-related ecosystem services is credits, for example for CO_2 compensation, biodiversity, wetlands or – especially in the context of water – thematic certificates, e.g. for the conservation of marine and coastal ecosystems or compensation for water pollution. The sale of credits, possibly in conjunction with cap-and-trade systems, can generate significant revenues for nature-based solutions and thus enable the measures to be scaled (EIB, 2023a), but it also involves challenges and risks (Box 8.3-2).

8.3.3 Organize funding: strategically strengthen intermediary institutions

In addition to a lack of awareness of water-related risks (Section 8.3.1) and uncertainty about revenue sources and the political and economic environment in many countries where there is a great need for investment, and thus uncertainty about the ability to repay investments (Section 8.3.2), there are other reasons why water-related projects often do not find financing and investors do not find suitable projects (Alaerts, 2019; Money, 2018, 2022; Laubenstein et al., 2023): actors in the water sector are not sufficiently aware of the requirements of different types of investors and have difficulties in preparing suitable projects; in the financial sector there is a lack of knowledge about the water sector, especially about evaluating projects and their risks, which are characterized by high initial investments and long repayment periods; the water sector is highly fragmented and projects are often context-specific and small, which means relatively high transaction costs for investors. Especially in the case of 'new' approaches, such as non-sewered sanitation or nature-based solutions (NbS) for regulating the water balance and water quality, a lack of experience in the formal water sector and even lock-ins (in planning, technology, economic networks, regulation, practices, etc.) play an important role. In some cases, NbS also lack mechanisms or institutions through which water actors could invest in other land uses or make payments for this to farmers (Section 6.3.3; Table 8.3-2).

Mediation, a better exchange between actors and a bundling of activities are therefore key – for the provision of suitable financing, but also for long-term strategic cooperation between different water actors and lenders or investors, as well as for bundling smaller projects and scaling up successful approaches. Appropriate cooperation platforms can play an important role here, bringing together, for example, water suppliers, water users in agriculture, energy, industry and commerce, land users like agriculture and forestry, settlements and transport, environmental and other NGOs, as well as the respective regulators and actors with public-sector donors, ODA, foundations and private investors (for a typology of investors, see Money, 2018). These platforms can be used to create a shared knowledge base and transparency, bring together existing expertise, coordinate strategies, plan and implement measures or commission, monitor and evaluate them – and also to agree on business and financing models in each case (Trémolet et al., 2019). There are already many examples of such platforms, e.g. the water funds of Quito, Nairobi, San Antonio in Texas and many other cities with their catchment areas (TNC, 2018; Vogl et al., 2017). Water cooperatives also exist in some European countries (Section 8.2.3).

Various financing models can be negotiated or prepared for investors within the framework of such platforms. On the one hand, compensation contracts can be concluded between actors on the platform who have direct access to water – e.g. water suppliers and companies that rely on clean water – and farmers who are paid by water suppliers and companies for not using certain pesticides or heavy fertilization. Examples of this include green-water credit systems developed in Kenya, Morocco and Algeria (ISRIC, 2024; Section 6.3) and cooperation between water suppliers and farmers in Bavaria (LfU Bayern, 2024), e.g. the 'Augsburg model', in

Box 8.3-2

Trading systems for reducing nutrient inputs into water bodies and financing nature-based solutions

The potential, challenges and risks of trading in pollution rights and the financing of nature-based solutions on this basis can be illustrated with the example of schemes to reduce nutrient inputs into water bodies. In principle, trading in pollution rights can either (1) take place within a framework of mandatory pollution reductions or (2) enable contributions to be made towards achieving voluntary targets.

The basic idea of a trading system with mandatory pollution reduction is, as with European emissions trading for greenhouse-gas emissions, to achieve a specified reduction in pollution as cost-effectively as possible (EPA, 2024). Typically, companies are subject to legal requirements to limit pollution (e.g. nutrient discharges into water bodies). If they succeed in reducing their pollution further, they can sell unneeded pollution allowances to other companies that do not meet their targets. In this way, a given reduction target for overall pollution is realized by those companies that can do so at the lowest cost.

In the USA especially, the trade in such pollution rights for water pollution is widespread (EPA, 2024). Authorizations for nitrogen and phosphorus in particular are traded. Companies such as industrial or municipal wastewater-treatment plants (so-called point sources) must limit their nutrient discharges into water bodies and can sell their authorizations if they achieve an additional reduction in pollution. In some cases, diffuse sources of pollution, for example in agriculture, which are often not obliged to reduce pollution, can have reductions in their nutrient inputs securitized in the form of so-called credits, and sell these credits to regulated companies to fulfil their obligations. Such credits can be used by regulated companies or municipalities, e.g. in Virginia and Pennsylvania in the Chesapeake Bay river basin, subject to further conditions (Stephenson and Shabman, 2017).

In this way, measures in the unregulated agricultural sector are financed by the regulated companies. Farmers and other landowners can be compensated for the creation or preservation of wetlands, afforestation or the conversion of arable land into grassland, for example, by participating in the trade. The stricter the legal requirements for point sources in relation to the technological possibilities, the greater their incentives to exploit reduction potential where it is cheap, for example in agriculture (Stephenson and Shabman, 2017).

In addition to reaching statutory targets, voluntary targets can also to be reached by trading in credits. Companies, organizations or municipalities that are not subject to regulation can use credits, e.g. for pollution reductions by agriculture, to compensate for nutrient inputs into water bodies, and thus comply with voluntary commitments to limit nutrient inputs. Here, too, payments for the credits finance measures to limit nutrient inputs.

Trading credits for best-practice methods in agriculture, for restoration or land conversion is also interesting for compensation measures with multiple benefits, such as nature-based solutions. Overall, the inclusion of agriculture in the trade with credits has the potential to generate contributions to financing nature-based solutions, but this also involves risks and challenges:

- Fundamental risks arise from uncertainties in the determination and reliable monitoring of the reduction of nutrient inputs from agriculture. The lack of additionality, i.e. the risk of remunerating measures that would be implemented without such remuneration (Stephenson and Shabman, 2017), also poses a challenge. These challenges are familiar from other systems of tradable credits, e.g. CO_2 certificates.
- Furthermore, experience with existing markets shows that the trading volumes for credits that reward farmers and landowners for nature-based measures are low (Stephenson and Shabman, 2017). This may be due to barriers to the participation of farmers and landowners in trading or a lack of demand for agricultural credits from companies and local authorities (Stephenson and Shabman, 2017). In the US markets analysed by Stephenson and Shabman (2017), trading with farmers is essentially limited to cases where urban developers use credits to offset phosphorus or nitrate inputs into water bodies from stormwater runoff from new construction projects. Markets focusing on trade between property developers and farmers or landowners have been emerging in the UK since 2022. Two examples that explicitly aim to accelerate the implementation of nature-based measures are the Somerset Catchment Market (SCM, 2024) in the south-west and the Solent Catchment Market in the south of England (Solent Catchment Market, 2024), which has just completed its pilot phase.

The approaches to trading with credits described leave pollution in agriculture mostly unregulated and rely on voluntary reductions that use financial incentives. However, it is questionable whether ambitious targets for reducing nutrient inputs into water bodies or catchment areas can be achieved through these incentives alone when agriculture is by far the largest source of nutrient inputs (Stephenson and Shabman, 2017). In this respect, options for including diffuse sources in such a trading system should be examined.

which farmers agree to limit their use of fertilisers and pesticides and are rewarded for doing so (swa, 2021).

On the other hand, public donors, foundations or banks can be involved in financing large or several bundled projects. If financing cannot be obtained at market conditions because the sources of revenue or refinancing are too low or risky, public or philanthropic donors can assume part of the financing costs or risks for sustainability-oriented water projects within the framework of blended finance (Box 8.3-3), so that private sources of funding can still be mobilized. Particularly for financing nature-based solutions or other projects in which non-commercial objectives or environmental and social multiple benefits play a significant role, results-based blended-finance approaches can be particularly interesting. One example are 'environmental impact bonds', where the public sector sets environmental targets for a project, private investors initially finance the project and are remunerated plus interest for their efforts, e.g. with public funds, if the targets are met. In the USA, such models have been used to finance green urban infrastructure as protection against flooding, measures against forest fires and nature-based

Table 8.3-2
Potential barriers to the implementation of nature-based solutions for improved water security, according to actors in the water sector, and ways to remove these barriers.
Source: based on Trémolet et al., 2019

Water actors	Potential barriers to nature-based solutions for improved water security	Ways to address the barriers
National governments/ political decision-makers	› Limited awareness of what can be achieved in this way (observed among all actors listed, partly due to a lack of proper advice) › Perception that nature-based solutions for improved water security are riskier than conventional 'grey' solutions, and concerns about compliance › Uncertainty about effectiveness and cost-effectiveness	› Establish global, regional or national support structures that provide specific information › Define and apply a common framework for evaluating effectiveness and cost-effectiveness › Disseminate knowledge across sectors about technical solutions and levers for their adoption (policy, governance, financing)
Local governments	› Existing procurement rules for water services focus excessively on grey infrastructure › Evaluation rules in procurement processes do not include options to assess nature-based solutions › Limited knowledge of how to plan, adopt and monitor nature-based solutions › Local policy documents on several areas that can influence nature-based solutions for improved water security are not well coordinated (e.g. urban planning, biodiversity, water)	› Define contracts based on outcomes rather than technical specifications or specific outputs › Supplement auditing criteria to allow nature-based solutions for improved water security › Improve the capacity of city decision-makers to develop plans that integrate nature-based solutions into systemic approaches to urban resilience › Participate in city networks and alliances that can help disseminate good practices › Develop guidelines to maximize co-benefits
Water service providers	› Operating model focuses on building grey infrastructure › Focus on regulatory compliance, limited potential for experiments and risk-taking	› Systematically consider combinations of green and grey infrastructure in optimized investment plans › Cooperate with other entities (local governments, water users) to invest in nature-based solutions in upstream catchment areas
Water regulators	› Short-term results and regulatory certainty rated higher than sustainable long-term results	› Accept greater uncertainty of short-term results in return for higher and better distributed benefits over time
Water regulators	› Reluctant to sell land or water-abstraction rights for conservation › Reluctant to modify farming practices for fear of yield and income losses › Lack of land that could be set aside for nature conservation	› Provide incentive payments or easier access to credit to finance transition › Disseminate information on improved agricultural practices and impact on yields › Assign resources to buy and convert land for conservation

Box 8.3-3

Blended finance: definition, typical structures and challenges

Blended Finance is generally defined as "the use of catalytic capital from public or philanthropic sources to increase private sector investment in sustainable development … a structuring approach that allows organizations with different objectives to invest alongside each other while achieving their own objectives (whether financial return, social impact, or a blend of both)" (Convergence, 2024) or, more specifically in the development context, as "strategic use of development finance and philanthropic funds to mobilize private capital flows to emerging and frontier markets, resulting in positive results for both investors and communities" (OECD and WEF, 2015).

Typical structures include (Convergence, 2024):

(1) direct financing, where private funds are provided at standard market conditions, and public or philanthropic funds are provided at concessional conditions in order to reduce financing costs;

(2) guarantees or insurance schemes against loan defaults that commercial lenders receive on favourable terms (credit enhancements);

(3) technical support for the project on the basis of non-repayable grants in order to reduce risks or increase returns;

(4) non-repayable grants for the design or structuring of the project.

One of the challenges is that efficiency incentives should be maintained even when shares of subsidized loans are higher and, if possible, the concessions should be successively reduced in order to increase the reach and effectiveness of limited public funds (see also the principles developed by a working group of various development banks on 'Blended Concessional Finance'; DFI BCF, 2023). Ideally, local investors should also be involved in order to reduce exchange-rate risks and develop financial markets.

solutions to improve water quality (Trémolet et al., 2019). In contrast to financing models that are tied to the use of a predetermined technique, results-focused models allow for readjustment, increase effectiveness and efficiency, and improve the data basis for further projects by focusing on measurability and transparency.

A third model that is not yet very widespread is to pool many small investors, for example via special crowd-funding approaches to finance public-private partnerships. When locally affected people or users of the respective water-related project take part in this way and transparency is created, this can increase local acceptance (Ross, 2017).

Local cooperation platforms can be complemented by overarching funding mechanisms and institutions at national or regional level, to which individual projects or local platforms can have recourse. Examples include specialized banks or so-called revolving funds, which pool various sources of financing, transfer them to water projects (usually as blended finance) and use the repayments for new financing in the water sector (revolving). These specialized financing institutions and other institutions that act as intermediaries between those seeking and those providing financing in the water sector, such as consulting firms, NGOs, universities or research institutions (Lardoux de Pazzis and Muret, 2021), often also play a key role in setting up local platforms (Lardoux de Pazzis and Muret, 2021; Laubenstein et al., 2023; Alaerts, 2019). Such institutions have been established for decades in some high-income countries, such as the publicly owned Netherlandse Waterschaps Bank (NWB Bank, 2024), Aquafin in Belgium or Agences de l'eau along river basins in France. One example of an international NGO that acts as an intermediary is The Nature Conservancy, which supports the establishment of water funds (TNC, 2018). There are also initial examples in low- and middle-income countries, such as the Philippine Water Revolving Fund (Word Bank, 2016c) and the Kenya Pooled Water Fund (van Oppenraaij et al., 2022), which are supported by international donors among others. However, the focus in these countries is often on safe water supply and wastewater disposal. Nature-based approaches to the use and conservation of water-related ecosystem services are still given too little consideration. Such structures should be further expanded in a targeted manner (Lardoux de Pazzis and Muret, 2021) and strategically used as public institutions for the necessary change of direction in the water sector – for achieving SDG 6 but also for environmental, climate and climate-adaptation goals. This can also support the new orientation of the World Bank in the water sector.

8.4 Science and education

The science system has a key role to play in dealing with the exacerbated challenges and problems described in this report.

8.4.1 Science

The WBGU defines science comprehensively – in line with the Humboldtian ideal of the inseparability of research and teaching – as research, education and teaching as well as policy advice and cross-border scientific cooperation.

8.4.1.1
Science in the light of the exacerbated challenges

The WBGU emphasizes the importance of interdisciplinary and transdisciplinary forms of research that enable knowledge production from multiple perspectives. This includes the disciplines of natural sciences, social and cultural sciences, medicine, computer science and engineering. In this understanding, science comprises basic research, applied research and research that accompanies change processes, as well as teaching and advisory services.

Science produces, disseminates and contextualizes knowledge and expertise on water cycles and hydrological regimes as well as the diverse interactions between them, ecosystems and human use. At the same time, science is a key building block in innovation systems that develop technological, institutional and social solution approaches to safeguard the water needs of people and ecosystems, as well as the quality of water. The spectrum of solution approaches ranges from methods for recovering raw materials from wastewater to the innovative interweaving of technology and nature for water management in cities, the development of new methods of agricultural land use, and new financing and legal instruments in environmental policy. Furthermore, on the one hand water research can only ensure its application orientation and potential suitability for the practical context of water management by interweaving it with teaching, postgraduate training and the promotion of young talent, as well as the exchange with the public and science-based policy advice. On the other hand, the above-mentioned interactions – as part of the research process – develop the broader societal expertise structures, awareness and detailed understanding that are essential for the subsequent application of the scientific results.

In Chapters 3 and 4, the WBGU has argued that exacerbated challenges in the water sector can lead to regional water emergencies with a planetary dimension. Science plays a decisive role in maintaining an appropriate distance from the limits of controllability. This is particularly important because of the non-stationarity of hydrological regimes as a result of anthropogenic climate change.

The end of stationarity leads to considerable uncertainty with regard to future precipitation and extreme events, as bandwidths for the amount and temporal distribution of precipitation and the frequency and intensity of extreme weather events derived from experience are no longer reliable, and forecasts of future developments derived from models are fraught with uncertainty.

Uncertainties in modelling the hydrological impacts of climate change can be reduced by improving data availability and enhancing both climate and hydrological models (Banda et al., 2022). Another necessary response to the exacerbated challenges is the significant expansion of scientific monitoring of water levels and abstractions in Germany and in close cooperation for the whole of Europe and worldwide. Scientific monitoring is needed to close knowledge gaps on stocks in the water balance and in consumption as a basis for planning. This helps to recognize emerging, serious problem constellations caused by changes in the hydrological regime and in water use at an early stage.

It also includes developing scenarios for climatic, ecological, socio-economic and geopolitical developments and their interactions with each other, as well as participatory, bottom-up approaches for the preparation of adaptation strategies. Participatory bottom-up approaches in science make it possible to recognize threats to the water supply for people and ecosystems as well as risks from extreme weather events at an early stage. They also support the development of locally integrated solution approaches, thereby making robust, context-specific and flexible decision-making processes possible (UNESCO, 2020).

On this basis, water-related science can support politicians, authorities and the water industry in responding to the expected changes in the water balance and the resulting greater uncertainties in the planning and management of water resources. One example is the funding programme of the Federal Ministry of Education and Research entitled 'Regional information on climate action', which was completed in 2023. Its aim was to "build up decision-relevant knowledge on climate change in municipalities and regions and, based on this, to develop suitable measures for adapting to climate change" (BMBF, 2021b).

The continuous production of new scientific knowledge necessitated by non-stationarity in conjunction with the collection of new data should be taken into account in all developments of organizational, social and technological innovations for securing water requirements (Smith et al., 2023). Otherwise, there is a risk that the planning and development of new solution approaches will be based on incorrect hydrological assumptions and thus be unsuitable for implementation. The increased application of digital monitoring technology for existing and planned infrastructure can optimize its use, especially in the case of extreme events.

Structural demands on science: inter- and transdisciplinarity

Safeguarding the water requirements of people and ecosystems and avoiding exacerbations require interdisciplinary cooperation between the natural, engineering and social sciences. Social sciences, economics and law play an important role in ensuring that water-management

Box 8.4-1

Protecting and promoting democracy via international scientific cooperation on water

Water-related science also plays an important role in dealing with exacerbated societal and political challenges. For some time now, an area that used to be focused on technology and the infrastructure has been dominated by the understanding that systemic and societally embedded approaches are necessary in order to make water management sustainable in its long-term practical design. Core principles of societal integration, inclusion, transparency, accountability, and gender and age equality are of key importance in the further development and safe implementation of existing water-management systems. Especially in water-related scientific collaborations, it therefore makes sense to incorporate cooperation formats that promote and protect democracy. The aim is to promote democratic principles such as participation, accountability and transparency in selected political processes at the micro and meso level in the field of water management. The centralized structure of many water-management systems means that the degree of state involvement is generally high, so that positive spillover effects are also possible in other areas of state control.

Some time ago, the Federal Ministry of Education and Research supported projects in non-democratic contexts (Borchardt et al., 2016) as part of its research funding for integrated water-resource management. These projects have been repeatedly criticized: it was necessary to weigh up the extent to which they were more likely to strengthen or weaken authoritarian regimes, e.g. in Uzbekistan, Mongolia or Jordan. Since the projects successfully compensated for deficits in existing local water management, the improvements that were achieved were mostly attributed to the national governments and rarely to the German Federal Government. At the same time, many of these projects showed that, as part of the cooperative research, spaces for reflection and exchange on different governance approaches were created by the participatory and inclusive governance instruments of Integrated Water Resources Management. Progressive representatives were able to use these spaces to boost transparency, accountability, self-organization and involvement (Hornidge et al., 2016; Ibisch et al., 2016b). In North Africa, too, researchers in the field of water management have observed how water-related cooperation has been able to strengthen basic elements of democratic governance (Freyburg, 2012; Houdret, 2021).

systems are subsequently embedded in the existing governance systems. If these systems are not integrated into research projects, it is not possible to understand the complex and diverse ways in which individuals and society deal with water, and how the political control mechanisms based on this develop. However, water-related research in the fields of social sciences, economics and law is still often underfunded. Furthermore, these fields are often assigned a subordinate role in the project design and are not involved in the key decision-making processes regarding research design and implementation (Martin-Ortega, 2023).

In addition to interdisciplinarity, it is necessary to link basic and applied research and to develop solution approaches in a transdisciplinary manner together with stakeholders from the private sector, politics and civil society. This can be illustrated by the role of science in climate-resilient water management (Chapter 6). For example, successful management of the landscape water balance requires the integration of fundamental knowledge into the application-orientated planning of human interventions in the household that builds on this knowledge. This knowledge includes, in particular, findings on the interactions between the water balance and different types of landscape. The BMBF strategy 'Water: N' takes up both aspects very prominently (BMBF, 2021a).

The comparison of different solution approaches in the context of climate-resilient water management, too, combines basic and application-orientated research with the integration of relevant stakeholders. Scientific capabilities for forecasting local water balances with a view to climate change serve as a basis for evaluating the available solutions in terms of technical feasibility, costs, societal acceptance and possible contributions to locally defined goals and targeted multiple benefits. Stakeholder integration is essential, for example, for identifying conflicts of use and evaluating multiple benefits (Turkelboom et al., 2021). The BMBF funding programme 'Water Extreme Events' (WaX), which enables research into innovative concepts for blue-green infrastructure and its management (BMBF, 2024a), is a forward-looking example in this context.

Furthermore, the use of innovative research methods, such as transdisciplinary real-world laboratories in which scientists conduct joint research and develop solution approaches together with representatives of civil society, politics and practice, is advantageous for testing the effects and acceptance of climate-resilient infrastructure. For example, depending on the research design, real-world laboratories for urban reorganization not only make it possible to test new blue-green infrastructures. By integrating stakeholders, they also allow mutual learning in an experimental and simultaneously public space under real operating conditions and support further-reaching societal change processes (Paton et al., 2021; Box 8.4-2). Real-world laboratories can also be used to identify in a practical way existing capacity deficits in politics, administration and water-management

Box 8.4-2

Examples of successful citizen labs

Citizens can actively participate in scientific research projects in citizen labs. Using crowdsourcing methods, they help to collect and analyse data in order to gain scientific knowledge. In view of water scarcity, water monitoring tasks (water availability and quality) can be undertaken with those involved, and solution approaches and implementation measures can be developed for better water storage and more efficient consumption. This information can be evaluated and used together with scientists, stakeholders and politicians (Bonn et al., 2022; Wagenknecht et al., 2021). By involving the population in the decision-making process, citizen labs, like deliberative participation processes, can contribute to more resilient structures in municipalities by revealing customized solutions for local challenges – such as water shortages – which are accepted via transparent decision-making.

In the 'How much water does my soil store' project at Bonn-Rhein-Sieg University of Applied Sciences, citizens were able to determine the green-water content and filtration capacity of the soil in their garden. Under the motto 'Climate protection and biodiversity – what potential does my garden have?', every citizen could learn how to increase the contribution of their own soil (H-BRS, 2019).

In the 'LassWissen' project in the Lower Lusatian Heath Nature Park, experts and citizens are jointly researching the water balance of the post-mining landscape in the Lusatian mining area (Naturpark NLH, 2024). The aim of the project is to build a data network with citizens in order to better understand the water balance in the post-mining landscape. The project is funded by the German Federal Ministry for the Environment's programme of Municipal Model Projects for the Implementation of Ecological Sustainability Goals in Regions undergoing Structural Change ('KoMoNa'; Naturpark NLH, 2024).

organizations, and to develop concrete approaches for capacity building. The networking and transfer approaches designed together with societal stakeholders are a good starting point for the diffusion of research results.

Science-based policy advice

To prevent global water crises and when selecting local adaptation options, science is increasingly playing an advisory and supporting role in the policy-making process. As emphasized above, science is of key importance in the development of solution approaches, the selection and implementation of which must be decided with the involvement of those affected in accordance with basic democratic principles. The complexity and speed of change of the relevant socio-ecological processes, exacerbated by climate change, simultaneously demand forward-looking, adaptive and adaptable local and global water governance. Independent, critical science is essential as a basis for all advisory activity. The aim is to provide scientifically based policy advice from an outside perspective, uninfluenced by power dynamics driven by party politics or other interests, and to act as a kind of 'sparring partner'. This freedom of science (Basic Law, Art. 5 III) and the independence of thought that results from it, the ability and willingness to question what is accepted as the truth, while at the same time remaining true to the constitution, must be preserved in the political consultation process and ensured time and again. This is just as much the responsibility of science funders as it is the responsibility of scientists and policy advisors. At the same time, science-based policy advice needs a recipient structure in the executive and legislative branches. Recipient structure refers to institutionalized mechanisms in which water-related scientific findings and arguments are heard and incorporated into the further policy process. This includes systematic exchange processes between science and politics, through which the mutual dialogue and exchange of expertise is possible, and the advisory products of science are systematically passed on within the ministries or the Bundestag (German Parliament). Science can only inform decision-making processes in a meaningful way if the advisory products are actively used.

The WBGU is in favour of further developing such recipient structures in the ministries responsible for water management at the federal level. Important points of reference for the further structural development of recipient structures can also be developed as part of the advisory-board dialogue under the auspices of the Science Platform for Sustainability and the Sustainable Development Solutions Network (SDSN) Germany, funded by the Federal Ministry of Education and Research (BMBF).

Chapter 6 also underlines that water infrastructure and its management must become more modular, error-friendly and flexible in order to deal appropriately with the exacerbated challenges. The role of science is to accompany the necessary reflective, learning planning processes by reviewing the effectiveness of the decisions made and, if necessary, proposing technological alternatives or new options for action. The intended and unintended effects of political decisions should also be scientifically determined on a permanent basis in order to enable faster learning and, if necessary, rapid readjustment.

8.4.1.2
International science cooperation for climate-resilient water management

Science systems continue to differ greatly across the world. In particular, there are differences in terms of personnel and financial resources, research infrastructure, disciplinary versus thematic organization, the focus on basic versus applied research and performance. Expenditure on research and development in high-income countries averaged 2.8 % of gross domestic product (GDP) in 2021. In middle-income countries, it amounted to between 1.2 and 1.6 % of GDP and in low-income countries to between 0.2 and 0.5 % (UIS, 2024). The expenditure includes both public and private investment in research and development and the funding areas of basic research, applied research and experimental development projects in publicly and privately organized science, tertiary education and civil-society organizations.

The differences in strength of the science systems are also reflected in the geographical distribution of research expenditure. North America (27.4 %), the European Union (18.7 %) and East and Southeast Asia (40.4 %) account for most of global research expenditure. Latin America has a share of just 2.7 % and sub-Saharan Africa a mere 0.4 % (UNESCO, 2021). The unequal distribution of scientific capacities reinforces existing differences. Scientific capacities are a key lever for developing locally adapted solutions to deal with the exacerbated challenges, and they play an important role in national innovation systems, which in turn are an important element in mobilizing private capital.

Scientific capacities are also a key factor in the integration of local knowledge, e.g. in the form of local stakeholders' experiential knowledge, in the development and review of solutions. Strengthening the opportunities for equal science is a prerequisite for finding locally viable transformation paths to avoiding greenhouse-gas emissions. Scientific collaborations are therefore an important instrument for jointly dealing with the exacerbated challenges described in Chapter 3.

External, bilateral and multilateral science funding can make an important contribution to expanding scientific capacities, especially in middle and low-income countries (Dean et al., 2015; Mormina, 2019; Blicharska et al., 2017). The International Science Council estimates that only 15 % of all science projects worldwide are carried out in bilateral cooperation, and only 5 % in multilateral cooperation (ISC, 2021). Measured in terms of co-authorship of scientific publications, only 0.6 % of all publications from high-income countries have been published in cooperation with scientists from low-income countries (Aksnes and Sivertsen, 2023; DUK, 2024).

In international collaborations, care should be taken to ensure that they are characterized by a high degree of equality between the partners. Without such equality, neither the sustainability of cooperation nor the local suitability of the knowledge, innovations or management approaches developed can be ensured. It is therefore important in project design and during project implementation to ensure that cooperating countries are given a say, personal responsibility and substantial resources. For the successful development and long-term application of local solutions, as a first step research agendas and research questions should be developed jointly. A good example of this is the BMBF funding line 'Water Security in Africa' (WASA), which began in 2021 and was developed in a consultation process with the participation of, among others, the Council of African Water Ministries and the water ministries of Angola, Botswana, Namibia, Zambia and South Africa (BMBF, 2024e).

However, the joint development of a research agenda does not automatically ensure the equally necessary equality in the cooperation within the project period (Schwachula, 2019). The operationalization of the research questions, the implementation and the evaluation of the results should also be carried out in cooperation with local stakeholders. The integration of Indigenous and local knowledge is necessary in order that solution approaches for overcoming or preventing water crises can do justice to the context-specific problems and develop customized solutions. This means that the possible existence and suitability of local and Indigenous knowledge must be determined before knowledge is produced.

Initial meta-analyses of adaptation projects to climate change in the water sector clearly show that, for example in Africa, measures that include indigenous and local knowledge show a higher degree of risk reduction than measures without it (Filho et al., 2023). Communication with the population, as well as the (further) training of users and other relevant stakeholders, are also necessary for the dissemination and long-term application of solutions.

To increase local research capacities, scientific institutions in partner countries must participate and be provided with substantial funding to create scientific jobs and research infrastructure. In addition, scientific qualification opportunities and the provision of funds for local research administrations strengthen local scientific capacity. Measures to achieve both goals reinforce each other in practice. As part of the BMBF funding programme 'Water Research in the Near and Middle East' (MEWAC), for example, joint applications with local partners were a prerequisite, and cooperation with companies was actively sought. However, partner countries were only allowed to apply for a maximum of 50,000 euros in funding. They were therefore only able to act as equal partners to a limited extent (BMBF, 2020). One example is the BMBF funding of two competence centres for climate change and adapted land management in Africa (BMBF, 2024d). The funding has been in place since 2012 and is open-ended, with funds totalling more than 250 million euros up until 2024.

In order to substantially increase funding for research cooperation in the future, a stronger emphasis on science policy in international forums such as the G20 or regional organizations such as the Association of Southeast Asian Nations (ASEAN) or the African Union (AU) is also necessary. At these levels, funding flows and work processes for the partnership-based development of research agendas and the necessary research infrastructure could be coordinated, and regional science policy could be strengthened in a similar way to that of the EU's European Research Council for the development and expansion of regional science landscapes (DUK, 2024; Taylor et al., 2022, Hornidge et al., 2023).

In international cooperation, research funders have the role of transnational systemic intermediaries in addition to guaranteeing the fulfilment of the above criteria. This means that funded research enables interactive learning processes between the scientific systems involved, integrating all the actors taking part in the creation of new knowledge (Heiberg and Truffer, 2022).

8.4.1.3 Water Mapping Initiative

The existing landscape for water-related scientific cooperation is characterized on the one hand by a high degree of fragmentation and the primacy of nationally organized scientific systems which cooperate at best regionally and selectively internationally. On the other hand, recent research is increasingly pointing to regional water emergencies with a planetary dimension, some of which are expected and some of which are already unfolding (Chapter 4). However, research is still in its infancy with regard to the potential extent, regional distribution, the range of its specific manifestations and possible societal reactions.

At the same time, extensive research findings are available on the global water balance and its changes, which, despite their increasing relevance for political decision-making processes, continue to be insufficiently collated and put to effective use. In order to counteract the gap between knowledge and action, the WBGU advocates establishing a Water Mapping Initiative whose planning and implementation is internationally shared. Its aim is to recognize impending regional water emergencies in advance, and to use the results of its work to inform decision-making processes. In this way, the initiative can help maintain the necessary distance to the limits of controllability.

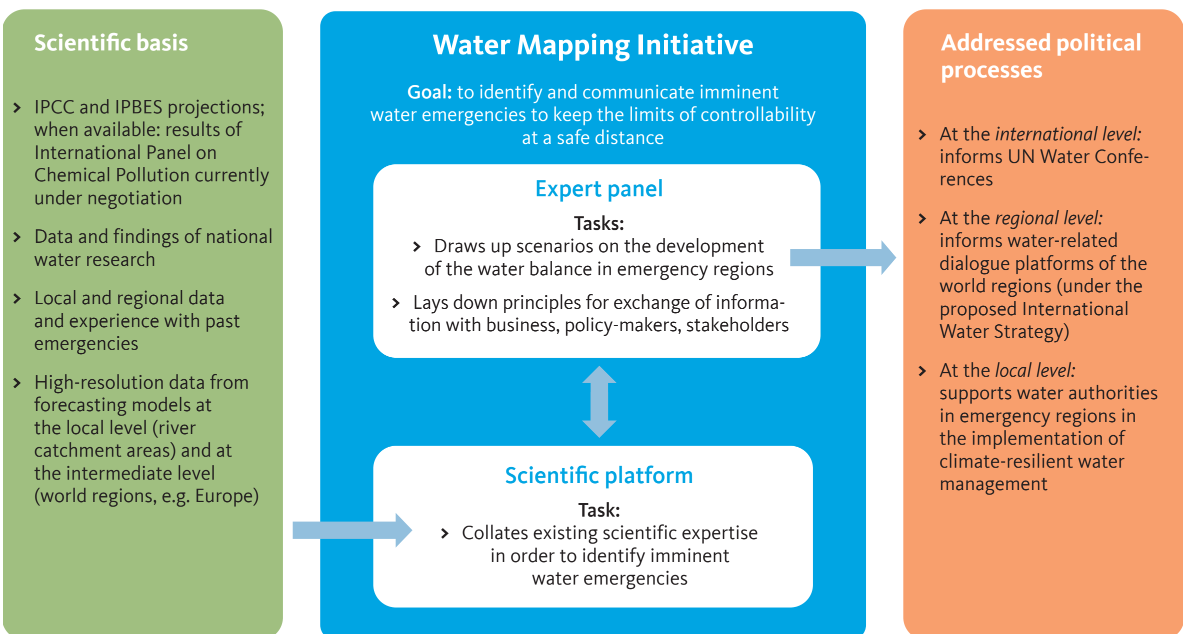


Figure 8.4-1
WBGU proposal for a Water Mapping Initiative to prevent imminent regional water emergencies. The scientific platform aims to recognize imminent water emergencies as early as possible by integrating scientific principles. On this basis, the panel of experts would inform and support international, regional and local policy processes.
Source: WBGU

Scientific working principles

Recognizing water emergencies at an early stage and being able to appropriately limit them regionally, or develop plans for dealing with them, requires the consolidation of global water data series and monitoring capacities (Fig. 8.4-1). This comprises long-term data series, monitoring and observation data from national monitoring facilities, as well as time-limited, diverse interdisciplinary quantitative and qualitative databases from regional and national research projects. The aim here is to establish binding standards for appropriate water monitoring worldwide. These standards for data collection, processing and storage would not only create the knowledge base for global water availability (green and blue water), they could also make it possible to develop them further and to integrate them into the operationalization of the largely nationally or regionally organized science systems worldwide (WBGU, 2023).

On the scientific side, the platform should continue to integrate the findings on the consequences of climate change, biodiversity loss and environmental pollution with data on and experience of past emergencies, the results of national and supra-regional water research, and local data and local experience of current emergencies. In addition, there are high-resolution spatial and temporal data from observations and forecasting models at the local level (river catchment areas), at the national or regional level (at the level of world regions, e.g. from EU Copernicus) and at the global level (e.g. IPCC and IPBES). With increasing temporal and spatial resolution, the platform should also provide relevant information for local water authorities to implement climate-resilient water management. For successful forecasts, the data should be evaluated both retrospectively (hindcasting) and prognostically by modelling, taking into account different climate models. As soon as the Science-Policy Panel on Chemicals, Waste and Pollution Prevention set up by the UN Environment Assembly has started its work (Section 7.1.3.2), its findings should also be taken into account.

Panel of scientific experts

A panel of experts is to be set up to oversee and manage the platform; it will be responsible for the following additional tasks: developing binding standards and indicators for the necessary water monitoring worldwide, evaluating data analyses and graphical representations, and preparing the work results for feeding into political processes. Once imminent regional water emergencies with a planetary dimension have been identified, the panel of experts will draw up forecasts for regions that are at risk. At the same time, it could promote the exchange of information between science, politics and stakeholders.

At the international level, the panel of experts should inform the UN Water Conferences. At the regional level, the initiative should initiate and inform water-related dialogue platforms in different regions of the world, as well as policy dialogues in different country alliances (e.g. G20, BRICS, OECD, Commonwealth of Nations, MIKTA – a consultation and coordination platform involving Mexico, Indonesia, South Korea, Turkey and Australia) and regional organizations (EU, ASEAN, AU, MERCOSUR, etc.) for designing an international water strategy and with a view to the UN Water Conferences in 2026 and 2028. Locally, the committee should also cooperate with water authorities in the implementation of climate-resilient water management.

For local, national and regional strategy development and implementation, the panel of experts should also provide the necessary science-based expertise on advancing changes in the availability of water worldwide and with the respective regional and local characteristics. However, the design of dialogue and cooperation processes based on this would go beyond the capacities of the Initiative and should instead be the responsibility of nation states and regional associations. The science platform and the panel of experts should be institutionally based at UN Water. The databases and the scientific analysis should be hosted by internationally commissioned national research institutions. It could be set up in a similar way to the IPCC and IPBES data centres.

Ideally, funding should be provided primarily by G7 and G20 countries. Other countries would be able to participate on a voluntary basis. Co-funding from middle and high-income countries is particularly important against the background of the growing global crisis of confidence between the 'south' and the 'north', and could also strengthen the perception of science as a factor in international negotiations.

A delegitimization of the Initiative's water scenarios based on a possible perception as 'western science' and the associated devaluation of the political process must be counteracted by the very architecture of the initiative. The same requirements should apply to the composition of the scientific staff and the implementation of scientific activities, as well as for the international scientific collaborations described in Section 8.4.1.2. Science should be organized in an inter- and transdisciplinary way and be carried out by scientists from high-, middle- and low-income countries in equal measures.

8.4.2 Education

Education is essential for the transition to a sustainable society in general and for the prevention of water crises in particular. Measures such as information, education, and knowledge acquisition through practical experience and public dialogue raise people's awareness of the importance of water as a resource. A better understanding of, for example, the connections between the production of goods and water quality, the new challenges in water management resulting from climate change, or global governance makes self-determined action and informed participation in political processes possible.

Education passes on the necessary knowledge for the individual development of competences that enable purposeful action in the sense of sustainable development and a life in harmony with nature. To this end, education promotes an awareness of water as a resource. The necessary change in educational institutions and content on the topic of water is based on the concept of Education for Sustainable Development (ESD). ESD supports the ability to criticize previous forms of education and demands an integrative perspective on problems and societal action. Education in the sense of ESD conveys systemic thinking and the ability to reflect on the ecological, social and economic effects of human behaviour in an integrative and independent manner, and to integrate different bodies of knowledge through participation (WBGU, 2023). The importance of the topic is reflected, among other things, in the National Action Plan ESD of the National Platform 'Education for Sustainable Development' and the ESD campaign 'Learning. Taking Action. Shaping the future together. Education for Sustainable Development', both of which are managed by the Federal Ministry of Education and Research (BMBF, 2017).

Although the importance of education for critical thinking and the transition to a sustainable society is fundamentally undisputed, the concept of ESD has also been criticized. Empirical social research has long established that awareness of environmental crises is growing, but that the patterns of behaviour and consumption that contribute to environmental crises are hardly changing. While the so-called 'knowledge to action gap' was initially explained primarily by a lack of long-term planning and risk aversion (e.g. WBGU, 2011), more recent criticism emphasizes that sustainable action finds its limits in unsustainable material and institutional infrastructures. These cannot be changed by increasing knowledge and expertise but only via political processes. The need for democratically legitimized political decisions to initiate societal change as a prerequisite for successful environmentally oriented action is, however, largely ignored in the context of ESD, the criticism continues (Christ and Sommer, 2023). For ESD, this means that the connection between action-enabling framework conditions and individual action, as well as the importance of democratically legitimized political decisions to change them, must be more strongly integrated into the content taught.

As a key global and locally relevant topic, water has always been part of ESD (Rieckmann, 2020). The National Water Strategy includes far-reaching measures for communication, education, training and advice, the implementation of which is supported by the WBGU. Plans include a comprehensive communication strategy, further-training programmes for experts and managers from different sectors and political decision-makers, as well as giving the topic of water a higher profile in schools (BMUV, 2023b). For some time, the Federal Ministry of Education and Research, too, has supported further training on the subject of water as part of its research-funding programmes. For example, the funding measure 'GRoW – Global Resource Water' promotes education and training programmes to improve the management of water resources (BMBF, 2024c). However, the exacerbated challenges described in Chapter 3 and the threat of regional water emergencies with a planetary dimension described in Chapter 4 justify devoting even more attention to this topic.

8.5 Recommendations for action

This section offers recommendations for action to strengthen a system of international water governance (Section 8.5.1) that makes use of the interfaces and opportunities of economic and trade relations, and improves cooperation with low- and middle-income countries. The following recommendations for action aim to promote the interaction between a proactive state and self-organization in civil society (Section 8.5.2) and to encourage more investment in the protection of water resources and resilient water infrastructures (Section 8.5.3). The section concludes with recommendations for a proactive role for science that brings actors and stakeholders together (Section 8.5.4).

8.5.1 Strengthen international water governance

At the international level, the WBGU proposes generating fresh impetus by means of an International Water Strategy, which should be compatible with existing international water-policy processes. Germany, the EU and companies with transnational supply chains should fulfil their international responsibility.

8.5.1.1
Advance water diplomacy at the international and regional level

An International Water Strategy to create a new impetus for international water diplomacy

The WBGU recommends developing an International Water Strategy. As an exchange and coordination platform, this should aim to help institutionalize the current processes. In terms of content, it should address the least controversial topics first and initially rely on non-binding instruments to increase consensus. Drinking water, integration, education and research as well as cooperation should be given priority. Furthermore, the International Water Strategy should help to address the possible regulation of green water under international law, and endeavour to better dovetail the water conventions with other water-related international treaties. Finally, the protection of water resources should be recognized as a common concern of humankind.

New water secretariat and scientific panel of experts to consolidate regular UN water conferences

The WBGU recommends the establishment of a UN Water Secretariat, which could in future be headed by the Special Envoy on Water, as well as a scientific panel of experts to support it in an advisory capacity. The scientific panel of experts should be diverse in terms of countries of origin and specialist expertise. It should cooperate with the Water Mapping Initiative platform (Section 8.5.4), which is also recommended by the WBGU.

Capacity building supported by an internationally funded task force

The aim should be to promote the capacities of low- and middle-income countries for data analysis, and to make relevant water data as freely accessible as possible (open access). Government authorities in all countries should be put in a position to plan and work out their water policy in such a way that it is no longer based on assumptions of stationarity. Climate-resilient planning can only be implemented if capacities are built up locally in the respective countries. Low-income countries should be given financial support and advice, e.g. from an internationally financed task force.

Promote the regional level and regional organizations: establishment of regional platforms as part of an International Water Strategy

In order to strengthen regional organizations, regional governance platforms for multilateral meetings could be set up as part of an International Water Strategy. The Sendai Framework for Disaster Risk Reduction can serve as a model (Box 8.1-3). Regional platforms could be used to formulate goals and measures for regional water strategies that address such issues as land use (WBGU, 2020). The management of forest areas of supra-regional importance, such as the Amazon rainforest, could be included in regional strategies, e.g. for South America. Protection measures could also be promoted by international funding or international cooperation. In Europe, a regional water strategy could relate to the European Green Deal and the European Biodiversity Strategy. As part of the proposed International Water Strategy, the regional governance platforms would be scientifically informed by the Water Mapping Initiative.

European Blue Deal

In view of increasingly frequent extreme weather events within Europe and the EU's credibility as an actor in international negotiations, the efforts made to date to integrate a climate-resilient European water policy, e.g. the EESC's EU Blue Deal and the EU Commission's Water Resilience Initiative, should be further pursued and prioritized. Germany should work to ensure that the European Green Deal and the Clean Industrial Deal are supplemented by a European Blue Deal.

Multilateral cooperation communities

In order to boost cooperation on sustainable land and water management, the WBGU proposes multilateral cooperation communities for 'coalitions of the willing'. These could fulfil three functions for their members: (1) implement integrated approaches to water and land use across national borders and exchange know-how, (2) advocate transformative land and water governance at the international and regional level, and (3) jointly protect valuable ecosystems by means of cooperative mechanisms (WBGU, 2020: 277).

8.5.1.2
Strengthen and make use of interfaces

Strengthen capacities at the interfaces for an active role in the International Water Strategy

The greater need for coordination at the national and global level should be met by an increase in administrative capacities. The capacities of administrations at the supranational, state and sub-state levels, which are already working at interfaces and have water-specific networks and expertise, should be expanded so that they can play an active role in negotiating an International Water Strategy, as proposed by the WBGU. To achieve this, financial and human resources should be increased in (ministerial) administrations working on water-related issues, e.g. in the areas of agriculture, economy and trade, environment, foreign policy and sustainable development.

Biodiversity governance based on integrated approaches

In order to implement the biodiversity targets of the Kunming-Montreal Global Framework Agreement (GBF), the WBGU recommends the integrated mosaic approach – which is based on the integrated landscape approach – and the reallocation of subsidies (WBGU, 2020, 2024). The implementation of the GBF area-based targets should be used as an opportunity to stabilize landscape water balances and restore the storage capacity of the landscape (Section 7.2).

Combine water governance with biodiversity protection: the example of shrinking glaciers

The melting of glaciers as a result of climate change is leading to the creation of new ecosystems. The protection of these new post-glacial ecosystems could make an important contribution to achieving the GBF's global biodiversity goals. By 2100, new aquatic and terrestrial ecosystems up to the size of Finland could emerge (Bosson et al., 2023). The newly emerging ecosystems can, for example, play a role as carbon sinks, and also retain glacial meltwater in some regions. These areas were previously inaccessible to humans, but the pressure to use them, e.g. for infrastructure development, is already increasing. These ecosystems should therefore be placed under protection as soon as possible.

Integrate and reify water as a separate component in the goals of climate adaptation and climate financing

Germany should work to further flesh out the water-related global adaptation target that was adopted in 2023 at the climate conference in Dubai (COP 28; UNFCCC, 2023b). Financing climate-resilient water management should play a key role in the negotiations on the new climate-financing target of the Paris Agreement.

8.5.1.3
Use the opportunities of economic and trade relations

Strengthen the protection of water resources in the WTO and regional trade agreements

The protection of water resources should be strengthened in the WTO, in regional trade agreements and in investment-protection agreements. Among other things, Germany should advocate the resumption of negotiations under the Environmental Goods Agreement on the removal of tariff and non-tariff barriers to trade in environmental goods and services: in the context of water, for example, technologies for treating wastewater, improving water productivity or drought-resistant grain varieties. Efforts should also be made to ensure that WTO law and regional and bilateral agreements encourage countries to introduce and implement measures that serve to protect water resources, or at least grant them sufficient room for manoeuvre, e.g. through clearly defined exceptions. It may also make sense to agree on safeguards allowing unilateral restrictions on free trade to protect water resources in urgent or serious cases. WTO law and regional trade agreements should provide for the elimination of subsidies that run counter to the protection of water resources, and for exemptions for beneficial subsidies (Zengerling, 2020; WBGU, 2020; GCEW, 2023b). Corresponding objectives in international agreements can be found, for example, for the protection of biodiversity in the Kunming-Montreal Global Framework Agreement (CBD, 2024). Regional trade agreements should specifically strengthen regional and international trade in sustainable products and services and the development of corresponding business models, for example through certification (Zengerling, 2020). Regulations agreed in regional agreements should be adopted by as many countries as possible for their trade relations in order to avoid a shift of negative environmental impacts to countries outside the agreements.

Make companies more responsible internationally and support countries with the introduction of reporting obligations

The goals and measures formulated in the German National Water Strategy can serve as a model for other countries. As part of the International Water Strategy, further countries should be encouraged and enabled to introduce reporting obligations on water use and risks, and to apply uniform standards wherever possible. Based on such reporting, companies and investors should be encouraged to take measures to avoid negative impacts of their activities on water resources. Low- and middle-income countries should furthermore be supported when introducing reporting obligations, e.g. with capacity-building measures (Section 8.1.3.3).

Consider making the protection of water resources and the documentation of risks an integral part of the Supply Chain Act

Germany should examine the extent to which protecting water resources and recording water risks can be more closely integrated into the German Supply Chain Act. For example, risks to ecosystems and biodiversity have not been documented up to now. Consideration should be given to the possibly limited data basis and the methodology for documentation, as well as the effort involved for companies in documentation.

Review and further develop certification programmes

It should be examined to what extent existing certification programmes can be improved in terms of design and implementation, or whether new certifications should be developed to promote the sustainable use of water more strongly. Relevant examples here include the Ecolabel at the EU level, the Blue Angel for products and services in Germany, and the Water Stewardship Standard of the Alliance for Water Stewardship, which certifies companies. In the case of a further or new development, care must be taken to ensure that producers in low-income countries also benefit as much as possible from participation in certification programmes – through higher producer prices or supporting measures, e.g. for capacity development (WBGU, 2020).

8.5.1.4 Cooperation with low- and middle-income countries

Internal and external policy coherence

Germany and the EU should establish policy coherence between the various external policy fields relating to water, as well as between the external and internal fields. This is particularly important for Europe's and Germany's international credibility, and for the expansion of strategic alliances with countries on all continents and from all income groups, and thus for Europe's ability to act at the international level.

Confidence-building measures in cooperation with partners

When supporting confidence-building measures, especially in conflict areas, it is important to pay attention to trust, institutional capacities and a sustainable dialogue, and not to concentrate solely on technological solutions and data availability. All too often, material infrastructure projects are prioritized. Changing norms, thought patterns and habits is more difficult. What is needed, therefore, is a focus on confidence-building measures in institutions, long-term partnerships and a genuine dialogue with partners – also in the funding of research projects.

Promotion of gender-sensitive water management

In international cooperation, it should be ensured that there is cooperation with large and small water users, for example both with industrial agriculture and with smallholder farms, and that attention is paid to gender-specific role distributions in project developments. For example, land-intensive agriculture and production for export is male-dominated in many countries, while vegetable and fruit production for local food security and diversity is small-scale and in women's hands. Accordingly, it is important to organize international cooperation and scientific cooperation in the field of sustainable water management in such a way that women in particular are empowered to secure, adapt and further develop their (often small-scale) agricultural activities.

Further research is also needed on opportunities and barriers to the implementation of WASH measures, which aim to ensure universal safe and efficient access to water and sanitation, have a positive impact on human health, reduce poverty and inequality and improve the safety of girls and women (UNWC, 2023).

Expand water-related cooperation with low- and middle-income countries, promote local and regional marketing systems

Low- and middle-income countries should be supported by capacity building and technical cooperation in using the potential of international trade and economic relations for growth, development and food security, while at the same time protecting domestic water resources from negative spillover effects. Sub-national and entrepreneurial cooperation should also be promoted. In addition, local and regional markets and marketing systems for food should be strengthened to create alternatives to the cultivation of water-intensive monocultures for export such as maize and soya. The Committee on World Food Security (CFS) could play a coordinating role in cooperation with the World Trade Organization (WTO). Smallholder organizations in particular should be consulted and closely involved (Tups, 2022).

Document spillover effects, reduce disincentives and promote the switch to water-saving economic models

EU trade relations should be analysed specifically for transregional spillover effects in the water sector. False incentives that exacerbate negative spillover effects – e.g. from regulations in trade agreements or the long-distant effects of European regulation – should be dismantled. Trade relations should be used to promote the switch to water-saving production and cultivation methods or alternative sources of income.

8.5.2 State policy and self-organization by civil society

In the WBGU's view, climate-resilient water governance requires interaction between a proactive state and self-organized actors. It should be structured in a context-specific way and enable effective implementation. Preparing for future water-related challenges on an unprecedented scale requires cooperation and understanding between state, sub-state and non-state actors.

Proactive state

The state should play a proactive role in the field of water governance. In order to do justice to the precautionary and polluter-pays principles, democratic processes are needed to negotiate, conceive and implement strategies and instruments for water policy. Cooperation with multiple actors is important ("with and not against society"), but this must not mean that the state withdraws and remains passive vis-à-vis the challenges of water governance. The WBGU recommends increasing administrative capacities and resources so that states can assume their role and responsibilities appropriately.

Promotion of self-organization and bottom-up structures in the IWRM context

Especially in regions of the world that are severely affected by exacerbated water-related challenges (Chapter 4), the WBGU advocates the targeted promotion of structures that enable self-organization at the local and regional level (bottom-up), compensate for possible weaknesses in formal water governance, which is often designed by the state, but, at the same time, point these out and ensure their rectification in the formal system. In the past, the promotion of bottom-up self-organization, especially in line with IWRM principles, has also proved its worth in expanding participatory and inclusive forms of decision-making. Especially in times of growing autocratization processes at the political level in the majority of countries worldwide, this promotion of inclusive governance approaches at the local level and in the supposedly apolitical field of water management is important and – based on experience – promising.

Further develop a systemic perspective and promote interaction between state and self-organized governance

An explicitly systemic perspective on water governance and management which involves both the different governance levels and the different actor groups and recognizes state and self-organized water governance as part of one and the same water-management system, makes it possible to successively further develop the system as a whole. Fragmentation, frictional losses and unclear responsibilities that are counteractive to management can be reduced by consciously promoting interaction between bottom-up and top-down water-governance approaches. The efficiency and sustainability of water management can be improved.

Promote dialogue forums to prevent conflicts and enable a collective search for solutions

The WBGU recommends dialogue forums on water to prevent water conflicts between different actors. This promotes democratic practice and contributes to peacekeeping both within countries and internationally. Dialogue forums also offer an opportunity to involve diverse forms of knowledge and actors in the search for solutions. Participation at the local level is an important component of polycentric water governance, and supports the networking and self-organization of the actors.

8.5.3 Mobilize and arrange financing

The realization of water-related goals requires extensive investment, so that the financial sector has an important enabling role to play. Increasing the efficiency and creditworthiness of water utilities as well as the attractiveness of the sector as a whole and the respective market environment (e.g. local financial markets) continue to be of key importance for the sustainable financing of water-related investments. This involves capacity building in public companies and institutions for efficient planning, investment and operation, as well as for supervision and regulation. Strategies of the World Bank (Khemka et al., 2023) and the BMZ (2017), as well as the German National Water Strategy (BMUV, 2023b) are already pursuing these goals. The following recommendations for action therefore emphasize aspects that have so far received less attention, yet also have a steering effect towards climate-resilient water management. The recommendations are grouped according to the three main topics in Section 8.3. Corresponding research recommendations follow in Section 8.6.3.

8.5.3.1 Increase willingness to invest, reduce financing costs: better transparency on water-related risks

Strengthen sustainability reporting through harmonization, support and data provision

The German government should promote the consideration of water-related risks in investment decisions by national and international companies, investors and local authorities in order to encourage the redirection of capital flows into the conservation of water resources, resource-compatible economic activities, water-resilient infrastructure and early-warning systems. To achieve this, first, the harmonization of non-financial reporting criteria for the implementation of SDG 6 should be driven forward at the international level. Building on the experience of German financial institutions in the design of 'blue' financial instruments such as NRW.Bank with the issue of green bonds to finance the restoration of the Emscher river, and initial practical experience with EU taxonomy reporting, Germany can play a pioneering role internationally (NRW.Bank, 2024). This also includes supporting the efforts of the International Platform on Sustainable Finance (IPSF) to harmonize international sustainability taxonomies, and advocating for this at its own events. Second, the conditions for applying the EU framework for sustainability reporting in Germany should be improved: existing public support services, knowledge platforms and contact points, such as the German Sustainability Code (DNK), should be strengthened and expanded in order to create more transparency with regard to water-related risks and opportunities, and to mediate between companies and private donors. In an early phase of their first or voluntary reporting by SMEs, it may also make sense to subsidize the administrative costs of preparing, reporting and marketing taxonomy-compliant water projects (in the sense of a 'taxonomy turbo', similar to the subsidy in Singapore, for example). Experience with support programmes and capacity-building measures should be exchanged with other EU countries (examples in Section 8.3.1.2). Third, the German government should ensure that better data (in some cases in real time) and long-term projections on local water volumes and water use, as well as knowledge on interregional and intersectoral linkages, are collected, made available and, if necessary, skills for their use imparted; it should also support other countries in doing so – depending on local conditions and the needs of the actors. In this context, efforts at EU level to establish a digital and free European Access Portal (ESAP) should also be supported, and corresponding requirements formulated in order to create transparency with regard to the sustainability of economic activities in relation to water and marine resources. The required disclosure information should be merged in national collection centres based on existing sources of information; duplicate data-collection processes should be avoided (file-once principle). In addition to disclosure information for assessing water-related financial risks as part of the European Sustainability Reporting Standards (ESRS), other sustainability-related frameworks could also be harmonized and further data points provided within the framework of the ESAP. Examples include the European Emissions Trading System for greenhouse gases and the Industrial Emissions Directive on the release of pollutants. This would raise the value and usability for financial market players but also for private individuals and social interest groups. At the national level, the improved information on water-related risks and the risk assessments by companies and municipalities should be used to better recognize systemic risks in the context of stress tests.

8.5.3.2
Stabilizing revenues of public and private investors

Strengthen comprehensive and socially balanced pricing of water

Water prices and charges should at least cover costs. Costs to be covered should also include environmental and resource-related costs, as required by the EU Water Framework Directive. The German government should support low-income countries in planning and implementing price reforms, e.g. via capacity building. The resulting revenues open up financial scope for the countries to invest in water infrastructure and nature-based solutions. The pricing structure and the use of revenue should be socially balanced. Low-income households should be given financial relief – with low prices for consumption volumes in line with basic needs, low basic charges for the water connection, or even user-independent grants where the water and wastewater charges contain incentives for an efficient use of water. Exemptions from abstraction charges for water-intensive industries such as agriculture should be abolished. A reform of water prices may initially require better data gathering in the field of water consumption and withdrawals.

Water-related support and subsidy reforms, in particular CAP 2028+

Activities and measures, especially (but not only) in agriculture, which have positive water-related effects for the general public – for example by stabilizing the water balance as a whole – can be co-financed by the public sector (e.g. with blended finance instruments), charged less in taxes and levies or directly subsidized. Subsidies that run counter to water and groundwater protection and sustainable water management, especially in the agricultural sector, should be abolished. In Europe, the Common Agricultural Policy (CAP) is the most important example – it should be reformed as from 2028 in such a way that it promotes the conservation of water resources and nature-based measures with multiple benefits, and does not offer disincentives. Specifically, Germany should work to ensure that the eco-regulations provided for in the first pillar of the CAP are further expanded and provided with additional financial resources from 2028. Funds could be deducted from the area-based direct payments for this purpose (WBGU, 2024). In low- and middle-income countries with governance systems that fulfil the necessary requirements in terms of accountability, transparency and proper management, water-related debt swaps can release funds to promote climate-resilient water management.

Avoiding indirect subsidies that damage water bodies

In order to safeguard public budget planning from possible water-related risks, and to avoid cross-subsidization that is harmful to water, public subsidies in water-intensive sectors such as industry, energy and agriculture, as well as in the field of international climate financing, should be aligned with water-related minimum standards, e.g. agricultural subsidies, climate treaties and NDCs. The Do No Significant Harm principles of the EU taxonomy, which are based on minimum technical criteria with regard to the protection and conservation of water and marine resources, could serve as the basis for a possible screening of investments that are supported by the state. Where conflicts of objectives between ecological, societal and economic interests are identified in public budget and subsidy planning, public expenditure at the expense of water quality can be avoided, for example, by taking account of environmental and water-related minimum standards ('green budgeting').

Generate revenue by extending producer responsibility

As part of an extended producer responsibility, distributors of water-polluting substances or products should be made more liable for the costs of measures to eliminate water pollution and/or for water protection. Such a participation could be achieved, for example, through levies on water-polluting products and substances. In Germany and at the EU level, there are already approaches for extended producer responsibility, which should be widened to cover more substance and product groups (e.g. household chemicals), as well as substance properties (classification according to persistence in the aquatic environment in addition to toxicity) (Section 7.5.1). Also from a global perspective, extended producer responsibility should be used more to finance measures. This could make a significant contribution to financing infrastructure in low- and middle-income countries. The German government should create the institutional capacities for this within the framework of its bilateral and multilateral partnerships.

EU-wide pesticide levy

Germany should advocate an EU-wide pesticide levy, e.g. in the form of a tax. It should cover both environmental and health risks, and put a higher price on substances that involve greater risks (Section 7.5.2). The revenue generated could be used on the one hand to finance water-protection measures (preventive measures and removal, and/or paying compensation for the effects of residual pesticides) and, on the other, to mitigate exceptional financial burdens caused by the levy, e.g. on farmers. It could also finance training measures and advisory services for farmers on the use of alternative crop-protection techniques. A proposal to introduce a pesticide tax at the EU level has already been submitted (Europäisches Parlament and Committee on the Environment, 2023).

Strengthen revenue generation and use at the local level

The implementation of many measures for a climate-resilient water-management system lies with the municipalities and cities. However, their powers to collect and use revenues are limited in many countries (Section 8.3.2.3). Germany should strengthen the opportunities for revenue generation at local level. At the EU level and beyond, such a step can also help to finance local measures in the water sector if accountability, transparency and standards of good governance are also observed when collecting the taxes. In Germany, for example, a reform of property or trade tax should be examined (Section 8.3.2.2) to enable municipalities to use it specifically to finance local water-related public goods, e.g. nature-based flood-prevention measures (see Section 8.6.3). The political incentive structure for the increased use of taxes to generate revenue at the local level should also be analysed and reformed if necessary. For example, poorly designed fiscal transfers from the national level can mean that opportunities to generate revenue at the local level are not used (von Haldenwang, 2017). In contrast, revenue from centrally levied charges, e.g. on pesticides, or charges as part of extended producer responsibility that are linked to tasks to be fulfilled at the local level (e.g. water treatment), should be allocated proportionately to cities and municipalities for the fulfilment of these tasks. Water-related compensatory payments between different regional or local authorities should also be considered. These could contribute to economic efficiency if other municipalities, cities or federal states also benefit from local measures because, for example, restoration measures on a river's upper reaches have a positive effect on flood protection in the river's lower reaches. However, considerations of fairness could also justify such compensatory payments, determined on the basis of previously defined financial requirements to ensure a climate-resilient water supply and the financial strength of federal states and municipalities.

In order to address the challenges relating to the collection and use of revenue in low- and middle-income countries, institutional and structural reforms are necessary in addition to increasing their capacity for transparent tax collection. This should involve expanding the tax base and improving the efficiency of revenue use, for example by combating corruption or reducing inefficient exemptions, as well as taking action against tax avoidance (World Bank, 2023a: 123 ff.; Redonda et al., 2021; von Haldenwang et al., 2024). Taxpayers should be informed about how the funds are used, and legal certainty should be created.

8.5.3.4
Strengthen intermediaries and local cooperation platforms

Strengthen intermediary institutions that bring together water actors, land users and financial actors, and can mediate between them

Intermediary institutions can play a key role in mediating between locally adapted, smaller approaches and projects on the one hand and the requirements of financially strong investors on the other. They can pool both public and private investors as well as different projects: they also have the necessary knowledge of the financial and water sector – as well as the environmental and climate sector – to arrange structured financing (in line with risk appetite, maturities, expectations of returns or public benefits, etc.; for example, long-term measures often require up-front or bridge financing). Correspondingly specialized banks, revolving water funds, NGOs or research institutions should be set up or supported.

Create comprehensive local governance and financing platforms involving water, land-use, environmental and financing actors

With the help of the intermediaries, the EU, national and sub-national governments should institutionalize 'across the board' local exchange and cooperation formats (e.g. in cities and their respective catchment areas) – for example between water utilities, water users, land users, environmental and other NGOs, as well as public, public-welfare and commercial donors. A common knowledge base and transparency can be created in such a format, strategies and measures coordinated, and financing organized. Climate-adaptation and biodiversity-conservation actors should also be involved here, firstly because synergies with projects for a resilient water supply already exist in some cases, and secondly because public water utilities, which have a lot of influence and a good reputation in many places, can be valuable partners in transforming the way land is used.

Build up skills and monitoring capacities for implementing results-oriented blended-finance approaches

For the success of results-oriented financing approaches, e.g. for nature-based solutions or other projects with environmental and social multiple benefits, it is crucial that the projects and remuneration model are carefully defined and planned, and that the success criteria can be precisely measured. Corresponding expertise and advisory capacities should be developed, for example in public institutions or agencies in cooperation with research institutions. Best-practice examples should be collected and developed into transferable/scalable financing models in cooperation with financial players.

8.5.4
Proactive role of science: bring policy-makers and stakeholders together

In the WBGU's view, the proactive and internationally cooperating role of science is essential in order to improve the way in which regional water emergencies with a planetary dimension are dealt with in the future. The establishment of a Water Mapping Initiative aims to strengthen the interface between science and politics.

Establish a Water Mapping Initiative

The WBGU recommends setting up a Water Mapping Initiative to identify and avoid local and regional water emergencies with a planetary dimension. It would consists of two units: a science platform and a panel of experts. The science platform aims to bring together existing scientific expertise and to record regionally specific changes in order to identify imminent regional water emergencies.

The WBGU continues to recommend the establishment of a panel of experts to direct the platform and feed the results of its work into political processes. With the results of the platform's work, the panel of experts can create the basis for dialogue between science, politics and other stakeholders, and develop forecasts for regions threatened by water emergencies. It can also inform the UN Water Conferences and water-related dialogue platforms in the world's regions, and cooperate with water authorities on the implementation of climate-resilient water management.

The platform and the panel of experts should be institutionally based at UN Water. The databases and the scientific analysis should be hosted by internationally commissioned national research institutions. Ideally, funding would be provided by the G7 and G20, as well as by other countries on a voluntary basis.

Promote inter- and transdisciplinary science for climate-resilient water management

Climate-resilient and socially balanced water management requires the continuous further development, renewal and the maintenance of infrastructures, as well as human and institutional capacities, in order to be able to meet the growing demand for water in an increasingly variable water supply. Management systems alone cannot achieve such a necessary innovative objective. Instead, interdisciplinary and transdisciplinary research, the promotion of young talent and policy advisory services, which are among the core tasks of science, are of key importance. The WBGU emphasizes the need to regard climate-resilient water management as a guiding principle for science policy in Germany. Inter- and transdisciplinary research approaches in relation to the water cycle and water management, which pursue both basic and applied research, should be promoted. This includes engineering and scientific research, as well as legal, social, cultural and macroeconomic disciplines, united by the guiding interest of providing all people worldwide with water of sufficient quantity and quality in the future.

Different actors from water management, agriculture, industry, etc. should be enabled to exchange knowledge on dealing with water-related challenges on an equal, inclusive and multidirectional basis on platforms and in working groups. This exchange should include new knowledge about non-stationarity and exacerbated challenges, as well as local knowledge and experience, for example from farmers and foresters. The WBGU continues to regard citizen science and citizen labs as important instruments of transdisciplinary research and advocates the further expansion of these forms of citizen participation.

Promote international scientific cooperation

Intergovernmental, international cooperation is a fundamental prerequisite for dealing with the exacerbated water-related challenges described in this report. It is necessary in order to recognize the systemic changes in water availability, provision and management, and to develop technological, social and institutional innovations for climate-resilient and socially balanced water management. Innovations must be adapted to the different societal and ecological contexts in which they are used if they are to be successful and promote climate-resilient water management. International scientific cooperation on water continues to be an instrument for exchanging societal and political norms, including the promotion of democracy through Integrated Water Resource Management, and for the further development of scientific standards.

Against this background, the WBGU recommends expanding bi-, tri- and multilateral scientific funding in the field of water. This comprises joint funding lines in the field of water-related science, designed and financed by research funders from different countries and regional organizations, as well as the promotion of multilateral funding formats, e.g. via the Belmont Forum, Future Earth and the recommended Water Mapping Initiative. Furthermore, the German government should espouse science-policy issues and the funding of science systems by national governments worldwide – but especially in middle-income countries and regional powers – at the level of the United Nations and club-governance formats, particularly the G20 and G7 (Hornidge et al., 2023; Taylor et al., 2022). In the multilateral context, science policy is still far too often dismissed as a 'purely western/northern affair'. This enables large regional powers and middle-income countries with large, young populations such as Indonesia, Nigeria, India, Brazil and South Africa in particular to continue investing comparatively small sums in science and the education and training of their populations as a proportion of their gross national product.

However, when jointly dealing with the multilateral exacerbated challenges described in Chapter 3, this means that negotiations are conducted from very differently structured and efficient scientific systems. Joint, science-based approaches to solutions are only found to a limited extent and are even less likely to gain majority support. This should be specifically addressed by jointly developing scientific solutions for climate-resilient water management, and by building and expanding scientific capacity, particularly in the major regional powers of Asia, Africa and Latin America, also through their own national policy-making, supported by science-policy objectives at the G20 level.

Set up a global information system

Moreover, the WBGU recommends the creation of a global information system for water, climate, land and environmental sustainability. To this end, the standardization and integration of databases should be expedited. There is also a need for joint analysis hubs, e.g. through the extension of science policy. This global information system is the basis for improving early-warning systems for extreme weather events. Early-warning systems are key, but in conventional thinking and application they usually do not cover the 'last mile'. This needs to be focused on. Here, too, it is important to concentrate more on planetary water emergencies and situations beyond the limits of controllability. This should also serve to improve modelling capacities in relation to drought and flood events, from which low- and middle-income countries in particular can benefit.

Improving the data situation also supports better implementation of the water-energy-food-ecosystem nexus (WEFE-Nexus) concept. As explained in Chapter 2, this concept aims to improve policy coherence and to better understand and manage the interdependencies between the Sustainable Development Goals (Srigiri and Dombrowsky, 2021, 2022). Implementation deficits arise i.a. because of the inadequate data situation, which prevents the measurement of interrelationships and conflicting objectives. In this context, the International Water Strategy should also address the necessary transformation of food and energy systems.

Create the legal conditions for direct fund management in partner countries

Up to now, the legal framework for international research collaborations has stipulated that all personnel, material and travel funds must be managed by the research institutions of the donor countries. As a way of boosting research capacities, the WBGU recommends creating the legal conditions for direct fund management, including accounting and auditing, in partner countries. This strengthens the role of the scientists conducting research there and generates skills in the administration of funds. The WBGU agrees with a recommendation by the German Commission for UNESCO to create the legal conditions in the German science-funding landscape to enable onward transfers to partner institutions outside Europe without transferring both liability risk and auditing activities entirely to the German scientific institutions. This is unaffordable particularly for non-university research institutions without private-sector income and with low staffing levels in the service areas. These in turn, e.g. Leibniz Institutes or non-university research institutions with close links to government departments, are often the type of interdisciplinary and international scientific institutions that carry out these forms of scientific cooperation with partner institutions in Africa, Asia or Latin America. In this context, the WBGU continues to recommend that shared liability be made possible between the research-funding organization, the German and forwarding institute and the foreign partner institute (DUK, 2024).

8.5.5
Education as the basis for an informed society

The chance to educate oneself about current and future water issues and contexts is the basis for a well-informed discourse on dealing with water and water emergencies for society as a whole. Societal interest in water issues can be strengthened via references to one's own living environment and by dealing with local water problems.

Specifically promote education, advisory and training programmes

The WBGU recommends initiating more targeted educational programmes at the national and international level, and launching an international discussion on new forms of economic activity and the appreciation of ecosystem services. In this context, knowledge should be exchanged globally among equals and with the involvement of all relevant actors. Support and education programmes should be jointly coordinated nationally and internationally and follow a common thread, so that people from different professions and backgrounds can be informed, addressed and can participate in equal measure.

Targeted advisory and training programmes – also based on the results of knowledge exchange – should be carried out at the regional level and tailored to local conditions in order to raise awareness of local water problems and to make solutions available. This would empower local actors to tackle the exacerbated challenges in the water sector. Digital technologies should also be used for this purpose, e.g. joint portals for sharing knowledge, or apps that can provide up-to-date information on water consumption, nitrate levels or groundwater levels.

Give the topic of water a higher profile in school curricula

Launching real-life lessons on the topic of water enables children and young people to learn more about water cycles, the water supply, water's importance for people and nature, and the consequences of climate change. A considerable amount of teaching material is already available for all ages and school types. Because the topic of water is of such paramount importance, the WBGU recommends that it becomes obligatory for curricula to take up the topic on an interdisciplinary basis across the entire school spectrum.

8.6
Research recommendations

There are already many future-oriented research projects on the subject of water that address the complexity of water governance both conceptually and empirically, such as the funding programmes 'Water: N' and 'Global Resource Water' (GRoW; BMBF, 2021a, 2024c). In order to develop an international water strategy and make it as participatory and effective as possible, further research is needed that looks at both blue and green water, as well as possible governance approaches on the subject. In order to trigger higher investments, potential water-related damage should be better quantified and financing approaches for nature-based solutions further developed.

8.6.1
Understanding and communicating international contexts

There is a need for basic research on the interdependencies of regional water emergencies of planetary dimensions, methodological innovations, research on policy integration, and dealing with interfaces between several policy areas.

Scientifically analyse the scale and dynamics of regional water emergencies with a planetary dimension and research options for action

The dynamics of global climate change and its impacts on the availability and distribution of water will confront the global community with medium and long-term challenges that transcend the range of experience of human societies. In some cases, this will also test the limits of controllability. Recent research has already identified the first planetary water emergencies. Research on the potential extent, regional distribution and range of their specific manifestations is still in its infancy. There is also a need for research into dealing with uncertainty and integrating long-term, potentially critical developments into today's decisions (policy, planning, prevention). The WBGU therefore recommends promoting such issues in national and international research agendas.

Exploring the cross-border dimension of green water

The complex international interactions and interdependencies between green and atmospheric water – e.g. through land-use changes, the effects on evaporation flows and precipitation in other countries – urgently need to be researched. On the one hand, this requires basic research on the cross-border effects of green water using modelling and scenarios (hydrology, physics, climate research) and, on the other hand, research in the fields of jurisprudence, political science and economics on the principles and options of cooperation, as well as applied research on regulatory options and the effectiveness of policy instruments.

Water and climate scenarios at the middle level

For global and regional climate-resilient water governance, water and climate scenarios at the middle level (meso- rather than micro-level) are particularly needed in order to recognize changes at the level of world regions such as Europe, North Africa or South-East Asia. As the majority of water research to date has focused on river catchment areas, there is an increased need here to further develop modelling methods and research approaches.

Socio-hydrological and social-science research

Dealing with the global water crisis requires a better understanding of the systemic relationships and interactions between nature and humans. Socio-hydrological research is highly relevant here as it makes it possible to study the complex interplay of scientific and societal factors in aquatic systems. Socio-hydrology is the combination of hydrological and sociological research, primarily using quantitative approaches and models. The WBGU furthermore recommends the promotion of social-science water research that analyses economic, political, social and legal aspects, particularly with regard to options for adaptation in different regional contexts.

Research on effective interfaces

There is a need for policy-related and jurisprudential research into whether and how effective interfaces between different policy areas can be designed or institutionally established. There is a need for research into the design both of interfaces for negotiations in the Conferences of the Parties and of the associated science-policy interfaces (e.g. in the areas of climate, biodiversity, plastics and pollution). Challenges of previous interface governance and possible institutional innovations should be discussed.

8.6.2 Expand bilateral and multilateral research funding

Create and promote new regional research alliances to initiate learning processes at the regional and global level

New regional research alliances could inform regional platforms. Scenarios at the middle level (meso rather than micro level) that show changes in the water cycle in regions of the world such as Europe, North Africa or the Middle East will be highly relevant here.

Regional and multilateral funding organizations should set up funding lines to which scientists can apply regardless of their geographical location and with special funding for South-South and South-North scientific cooperation, such as Future Earth or the Belmont Forum. At present, the EU is a global exception as a regional science-funding organization. According to the International Science Council, over 80 % of research worldwide has so far been organized on the basis of a national logic of science funding (ISC, 2021: 13). Bi- and multilateral science funding to achieve jointly defined funding objectives and for dealing with global challenges should be urgently and substantially expanded. Developed solution approaches and transformation paths are taking too little account of regional and transregional spillover effects. There is also a need to explicitly promote transregional science and innovation networks to enable and target mutual learning processes in the design of water governance and with regard to sustainability and quality standards.

Science funding should be strengthened via joint bilateral and trilateral funding lines, on all continents and with countries of all income groups (low-, middle- and high-income countries), as in the case of the cooperation between the BMBF and funding organizations of nation states. This means, for example, expanding funding lines jointly between the BMBF and the science ministries of other countries, like those that already exist e.g. in cooperation with South Africa, Poland and Israel, or within the framework of science funding by the European

Union. The same applies to the respective research organizations, e.g. the German Research Foundation (DFG) or the Academic Council of the United Nations.

Promotion of inter- and transdisciplinary projects on sustainable water management

The German and European science-funding landscape should specifically promote interdisciplinary and transdisciplinary projects in the field of sustainable water management in different regions of the world that face different management challenges. This includes scientific and locally adapted innovation development in the field of irrigated agriculture, as well as urban water supply and disposal, wastewater treatment and hydropower generation. It is important in this context to pay attention to transdisciplinary research designs in which the transformative co-production of water-management knowledge is promoted in close cooperation among scientists and practitioners. Particular attention should be paid here to ensuring that the institutional structures and capacities are also developed, in addition to innovations and new areas of knowledge in the field of sustainable water management, so that this knowledge can be implemented in the local systems.

Further development of methods for documenting and assessing water-related environmental impacts and spillovers

To strengthen the positive impacts of trade on water supply and quality and to avoid negative spillovers, the methods for documenting and evaluating water-related environmental impacts and spillovers must first be further developed, e.g. by further developing the concept of an impact-based water footprint. This can be based, for example, on the results of the 'WELLE' research project to determine the water footprint of companies as part of the BMBF's 'Global Resource Water (GRoW)' funding programme (TU Berlin, 2020) and a research project funded by the Federal Environment Agency on the conceptual development and documentation of Germany's water footprint (UBA, 2022b). The further development of models for environmental impact assessment in bi- or multilateral trade agreements should also be considered. The EU presented a new concept for this in 2021 (IEEP, 2021), although it does not take into account any impact-based documentation of the water footprint, for example. Environmental impacts, too, are not comprehensively assessed in many countries. Furthermore, research is needed on governance mechanisms that effectively integrate these environmental impacts into private and governmental decisions.

Strengthen international relations through scientific cooperation and research alliances

When setting up funding lines in the field of water management and water research, specific attention should be paid to promoting cooperative research projects with different countries. The following three groups of countries should be considered: (1) countries that face increasing challenges in water management (e.g. droughts, floods), such as Jordan, Lebanon, Mongolia or Uzbekistan, (2) countries that are affected by social polarization and political autocratization processes, and (3) countries that are of high strategic relevance as partners and alliances for Germany and Europe at the level of geopolitical negotiation processes.

The scientific cooperation recommended here should embrace all scientific actors, including universities, advisory institutes and think tanks. This offers extensive opportunities to engage in close dialogue with very different societal actors (NGOs, semi-governmental water-user communities, women's organizations, etc.). The joint technical and knowledge-oriented cooperation work enables a very close and trust-building exchange. Participatory and socially inclusive approaches to cooperation can be practised, thereby improving water management and simultaneously developing and establishing broader institutional structures and cultures for inclusive and accountable governance.

For funding lines in the field of sustainable water governance, care should be taken to ensure that both the formal and informal, i.e. 'de jure' and 'de facto' aspects of the water-management system are empirically surveyed and analysed for weaknesses or adaptability in dealing with water emergencies. This requires inter- and transdisciplinary project designs and a correspondingly interdisciplinary composition of the social-science parts of the project teams (law, sociology and ethnology). Building on this, the development of institutional innovations and solutions for forms of management that integrate bottom-up and top-down systems should be secured and implemented.

8.6.3 Research for sustainable financing

Greater commitment by companies, financial-market players and the public sector to mitigating water-related risks and conserving water resources and climate-resilient infrastructure requires a solid information base on such risks and on the multiple benefits of nature-based measures in particular. Financing models should be further developed for the latter. The possibilities for improving the financing of local public goods, as well as the impacts and reform requirements of water-related levies should be comprehensively analysed.

Improve projections or data and modelling on potential water-related damage, adaptation costs and multiple benefits

Estimates of possible regional damage caused by water-related climate risks, the costs of adaptation measures and any remaining residual risks and possible additional benefits (e.g. for health and the environment) are still subject to great uncertainty. The empirical data basis should be improved and projections and the modelling of uncertainties further developed (Caretta et al., 2022: 652 f.) – also to determine the best time for often irreversible adaptation investments in view of conflicting aims of timely precautions and an information base improved by a longer wait (Ginbo et al., 2021). In addition to infrastructure measures, the costs and benefits of nature-based solutions, efficiency measures on the consumption side and changes in regulations and water prices should also be analysed (Caretta et al., 2022: 652 f.; Section 6.5.1).

Assessment of the economic and financial costs of inaction: 'stress testing' of national economies with their global interdependencies

The impacts of possible physical damage to the economy and the financial sector caused by 'too little' or 'too much' water should also be better analysed at the level of entire national economies. International impacts of national crises, e.g. via trade, transport routes and financial markets, should be included. The time scales considered should take into account the sometimes decades-long lifespans of many capital stocks and especially infrastructures. The analysis should include direct impacts due to capital-stock losses, indirect economic restrictions and cross-sector effects, as well as the associated credit-default risks for banks and the impacts on the insurance industry.

Develop hybrid financing instruments and new business models for nature-based approaches

In view of the high investment requirements, there is also a need for increased private participation in the financing of nature-based approaches. Hybrid financing together with state actors can play an important role here. Transdisciplinary research involving financial sector players and local investors is required to develop and implement corresponding business models. The research should cover the design of the financing forms and instruments, as well as monitoring and an impact analysis of social and ecological benefits. There should also be analysis of the best incentive and steering effects, especially on institutional investors, that can be achieved by disclosing water-related risks and external costs.

Further develop and implement the valuation of multiple benefits

Nature-based approaches lead to societal and ecological multiple benefits, the monetization and compensation of which can lead to reliable sources of income for private investors. Despite existing efforts to value ecosystem services, and despite discussions about their remuneration, for example in the forest context, these additional benefits have not yet been systematically incorporated into state funding. As in the past, the data situation is one reason for the lack of implementation. Ecosystem services are locally differentiated and diverse. Further research is needed, particularly with regard to water-related multiple benefits – from their documentation and evaluation to their efficient and effective integration into policy and government measures.

Impact analysis of an extended reform of levies

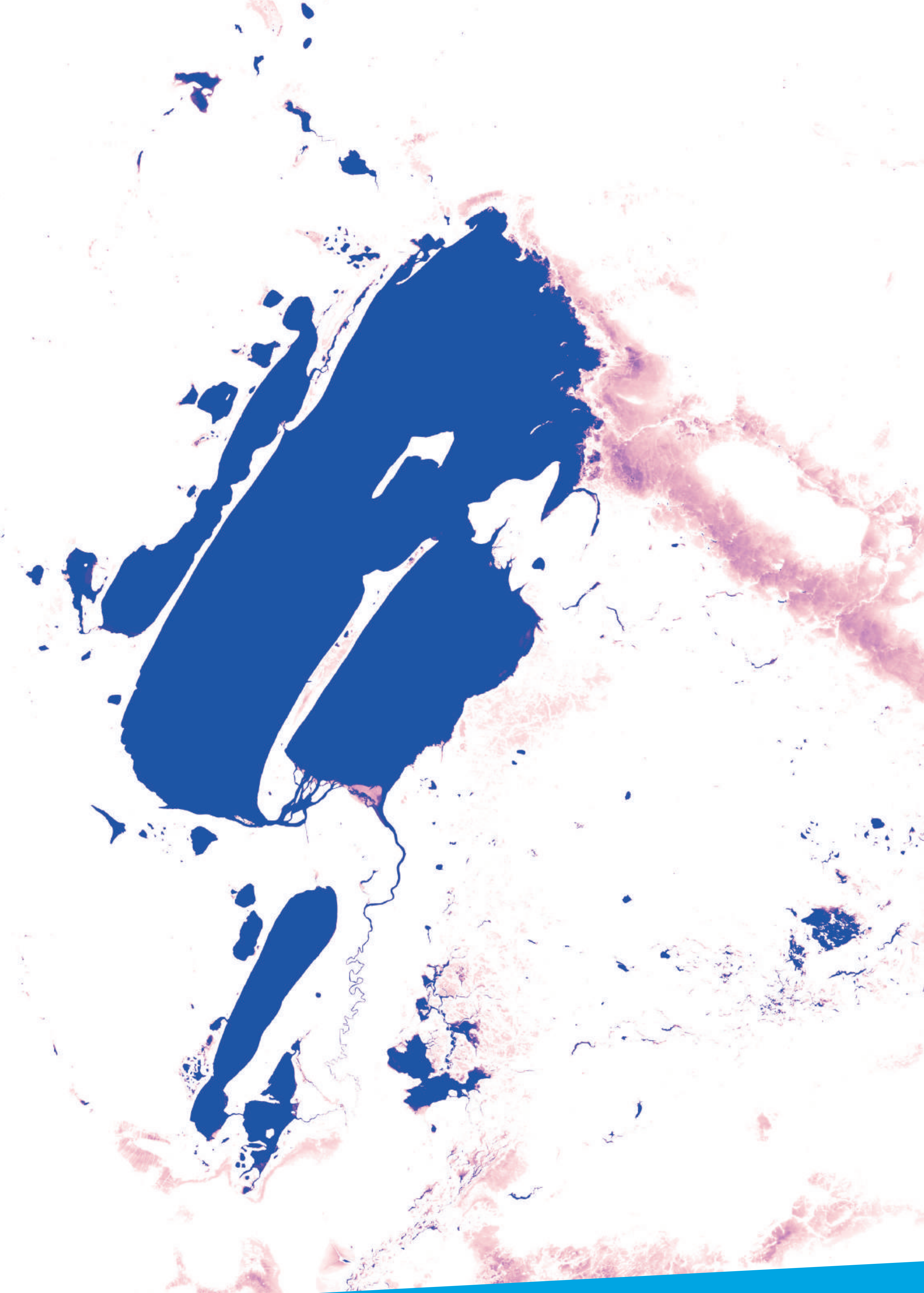
Countries should analyse the impacts of a possible reform of water-related levies in line with the approaches discussed in Chapter 8.3.2 on ecosystems, private households and important economic sectors such as agriculture and industry. Undesirable side effects of the measures – such as unintended burdens on actors outside the target group, or displacement effects, e.g. migration of pollution-intensive economic activities – should be taken into account and analysed to determine how they can be prevented. To this end, a reform or introduction of water-related levies should be seen systemically in the context of a reform of other taxes, fees or contributions: e.g. Denmark refunds some of the revenue from the pesticide tax to farmers by reducing other taxes.

8.6.4 Research on the challenges of political communication

A general decline in the popularity of topics related to sustainability and transformation can be observed in line with the social polarization and political autocratization processes described in Chapter 3. This includes topics on dealing with the climate and biodiversity crisis as well as shaping the necessary structural change in production systems and consumption patterns with the aim of climate stabilization. The EU Commission's Green Deal and the Global Gateway, which was originally intended as a response to China's Belt and Road Initiative, are perceived as 'green colonialism' in parts of southern Africa. Ursula Van der Leyen's guidelines for 2024–2029 will determine the European Commission's political action in the coming years. However, they do not adequately address the international dimension of sustainable development. The 2030 Agenda was considered to be too complex, and there was no mention of a post-2030 agenda in the guidelines (von der Leyen, 2024).

Promote research on political communication

Because climate-resilient water management requires majorities, the WBGU recommends promoting research into the communicative challenges of dealing with multiple exacerbated challenges. What is needed is the ability to react to political communication, which is currently characterized by fake news, and to enable fair, public, democratic discourse. The focus should be on the following research questions: what can be empirically proven and communicated to make the communication of climate-resilient water management and other sustainability issues more effective, in order to reach those affected and to make majorities possible for transformative water management by means of a fair democratic debate? In order to strengthen democracy, research should also be conducted into how highly complex and difficult issues relating to regional exacerbated challenges that develop global-scale dynamics can be reflected on with voters in such a way that climate-stabilizing and socially acceptable policies are possible.



Core messages

9

Maintain a safe distance from the limits of controllability

Water crises are already common today all over the world. In the future, the global hydrological cycle is expected to undergo ongoing, accelerated changes, further exacerbating the effects of climate change, the overuse of water resources, the unequal distribution of water, the loss of ecosystem services, and the threats posed by water-related health risks. This will increasingly lead to threatening situations that lie beyond the spectrum of human experience. In combination with existing water-use challenges, they could escalate into regional water emergencies. In extreme cases, situations will arise in which the limits of controllability are exceeded, societal structures and ecosystems are substantially destabilized, and there is simply no longer any room for manoeuvre. Life-support systems will be being lost.

In order to maintain some leeway for action, maximize the distance from the limits of controllability and create greater resilience, forward-looking adaptation measures will increasingly be needed to safeguard water supply and water quality. In concrete terms, this means a willingness to radically change direction, which also requires the initiation and monitoring of structural change, for example via policies on land use, industry, settlements and infrastructure. If this does not succeed and transformative measures no longer help either, an orderly and timely retreat may be the only option left.

These are threatening scenarios with a planetary dimension. It is therefore of the utmost urgency to place the issue of water higher on the international agenda. The current strong momentum from the UN Water Conferences in 2023, 2026 and 2028 should be used by governments to maintain a sufficient distance from the limits of controllability worldwide by taking comprehensive precautions. In the short term, effective strategies for resilient water management should be developed that strengthen global cooperation in the medium term and lead to a water agreement supported by the international community in the long term.

Anticipate and avert regional water emergencies with a planetary dimension

Regional water emergencies are looming on all continents, affecting a large number of people and adversely affecting large natural areas and their biodiversity. Everywhere – from glacial melting in the Himalayas, massive flash floods in Brazil, the steady progression of land degradation in Sub-Saharan Africa, extreme heat waves and long periods of drought in Canada and southern Europe, to the depletion of North American freshwater aquifers and flooding events in Europe, including Germany – various patterns can be recognized that are also being repeated in other regions of the world. Through shared river catchment areas and aquifers, altered evaporation and precipitation patterns, trade relations or migration, each of these patterns can have far-reaching, even transregional consequences and, if combined, lead to a global emergency (e.g. a food or refugee crisis).

A Water Mapping Initiative should therefore be launched internationally in order to recognize and continuously monitor crisis developments at an early stage, inform the global community, and develop precautionary action strategies within the UN framework. Furthermore, there should be a systematic international exchange on effective adaptation and resilience strategies. These challenges confront all countries, and an International Water Strategy should be sought to meet these challenges as a global community.

Implement climate-resilient water management and maintain near-natural water quality

Infrastructures and management approaches must be adapted to changes in local water balances and the increasing occurrence of extreme events. This means that not only present-day data are relevant for planning and operation; rather, the evaluation of measures also requires a long-term view that takes into account the continuous dynamics of change in the hydrological cycle

Lake Bangweulu (Zambia)

and the new quality of uncertainty. Essentially, the aim is to locally slow down the globally changing hydrological cycle and to establish more climate-resilient solutions in the long term through transformative adaptation strategies. Green water – and with it the restoration and preservation of a climate-resilient landscape water balance – plays a key role in stabilizing local and regional water supplies. It should be included as a protected good in international and German water law. Green water should therefore become an elementary component of water-law management in Germany. This means that we cannot think in terms of grey infrastructure and blue water alone. The portfolio of possible measures and their combinations should be expanded even further. Infrastructure and natural and technological water-management systems need to be much more capable than before of avoiding path dependencies, buffering water volumes, continuously adjusting them and thus reacting flexibly to changes. These new challenges for water management must also be reflected in the allocation of budgets and competences.

To safeguard water quality, it is necessary to implement the zero-pollution approach and the model of a circular water economy and to involve healthy ecosystems. The core elements are the need to effectively reduce the input of persistent pollutants, strengthen the self-purification capacity of natural and artificial water bodies, develop purification and circulation processes in parallel with the development and application of new substances, and improve the availability of data on material cycles in the transport medium of water. There is also a need to develop testing procedures independent of animal testing for assessing the effects of new substances on nature and humans – in particular automated biotest procedures and AI-supported computer models. These must take into account the complexity of mixtures and keep pace with chemical innovations. Economic actors should be specifically supported in the development and market launch of necessary processes and substances for purification by creating innovation-friendly framework conditions.

The WBGU recommends taking into account four requirements when selecting and implementing measures to create climate-resilient and socially balanced water management:

1. The efficacy of measures should be assessed on the one hand with regard to specific objectives and, on the other, with regard to their respective contribution to the restoration of a climate-resilient landscape water balance.
2. Furthermore, the suitability and feasibility of measures should be analysed in a context-specific manner, taking into account technical limitations, their need for land and other resources (also in view of other conservation objectives, e.g. climate-change mitigation and biodiversity protection), and the way framework conditions change over time.
3. Possible multiple benefits for climate-change mitigation and biodiversity protection, as well as health, the social and economic benefits of measures, and impacts on the reduction of inequalities should be anticipated, evaluated and taken into account in the assessment of measures.
4. In order to avoid maladaptation and other unintended water-related, ecological, health, social and economic consequences, all impacts of measures on different time scales (from today until 2050 and beyond) should be identified, evaluated and taken into account using a systemic and transdisciplinary approach.

Policy that integrates climate, biodiversity and social policy is effective water policy

Effective water policy requires limiting global drivers that have a direct impact on the global hydrological cycle; an ambitious climate policy, including compliance with the goals of the Paris Agreement, is a prerequisite for this. This is the only way to limit the changes to the global and local water balance caused by climate change. Equally important is the implementation of the Kunming-Montreal Global Biodiversity Framework in order to protect the fundamental role of nature in the global hydrological balance. The earlier action is taken, the more options there are.

However, integrated governance for climate-resilient and socially balanced water management can only succeed if close coordination between policy areas is ensured both in Germany and at EU level, multilaterally within the framework of the United Nations and in the G7 and G20 context. A particular prerequisite for an effective water policy is the harmonization of international climate and biodiversity policy with global social, economic and trade policy. These are the key policy areas for preserving natural life-support systems and combating social inequalities – between social groups, societies and regions of the world. Overcoming the associated challenges will determine whether labour markets and social security systems can survive, livelihood practices that are closely linked to nature can be safeguarded, and the preservation of natural life-support systems can succeed worldwide, so that future options are available locally for younger and future generations. In this respect, coordination and cooperation across departments, policy areas, regions and governance levels is of key importance. In a heated-up world, integrated policy-making for climate-resilient water management, for securing prosperity while reversing the climate and biodiversity crises is the prerequisite for a WaterFuture without existential threats to human life.

Transformative WaterKnowledge: practise forward-looking and supporting science

Changes to the global hydrological cycle as a result of climate change and increased human demands are continuing unabated. The assumption of stationarity – i.e. the idea that natural systems exhibit predictable variability within a defined time window on the basis of empirical observations – is no longer valid. Uncertainty about what will be available in the future is increasing.

This is where science comes in: it should develop and make available projections and scenarios on water quality and supply, and bring information on expected impacts of climate change together with local data and projections on water use and context-specific empirical knowledge. These assessments can be the basis for a socially balanced approach to ecological, climatic, political, social and economic challenges and exacerbations. This requires the development of technological, social and institutional solutions that are adapted in the respective societal implementation contexts and make climate-resilient water management possible.

In other words, in addition to interdisciplinary research into the exacerbated challenges in the water sector itself, transdisciplinary approaches are required in order to develop suitable solutions and management approaches. As part of transformative adaptation, this requires innovative approaches for the continuous monitoring of adaptation strategies and for dealing with large-scale and disruptive changes in water supply and increasing extreme events, as well as precautionary action to protect water quality. Where the limits of controllability are exceeded, the options for action are severely reduced to reactive crisis and disaster management. These should also be anticipated at an early stage.

With society, not against it: the proactive state and self-organized civil society must assume responsibility

The aim of water policy at every policy level must be to conserve, sustainably use and regenerate water resources as far as possible. Sustainable use in the face of increasingly difficult conditions means, in particular, distributing the changing resource of water appropriately – also between humans and nature. Conflicts of use must be resolved with the help of state or self-organized water management that opens up trade-offs and involves those affected (stakeholders, civil society). Water is a life-giving resource and must not become a political pawn. Water management is therefore an important factor in protecting democracy and securing peace.

A sustainable WaterFuture requires goals and responsibility to be borne not only by the state but also by business and society. The state must create the necessary conditions for this and create a political and regulatory framework for firmly enshrining the value of water at all levels of society and the economy. Such a framework includes both an education campaign on the responsible use of water and the creation of scope for action for climate-resilient water supply and use. Both public and private local water actors must be put in a position – organizationally and financially – to tackle future challenges together. Companies must be provided with the necessary information and incentives to fulfil their responsibility for sustainable water use at a supra-regional level. As a valuable resource, water should be priced consistently and in a socially balanced way in order to promote its efficient and sustainable use both locally and globally. Furthermore, incentives should be created to attract private capital to supplement public funding. The financial leeway gained by activating private investment and increasing public revenue is urgently needed for adapting water-related infrastructure to climate change. In view of the necessary adaptation strategies and the need for accelerated implementation, the existing social self-organization for dealing with water should also be strengthened – by means of a suitable legal framework, as well as organizational and, if necessary, financial support for non-state actors. Cooperation platforms can bring together local water and land users, government, civil-society and scientific actors to share knowledge and develop strategies and financial compensation and financing models. Examples include water funds in which actors from cities and/or municipalities and their water catchment areas come together. The interplay between state and self-organized water governance – i.e. a combination of top-down and bottom-up approaches in the planning and implementation of water management that corresponds to the evolved societal, infrastructural and ecological realities on the ground – is of key importance for sustainable and coherent water management across all levels of governance.

In order to attract new actors such as farmers and foresters to the protection and management of green water in particular, appropriate motivation and incentives are required. On the financial side, this involves both a reorientation of subsidies and the kind of remuneration models that reflect societal and ecological added value. In addition, the value of a climate-resilient water supply for people and nature must be better communicated to the relevant actors and the public. Farmers in particular, who play a key role in restoring a climate-resilient landscape water balance, should be valued and supported in this role.

Assume responsibility internationally – develop an International Water Strategy

International water governance must adapt to advancing and accelerated changes in the global hydrological cycle and the resulting exacerbation of water-related challenges. On the one hand, water must be included and taken into account as a cross-cutting issue in many forums – e.g. on climate, biodiversity, desertification, pollution, social inequality and poverty – but it also needs its own process and political attention. Germany should take a leading role in international water governance, strengthen capacities at the interfaces, promote international cooperation and lead the way with adaptation strategies for climate-resilient water management.

The UN Water Conferences planned for 2026 and 2028 should be well prepared. At the Federal Government level, this means making water a matter for the top echelons of government, identifying it as a priority policy area in the interdepartmental dialogue under the leadership of the Federal Ministry of the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) and bringing the German strategic priorities to the talks at European Union level at an early stage. Here, it makes sense to use the Green Deal framework and strengthen it with a focus on water in a newly appointed European Commission in 2024, while at the same time using the Team Europe initiative to promote coordinated EU-wide policy-making in the sphere of water. At the multilateral level, it would be expedient to use the G7 Water Coalition adopted in 2024 as a platform for reaching early agreement on strategic goals, time frames, finances and institutional structures in the area of water governance for climate-resilient and socially balanced water management. In particular, Canada's G7 presidency in 2025 should be used to further shape the Water Coalition and to successively transfer its priorities to the Water Dialogues at the G20. South Africa's G20 presidency in 2025 in particular offers another political window of opportunity here.

The WBGU recommends developing an International Water Strategy with regional platforms by 2030. The objectives and measures of the Strategy should also be incorporated into intergovernmental economic and trade relations to make synergies possible between the protection of water resources and support for climate-neutral development and food security. In the long term, the strategy should be developed into a separate global agreement for water – comparable to the Rio Conventions.

The aim is therefore to use these various platforms to prepare the priorities and strategic design of the UN Water Conferences, initially with like-minded countries (G7) and then, as the next step, with the major middle-income countries (G20), and to incorporate them into the planning for the UN Water Conferences in 2026 and 2028 as a comprehensive policy programme for a peaceful WaterFuture on a heated planet. These conferences require support from an internationally diverse panel of scientific experts (Water Mapping Initiative), which identifies critical water-related changes for ecosystems and settlement areas in different regions of the world as well as impending water emergencies.

In addition to an awareness of the new dimension of water-related challenges and the shared concern, incentives are also needed for states to participate in international cooperation. One such incentive is a better understanding of the complex interdependencies that exist, for example, through cross-border atmospheric water transport between countries (precipitation and evaporation effects) or the virtual water trade, but also the prospect that these will be regulated in a way that is in line with the interests of all parties. Support measures and financial compensation mechanisms that are beneficial to all sides should be developed, with a particular focus on the land-use sector, which is pivotal for green water.

Introduce the national water strategy into the international discourse

The German government's National Water Strategy, with its vision for the future and the needs for action and the measures derived from it, is a major step towards preventing regional water emergencies that deserves international attention. However, it will only be effective if it is comprehensively resourced and implemented in the long term, both at national level and in cross-border cooperation. Even the National Water Strategy does not yet fully recognize the extent of the challenges that lie ahead. This applies above all with a view to recognizing and dealing with the limits of controllability, the loss of stationarity and the recognition and necessary active management of green water. This means that systems for the provision and use of water must be kept resilient in the face of hitherto unknown fluctuations and ongoing changes that cannot be precisely predicted; they should be re-coordinated on a scientific basis. These aspects should be included in departmental research and the Federal Government's research programme (e.g. 'Water: N – Research and Innovation for Sustainability').

In addition, the National Water Strategy is linked to a number of other national strategies and legal regulations of the Federal Government, whose measures could have considerable synergy effects for the water sector – such as the Climate Protection Act, the Climate Adaptation Act, the German Sustainability Strategy, the Nature-Based Climate Action Programme, the National Security Strategy and the Research for Sustainability Programme. This requires cross-departmental harmonization and coordination.

References

Abarzúa, G. E. B. and Glückler, J. (2023): Network Governance at the Margin of the State: Rural Drinking Water Communities in Chile. Environmental Management 71 (2), 451–464. https://www.doi.org/10.1007/s00267-022-01760-2.

Abraham, A. and Chakraborty, P. (2020): A review on sources and health impacts of bisphenol A. Reviews on Environmental Health 35 (2), 201–210. https://www.doi.org/10.1515/reveh-2019-0034.

Abramovsky, L. F., Andres, L. A., Joseph, G., Rud, J. P., Sember, G. E. and Thibert, M. D. (2020): Study of the distributional performance of piped water consumption subsidies in 10 developing countries. Washington, D.C.: World Bank. https://doi.org/10.1596/1813-9450-9245.

Acreman, M. and Holden, J. (2013): How Wetlands Affect Floods. Wetlands 33 (5), 773–786. https://www.doi.org/10.1007/s13157-013-0473-2.

ADB – Asian Development Bank (2021): What Is Citywide Inclusive Sanitation and Why Is It Needed? Metro Manila, Philippines: ADB. https://dx.doi.org/10.22617/TIM210395-2.

Adedeji, A. A., Häggblom, M. M. and Babalola, O. O. (2020): Sustainable agriculture in Africa: Plant growth-promoting rhizobacteria (PGPR) to the rescue. Scientific African 9, e00492. https://doi.org/10.1016/j.sciaf.2020.e00492.

Adeel, M., Zain, M., Shakoor, N., Ahmad, M. A., Azeem, I., Aziz, M. A., Supe Tulcan, R. X., Rathore, A., Tahir, M., Horton, R., Xu, M. and Yukui, R. (2023): Global navigation of Lithium in water bodies and emerging human health crisis. npj Clean Water 6, 33. https://www.doi.org/10.1038/s41545-023-00238-w.

Adegbeye, M. J., Ravi Kanth Reddy, P., Obaisi, A. I., Elghandour, M. M. M. Y., Oyebamiji, K. J., Salem, A. Z. M., Morakinyo-Fasipe, O. T., Cipriano-Salazar, M. and Camacho-Dîaz, L. M. (2020): Sustainable agriculture options for production, greenhouse gasses and pollution alleviation, and nutrient recycling in emerging and transitional nations - An overview. Journal of Cleaner Production 242, 118319. https://doi.org/10.1016/j.jclepro.2019.118319.

AfDB – African Development Bank, UNEP – United Nations Environment Programme and GRID-Arendal (2020): Sanitation and Wastewater Atlas of Africa. Abidjan, Nairobi, Arendal: AfDB, UNEP, GRID-Arenda.

Agarwal, A., de los Angeles, M. S., Bhatia, R., Chéret, I., Davila-Poblete, S., Falkenmark, M., Gonzalez-Villarreal, F., Jønch-Clausen, T., Aït Kadi, M., Kindler, J., Rees, J. A., Roberts, P., Rogers, P., Solanes, M. and Wright, A. (2000): Integrated Water Resources Management. TAC Background Paper No. 4. Stockholm: Global Water Partnership (GWP). https://hdl.handle.net/10535/4986.

Agusdinata, D. B., Liu, W., Eakin, H. and Romero, H. (2018): Socio-environmental impacts of lithium mineral extraction: towards a research agenda. Environmental research letters 13, 123001. https://www.doi.org/10.1088/1748-9326/aae9b1.

Aksnes, D. W. and Sivertsen, G. (2023): Global trends in international research collaboration, 1980–2021. Journal of Data and Information Science 8 (2), 26–42. https://www.doi.org/10.2478/jdis-2023-0015.

Alaerts, G. (2019): Financing for Water—Water for Financing: A Global Review of Policy and Practice. Sustainability 11 (3), 821. https://www.doi.org/10.3390/su11030821.

Albert, J. S., Destouni, G., Duke-Sylvester, S. M., Magurran, A. E., Oberdorff, T., Reis, R. E., Winemiller, K. O. and Ripple, W. J. (2021): Scientists' warning to humanity on the freshwater biodiversity crisis. Ambio 50 (1), 85–94. https://doi.org/10.1007/s13280-020-01318-8.

Albrecht, T. R., Crootof, A. and Scott, C. A. (2018): The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. Environmental Research Letters 13, 043002. https://www.doi.org/10.1088/1748-9326/aaa9c6.

Allan, C., Curtis, A., Stankey, G. and Shindler, B. (2008): Adaptive Management and Watersheds: A Social Science Perspective 1. JAWRA Journal of the American Water Resources Association 44 (1), 166–174. https://doi.org/10.1111/j.1752-1688.2007.00145.x.

Allan, J. A. (1998): Virtual Water: A Strategic Resource Global Solutions to Regional Deficits. Ground water 36 (4), 545–546. https://doi.org/10.1111/J.1745-6584.1998.TB02825.X.

Allison, E. and Mandler, B. (2018): Spills in Oil and Natural Gas Fields: Spill types, numbers, sizes, effects, and mitigation/cleanup efforts. Petroleum and the Environment 14/24. Alexandria: American Geosciences Insitute (AGI). https://www.americangeosciences.org/geoscience-currents/spills-oil-and-natural-gas-fields.

Almeida, R. M., Schmitt, R., Grodsky, S. M., Flecker, A. S., Gomes, C. P., Zhao, L., Liu, H., Barros, N., Kelman, R. and McIntyre, P. B. (2022): Floating solar power: evaluate trade-offs. Nature 606, 246–249. https://doi.org/10.1038/d41586-022-01525-1.

Alves, A., Gersonius, B., Sanchez, A., Vojinovic, Z. and Kapelan, Z. (2018a): Multi-criteria Approach for Selection of Green and Grey Infrastructure to Reduce Flood Risk and Increase CO-benefits. Water Resources Management 32 (7), 2505–2522. https://www.doi.org/10.1007/s11269-018-1943-3.

Alves, A., Patiño Gómez, J., Vojinovic, Z., Sánchez, A. and Weesakul, S. (2018b): Combining Co-Benefits and Stakeholders Perceptions into Green Infrastructure Selection for Flood Risk Reduction. Environments 5 (2), 29. https://www.doi.org/10.3390/environments5020029.

Alves, C. A., Vicente, A. M. P., Calvo, A. I., Baumgardner, D., Amato, F., Querol, X., Pio, C. and Gustafsson, M. (2020): Physical and chemical properties of non-exhaust particles generated from wear between pavements and tyres. Atmospheric Environment 224, 117252. https://doi.org/10.1016/j.atmosenv.2019.117252.

Ambade, B., Sethi, S. S., Kumar, A., Sankar, T. K. and Kurwadkar, S. (2021): Health Risk Assessment, Composition, and Distribution of Polycyclic Aromatic Hydrocarbons (PAHs) in Drinking Water of Southern Jharkhand, East India. Archives of Environmental Contamination and Toxicology 80 (1), 120–133. https://www.doi.org/10.1007/s00244-020-00779-y.

AMCOW – African Ministers' Council on Water (2021): African Sanitation Policy Guidelines. Abuja, Nigeria: AMCOW.

Amos, C. B., Audet, P., Hammond, W. C., Bürgmann, R., Johanson, I. A. and Blewitt, G. (2014): Uplift and seismicity driven by groundwater depletion in central California. Nature 509 (7501), 483–486. https://www.doi.org/10.1038/nature13275.

Andres, L. A., Thibert, M., Lombana Cordoba, C., Danilenko, A. V., Joseph, G. and Borja-Vega, C. (2019): Doing more with less: Smarter subsidies for water supply and sanitation. Washington, D.C.: World Bank.

Anguelovski, I., Connolly, J. J. T., Pearsall, H., Shokry, G., Checker, M., Maantay, J., Gould, K., Lewis, T., Maroko, A. and Roberts, J. T. (2019): Why green "climate gentrification" threatens poor and vulnerable populations. Proceedings of the National Academy of Sciences 116 (52), 26139–26143. https://www.doi.org/10.1073/pnas.1920490117.

Anik, A. H., Hossain, S., Alam, M., Sultan, M. B., Hasnine, M. T. and Rahman, M. M. (2021): Microplastics pollution: A comprehensive review on the sources, fates, effects, and potential remediation. Environmental Nanotechnology, Monitoring & Management 16, 100530. https://www.doi.org/10.1016/j.enmm.2021.100530.

Antonelli, M., Laio, F. and Tamea, S. (2017): Water Resources, Food Security and the Role of Virtaul Water Trade in the MENA-Region. In: Behnassi, M. and McGlade, K. (Hrsg.): Environmental Change and Human Security in Africa and the Middle East. Cham: Springer, 199–217. https://doi.org/10.1007/978-3-319-45648-5_11.

Anyanwu, I. N., Beggel, S., Sikoki, F. D., Okuku, E. O., Unyimadu, J.-P. and Geist, J. (2023): Pollution of the Niger Delta with total petroleum hydrocarbons, heavy metals and nutrients in relation to seasonal dynamics. Scientific Reports 13 (1), 14079. https://doi.org/10.1038/s41598-023-40995-9.

AQUASTAT – FAO's Global Information System on Water and Agriculture (2024): Water use: Pressure on water resources (worldwide). Rome: FAO. https://data.apps.fao.org/aquastat/?lang=en&share=f-8fd8d517-0a8f-4c8b-87c0-caf57a495585, accessed on 15.07.2024.

Araral, E. and Yu, D. (2013): Comparative water law, policies, and administration in Asia: Evidence from 17 countries. Water Resources Research 49 (9), 5307–5316. https://doi.org/10.1002/wrcr.20414.

Arden, S. and Ma, X. (2018): Constructed wetlands for greywater recycle and reuse: a review. Science of the Total Environment 630, 587–599. https://doi.org/10.1016/j.scitotenv.2018.02.218.

Arnbjerg-Nielsen, K., Leonardsen, L. and Madsen, H. (2015): Evaluating adaptation options for urban flooding based on new high-end emission scenario regional climate model simulations. Climate Research 64 (1), 73–84. https://www.doi.org/10.3354/cr01299.

Arnold, J. L., Cauthorn, T., Eckert, J., Klein, C. and Rink, S. (2023): Let's talk numbers: EU Taxonomy reporting by German companies. Berlin: econsens. https://econsense.de/wp-content/uploads/2023/07/Lets-talk-numbers_EU-Taxonomy-reporting-by-German-companies.pdf.

Arojojoye, O. A., Oyagbemi, A. A., Ola-Davies, O. E., Asaolu, R. O., Shittu, Z. O. and Hassan, B. A. (2021): Assessment of water quality of selected rivers in the Niger Delta region of Nigeria using biomarkers in Clarias gariepinus. Environmental Science and Pollution Research 28, 22936–22943. https://doi.org/10.1007/s11356-020-11879-6.

Arvonen, V., Kibocha, S. N., Katko, T. S. and Pietilä, P. (2017): Features of Water Cooperatives: A Comparative Study of Finland and Kenya. Public Works Management & Policy 22 (4), 1–22. https://doi.org/10.1177/1087724X17715267.

Atelier Dreiseitl GmbH and Rambøll Group (2013): Cloudburst Economics – An Urban Flood Protection Masterplan for the Central City Catchments of Lådegåds-Åen and Vesterbro in Copenhagen, Denmark. Überlingen, Copenhagen: Atelier Dreiseitl GmbH, Rambøll.

Audet, J., Zak, D., Bidstrup, J. and Hoffmann, C. C. (2020): Nitrogen and phosphorus retention in Danish restored wetlands. Ambio 49 (1), 324–336. https://www.doi.org/10.1007/s13280-019-01181-2.

aus der Beek, T., Weber, F.-A., Bergmann, A., Hickmann, S., Ebert, I., Hein, A. and Küster, A. (2016): Pharmaceuticals in the environment—Global occurrences and perspectives. Environmental Toxicology and Chemistry 35 (4), 823–835. https://doi.org/10.1002/etc.3339.

Ayilara, M. S., Adeleke, B. S., Akinola, S. A., Fayose, C. A., Adeyemi, U. T., Gbadegesin, L. A., Omole, R. K., Johnson, R. M., Uthman, Q. O. and Babalola, O. O. (2023): Biopesticides as a promising alternative to synthetic pesticides: A case for microbial pesticides, phytopesticides, and nanobiopesticides. Frontiers in Microbiology 14, 1258968. https://www.doi.org/10.3389/fmicb.2023.1040901.

Ayres, A., Peterson, C. and Rosser, A. (2023): Water Use in California's Communities. San Francisco, California: Public Policy Institute of California (PPIC).

Azam, M. F., Kargel, J. S., Shea, J. M., Nepal, S., Haritashya, U. K., Srivastava, S., Maussion, F., Qazi, N., Chevallier, P., Dimri, A. P., Kulkarni, A. V., Cogley, J. G. and Bahuguna, I. (2021): Glaciohydrology of the Himalaya-Karakoram. Science 373 (6557), eabf3668. https://www.doi.org/10.1126/science.abf3668.

BAFU – Bundesamt für Umwelt (2012): Auswirkungen der Klimaänderung auf Wasserressourcen and Gewässer. Synthesebericht zum Projekt „Klimaänderung and Hydrologie in der Schweiz" (CCHydro). Bern: BAFU.

Bai, Y., Muralidharan, N., Sun, Y.-K., Passerini, S., Whittingham, M. S. and Belharouak, I. (2020): Energy and environmental aspects in recycling lithium-ion batteries: Concept of Battery Identity Global Passport. Materials Today 41, 304–315. https://doi.org/10.1016/j.mattod.2020.09.001.

Bakken, T. H., Modahl, I. S., Engeland, K., Raadal, H. L. and Arnøy, S. (2016): The life-cycle water footprint of two hydropower projects in Norway. Journal of Cleaner Production 113, 241–250. https://doi.org/10.1016/j.jclepro.2015.12.036.

Balasubramanian, P., Burchi, F. and Malerba, D. (2023): Does economic growth reduce multidimensional poverty? Evidence from low-and middle-income countries. World Development 161, 106–119. https://doi.org/10.1016/j.worlddev.2022.106119.

Balasubramanya, S. and Buisson, M.-C. (2022): Positive incentives for managing groundwater in the presence of informal water markets: perspectives from India. Environmental Research Letters 17, 101001. https://doi.org/10.1088/1748-9326/ac914f.

Banaszuk, P., Wysocka-Czubaszek, A. and Kamocki, A. K. (2011): Internal eutrophication of restored peatland stream: The role of bed sediments. Ecological Engineering 37 (2), 260–268. https://www.doi.org/10.1016/j.ecoleng.2010.11.016.

Banda, V. D., Dzwairo, R. B., Singh, S. K. and Kanyerere, T. (2022): Hydrological Modelling and Climate Adaptation under Changing Climate: A Review with a Focus in Sub-Saharan Africa. Water 14 (24), 1–27. https://doi.org/10.3390/.

Barataud, F., Aubry, C., Wezel, A. and Mundler, P. (2014): Management of drinking water catchment areas in cooperation with agriculture and the specific role of organic farming. Experiences from Germany and France. Land Use Policy 36, 585–594. https://doi.org/10.1016/j.landusepol.2013.10.010.

Barcellos, D. d. S., Procopiuck, M. and Bollmann, H. A. (2022): Management of pharmaceutical micropollutants discharged in urban waters: 30 years of systematic review looking at opportunities for developing countries. Science of The Total Environment 809, 151128. https://doi.org/10.1016/j.scitotenv.2021.151128.

Bardhan, P. (2004): Scarcity, conflicts, and cooperation: essays in the political and institutional economics of development. Cambridge, Massachusetts: MIT Press.

Barreto, A., Santos, J., Calisto, V., Rocha, L. S., Amorim, M. J. B. and Maria, V. L. (2023): Cocktail effects of emerging contaminants on zebrafish: Nanoplastics and the pharmaceutical diphenhydramine. NanoImpact 30, 100456. https://www.doi.org/10.1016/j.impact.2023.100456.

Bassi, N., Rishi, P. and Choudray, N. (2010): Institutional organizers and collective action: the case of water users' associations in Gujarat, India. Water International 35 (1), 18–33. https://doi.org/10.1080/02508060903515275.

Bayliss, K. (2014): The Financialization of Water. Review of Radical Political Economics 46 (3), 292–307. https://www.doi.org/10.1177/0486613413506076.

Bearden, B. (2010): The legal regime of the Mekong River: a look back and some proposals for the way ahead, Water Policy. Water Policy 12 (6), 798–821. https://doi.org/10.2166/wp.2009.060.

Bednarek, A. T. (2001): Undamming Rivers: A Review of the Ecological Impacts of Dam Removal. Environmental Management 27 (6), 803–814. https://doi.org/10.1007/s002670010189.

Beek, E. v., Nolte, A. J., Maat, J. t., Fanesca-Sanchez, M., Asselman, N. and Gehrels, H. (2022): Strategic Water Systems Planning - A Framework for Achieving Sustainable, Resilient and Adaptive Managemen. Delft, Niederlande: Deltares. https://publications.deltares.nl/Deltares234.pdf.

Beisheim, M. (2013): Der „Nexus" Wasser-Energie-Nahrung: wie mit vernetzten Versorgungsrisiken umgehen? SWP-Studie 2013/S 11. Berlin: Stiftung Wissenschaft and Politik (SWP).

Bekchanov, M., Lamers, J. P. A. and Martius, C. (2010): Pros and Cons of Adopting Water-Wise Approaches in the Lower Reaches of the Amu Darya: A Socio-Economic View. Water 2 (2), 200–216. https://www.doi.org/10.3390/w2020200.

Belletti, B., Garcia de Leaniz, C., Jones, J., Bizzi, S., Börger, L., Segura, G., Castelletti, A., van de Bund, W., Aarestrup, K., Barry, J., Belka, K., Berkhuysen, A., Birnie-Gauvin, K., Bussettini, M., Carolli, M., Consuegra, S., Dopico, E., Feierfeil, T., Fernández, S., Fernandez Garrido, P., Garcia-Vazquez, E., Garrido, S., Giannico, G., Gough, P., Jepsen, N., Jones, P. E., Kemp, P., Kerr, J., King, J., Łapińska, M., Lázaro, G., Lucas, M. C., Marcello, L., Martin, P., McGinnity, P., O'Hanley, J., Olivo del Amo, R., Parasiewicz, P., Pusch, M., Rincon, G., Rodriguez, C., Royte, J., Schneider, C. T., Tummers, J. S., Vallesi, S., Vowles, A., Verspoor, E., Wanningen, H., Wantzen, K. M., Wildman, L. and Zalewski, M. (2020): More than one million barriers fragment Europe's rivers. Nature 588 (7838), 436–441. https://doi.org/10.1038/s41586-020-3005-2.

Bellmore, J. R., Pess, G. R., Duda, J. J., O'Connor, J. E., East, A. E., Foley, M. M., Wilcox, A. C., Major, J. J., Shafroth, P. B., Morley, S. A., Magirl, C. S., Anderson, C. W., Evans, J. E., Torgersen, C. E. and Craig, l. S. (2019): Conceptualizing Ecological Responses to Dam Removal: If You Remove It, What's to Come? BioScience 69 (1), 26–39. https://www.doi.org/10.1093/biosci/biy152.

Bennett, G., Leonardi, A. and Ruef, F. (2017): State of European Markets 2017: Watershed Investments. Washington, D.C.: Forest Trends' Ecosystem Marketplace.

Berbel, J. and Expósito, A. (2020): The Theory and Practice of Water Pricing and Cost Recovery in the Water Framework Directive. Water Alternatives 13 (3), 659–673. https://www.water-alternatives.org/index.php/alldoc/articles/vol13/v13issue3/602-a13-3-20.

Berga, L. (2016): The Role of Hydropower in Climate Change Mitigation and Adaptation: A Review. Engineering 2 (3), 313–318. https://www.doi.org/10.1016/j.Eng.2016.03.004.

Berger, A., Brandi, C., Bruhn, D. and Morin, J.-F. (2017): TREND Analytics: Environmental Provisions in Preferential Trade Agreements. Bonn, Québec: Deutsches Institut für Entwicklungspolitik (DIE), Université Laval. https://www.doi.org/10.23661/trendanalytics_2017_1.0.

Bergmann, J. (2022): Desert Rose or Fata Morgana? The G5 Sahel and Its Partnership with the European Union. In: Muntschick, J. (Hrsg.): Regionalism in Africa and External Partners: Uneven Relationships and (Un)Intended Effects. Cham: Springer International Publishing, 127–154. https://www.doi.org/10.1007/978-3-031-10702-3_6.

Bertassello, L., Winters, P. and Muller, M. (2023): Access to global wheat reserves determines country-level vulnerability to conflict-induced Ukrainian wheat supply disruption. Nature Food 4, 1–4. https://www.doi.org/10.1038/s43016-023-00806-w.

BfN – Bundesamt für Naturschutz (2024): Moore: Entstehung and Zustand. Bonn: BfN. https://www.bfn.de/entstehung-and-zustand, accessed on 4.07.2024.

BfR – Bundesinstitut für Risikobewertung (2023): Therapiehäufigkeit and Antibiotika Verbrauchsmengen 2022: Entwicklung in zur Fleischerzeugung gehaltenen Rindern, Schweinen, Hühnern and Puten. Berlin: BfR.

BGR – Bundesanstalt für Geowissenschaften and Rohstoffe (2020): Kupfer - Informationen zur Nachhaltikeit. Hannover: BGR. https://www.bgr.bund.de/DE/Gemeinsames/Produkte/Downloads/Informationen_Nachhaltigkeit/kupfer.html.

Bhalla, G. (2021): How Chennai, Among World's Wettest Cities, Ran Out of Water. Mumbai: The Times of India. https://www.indiatimes.com/news/india/how-chennai-among-world-wettest-cities-ran-out-of-water-533587.html, published on 4.02.2021.

Biemans, H., Siderius, C., Lutz, A. F., Nepal, S., Ahmad, B., Hassan, T., von Bloh, W., Wijngaard, R. R., Wester, P., Shrestha, A. B. and Immerzeel, W. W. (2019): Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. Nature Sustainability 2 (7), 594–601. https://www.doi.org/10.1038/s41893-019-0305-3.

Bierkens, M. F. and Wada, Y. (2019): Non-renewable groundwater use and groundwater depletion:a review. Environmental Research Letters 14 (6), 1–43. https://www.doi.org/10.1088/1748-9326/ab1a5f.

Biggel, M., Zurfluh, K., Treier, A., Nüesch-Inderbinen, M. and Stephan, R. (2021): Characteristics of fosA-carrying plasmids in E. coli and Klebsiella spp. isolates originating from food and environmental samples. Journal of Antimicrobial Chemotherapy 76 (8), 2004–2011. https://www.doi.org/10.1093/jac/dkab119.

Bijay, S. and Craswell, E. (2021): Fertilizers and nitrate pollution of surface and ground water: an increasingly pervasive global problem. SN Applied Sciences 3, 518. https://www.doi.org/10.1007/s42452-021-04521-8.

Biswas, A. K. (2004): Integrated water resources management: a reassessment: a water forum contribution. Water international 29 (2), 248–256. https://doi.org/10.1080/02508060408691775.

Bjornlund, H. (2004): Formal and informal water markets: Drivers of sustainable rural communities? Water resources research 40 (9), 1–12. https://doi.org/10.1029/2003WR002852.

Blackstock, K. L., Ingram, J., Burton, R., Brown, K. M. and Slee, B. (2010): Understanding and influencing behaviour change by farmers to improve water quality. Science of The Total Environment 408 (23), 5631–5638. https://doi.org/10.1016/j.scitotenv.2009.04.029.

Blauhut, V., Stoelzle, M., Ahopelto, L., Brunner, M. I., Teutschbein, C., Wendt, D. E., Akstinas, V., Bakke, S. J., Barker, L. J., Bartošová, L., Briede, A., Cammalleri, C., Kalin, K. C., De Stefano, L., Fendeková, M., Finger, D. C., Huysmans, M., Ivanov, M., Jaagus, J., Jakubínský, J., Krakovska, S., Laaha, G., Lakatos, M., Manevski, K., Neumann Andersen, M., Nikolova, N., Osuch, M., van Oel, P., Radeva, K., Romanowicz, R. J., Toth, E., Trnka, M., Urošev, M., Urquijo Reguera, J., Sauquet, E., Stevkov, A., Tallaksen, L. M., Trofimova, I., Van Loon, A. F., van Vliet, M. T. H., Vidal, J.-P., Wanders, N., Werner, M., Willems, P. and Živković, N. (2022): Lessons from the 2018–2019 European droughts: a collective need for unifying drought risk management. Natural Hazards and Earth System Sciences 22 (6), 2201–2217. https://www.doi.org/10.5194/nhess-22-2201-2022.

BLE – Bundesanstalt für Landwirtschaft and Ernährung (2023): Waldbrandstatistik der Bundesrepublik Deutschland für das Jahr 2022. Bonn: BLE.

BLE – Bundesanstalt für Landwirtschaft and Ernährung (2024): Unsere Themen: Klima. Bonn: BLE. https://www.ble.de/DE/Themen/Klima-Energie/klima_node.html, accessed on 1.07.2024.

Blicharska, M., Smithers, R. J., Kuchler, M., Agrawal, G. K., Gutiérrez, J. M., Hassanali, A., Huq, S., Koller, S. H., Marjit, S., Mshinda, H. M., Masjuki, H. H., Solomons, N. W., Staden, J. V. and Mikusiński, G. (2017): Steps to overcome the North–South divide in research relevant to climate change policy and practice. Nature Climate Change 7 (1), 21–27. https://www.doi.org/10.1038/nclimate3163.

Blömer, S., Schoor, B., Baumann, P., Keller, J., Maier, W., Münch, K. and Reinhardt, T. (2023): Potenzial der Abwasserwärmenutzung aus dem Auslauf von Kläranlagen. Lokalisierung von Standorten in Baden-Württemberg. Korrespondenz Abwasser, Abfall 70 (2), 106–113. https://doi.org/10.3242/kae2023.02.003.

Blomkvist, P., Nilsson, D., Juma, B. and Sitoki, L. (2020): Bridging the critical interface: Ambidextrous innovation for water provision in Nairobi's informal settlements. Technology in society 60, 1–12. https://doi.org/10.1016/j.techsoc.2019.101221.

Blum, M., Colell, A. and Treichel, K. (2022): Deliberation: Neue Räume für die Aushandlung von Politikoptionen. In: Zilles, J., Drewing, E. and Janik, J. (Hrsg.): Umkämpfte Zukunft. Zum Verhältnis von Nachhaltigkeit, Demokratie and Konflikt. Bielefeld: transcript Verlag, 291–312. https://doi.org/10.14361/9783839463000-016.

Blum, M. (2024): Science and citizen deliberation – a promising coalition? Innovation: The European Journal of Social Science Research, 1–40. https://doi.org/10.1080/13511610.2024.2349631.

Blum, P., Menberg, K., Koch, F., Benz, S. A., Tissen, C., Hemmerle, H. and Bayer, P. (2021): Is thermal use of groundwater a pollution? Journal of Contaminant Hydrology 239, 103791. https://doi.org/10.1016/j.jconhyd.2021.103791.

Blum, P., Felke, C., von Ondarza, V., Pittelkow, S., Strunz, B., Izoard, C., NDR – Norddeutscher Rundfunk and WDR – Westdeutscher Rundfunk Köln (2023): Schwere Vorwürfe gegen BMW-Zulieferer. Hamburg: tagesschau. https://www.tagesschau.de/investigativ/ndr-wdr/umweltstandards-bmw-zulieferer-kobalt-marokko-100.html, published on 12.11.2023.

BMBF – Bundesministerium für Bildung and Forschung (2017): Nationaler Aktionsplan für nachhaltige Entwicklung - Der deutsche Beitrag zum UNESCO-Weltaktionsprogramm. Berlin: BMBF.

BMBF – Bundesministerium für Bildung and Forschung (2020): Bekanntmachung der Richtlinie zur Förderung von Zuwendungen für Forschungs- and Entwicklungsvorhaben zum Thema „Wasserforschung im Nahen and Mittleren Osten". Berlin: BMBF. https://www.bmbf.de/bmbf/shareddocs/bekanntmachungen/de/2020/06/3038_bekanntmachung, published on 3.06.2020.

BMBF – Bundesministerium für Bildung and Forschung (2021a): Gut Informiert - RegIKlim unterstützt Klimahandeln vor Ort. Bonn: BMBF.

BMBF – Bundesministerium für Bildung and Forschung (2021b): Wasser: N. Research and Innovation for Sustainability. Bonn: BMBF. https://www.bmbf.de/SharedDocs/Publikationen/de/bmbf/FS/270264_Wasser_N_en.html.

BMBF – Bundesministerium für Bildung and Forschung (2023): Zukunftsstrategie Forschung and Innovation. Berlin: BMBF.

BMBF – Bundesministerium für Bildung and Forschung (2024a): Globale Ressource Wasser - GRoW. Berlin: BMBF. https://bmbf-grow.de/de, accessed on 27.06.2024.

BMBF – Bundesministerium für Bildung and Forschung (2024b): Forschungsprogramm Wassersicherheit in Afrika (WASA). Berlin: BMBF. www.watersecurityafrica.org., accessed on 15.07.2024.

BMBF – Bundesministerium für Bildung and Forschung (2024c): STEER: Erhöhung der Steuerungskompetenz zur Erreichung der Ziele eines integrierten Wassermanagements. Berlin: BMBF. https://bmbf-grow.de/de/steer, accessed on 27.06.2024.

BMBF – Bundesministerium für Bildung and Forschung (2024d): Die Fördermaßnahme „Wasser-Extremereignisse" (WaX). Berlin: BMBF. https://www.bmbf-wax.de, accessed on 27.07.2024.

BMBF – Bundesministerium für Bildung and Forschung (2024e): Kompetenzzentren für Klimawandel and angepasstes Landmanagement in Afrika. Berlin: BMBF. https://www.fona.de/de/massnahmen/foerdermassnahmen/klimakompetenzzentren-afrika.php, accessed on 15.07.2024.

BMEL – Bundesministerium für Ernährung and Landwirtschaft (2022a): Digitalisierung in der Landwirtschaft. Bonn: BMEL. https://www.bmel.de/DE/themen/digitalisierung/digitalisierung-landwirtschaft.html, accessed on 1.07.2024.

BMEL – Bundesministerium für Ernährung and Landwirtschaft (2022b): Digitalisierung in der Landwirtschaft: Chancen nutzen – Risiken minimieren. Bonn: BMEL.

BMEL – Bundesministerium für Ernährung and Landwirtschaft and BMUV – Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit and Verbraucherschutz, (2024): Nitratbericht 2024. Bericht der Bundesrepublik Deutschland gemäß Richtlinie 91/676/EWG zum Schutz der Gewässer vor Verunreinigung durch Nitrat aus landwirtschaftlichen Quellen. Bonn, Berlin: BMEL.

BMJ – Bundesministeriums der Justiz (2023): Trinkwasserverordnung vom 20. Juni 2023 (BGBl. 2023 I Nr. 159, S. 2). Berlin: BMJ. https://www.gesetze-im-internet.de/trinkwv_2023/index.html.

BMU – Bundesministerium für Umwelt (2021): Nationale Wasserstrategie. Entwurf des Bundesumweltministeriums. Bonn: BMU.

BMUB – Bundesministerium für Umwelt, Naturschutz, Bau and Reaktorsicherheit (2017): Handlungsempfehlungen für die Erstellung von Hitzeaktionsplänen zum Schutz der menschlichen Gesundheit. Bonn: BUMB.

BMUV – Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit and Verbraucherschutz and UBA – Umweltbundesamt (2022): Die Wasserrahmenrichtlinie – Gewässer in Deutschland 2021. Fortschritte and Herausforderungen. Bonn, Dessau-Roßlau: BMUV, UBA.

BMUV – Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit and Verbraucherschutz (2023a): Wie werden die Maßnahmen, die in der Nationalen Wasserstrategie vorgesehen sind, finanziert? FAQ zur Nationalen Wasserstrategie. Berlin: BMUV. https://www.bmuv.de/faq/wie-werden-die-massnahmen-die-in-der-nationalen-wasserstrategie-vorgesehen-sind-finanziert, accessed on 1.07.2024.

BMUV – Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit and Verbraucherschutz (2023b): Nationale Wasserstrategie. Kabinettsbeschluss vom 15. März 2023. Berlin: BMUV.

BMUV – Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit and Verbraucherschutz (2024): Junge Menschen beteiligen. Bonn: BMUV. https://www.endlagersuche-infoplattform.de/webs/Endlagersuche/DE/Beteiligung/Buergerbeteiligung/Jugendbeteiligung/jugendbeteiligung_node.html, accessed on 13.05.2024.

BMWSB – Bundesministerium für Wohnen, Stadtentwicklung and Bauwesen, (2024): Referentenentwurf - Entwurf eines Gesetzes zur Stärkung der integrierten Stadtentwicklung, 29.07.2024. Berlin: BMWSB.

BMZ – Bundesministerium für wirtschaftliche Zusammenarbeit and Entwicklung (2017): BMZ Wasserstrategie. Schlüssel zur Umsetzung der Agenda 2030 and des Klimaabkommens. Bonn, Berlin: BMZ.

BMZ – Bundesministerium für wirtschaftliche Zusammenarbeit and Entwicklung (2023): Integriertes Wasserressourcen-management and Nexus-Ansatz. Bonn, Berlin: BMZ. https://www.bmz.de/de/themen/wasser/wasserpolitik/integriertes-wasserressourcenmanagement-and-nexus-ansatz-20636, accessed on 16.10.2023.

BMZ – Bundesministerium für wirtschaftliche Zusammenarbeit and Entwicklung (2024): Reform der Weltbankgruppe. Bonn, Berlin: BMZ. https://www.bmz.de/de/ministerium/internationale-organisationen/weltbank/reform-der-weltbank-gruppe-147428, accessed on 27.03.2024.

Boano, F., Caruso, A., Costamagna, E., Ridolfi, L., Fiore, S., Demichelis, F., Galvão, A., Pisoeiro, J., Rizzo, A. and Masi, F. (2020): A review of nature-based solutions for greywater treatment: Applications, hydraulic design, and environmental benefits. Science of the total environment 711, 134731. https://doi.org/10.1016/j.scitotenv.2019.134731.

Boboyorov, H., Poos, H. and Schetter, C. (2009): Beyond the State – Local Politics in Afghanistan. Bonn: Center for Development Research (ZEF).

Bodansky, D., Brunnée, J. and Rajamani, L. (2017): International climate change law. Oxford: Oxford University Press.

Boedeker, W., Watts, M., Clausing, P. and Marquez, E. (2020): The global distribution of acute unintentional pesticide poisoning: estimations based on a systematic review. BMC Public Health 20 (1), 1875. https://www.doi.org/10.1186/s12889-020-09939-0.

Boelens, R. and Vos, J. (2012): The danger of naturalizing water policy concepts: Water productivity and efficiency discourses from field irrigation to virtual water trade. Agricultural Water Management 108, 16–26. https://www.doi.org/10.1016/j.agwat.2011.06.013.

Bogardi, J. J., Gupta, J., Nandalal, K. D. W., Salamé, L., van Nooijen, R. R. P., Kumar, N., Tingsanchali, T., Bhaduri, A. and Kolechkina, A. G. (2021): Handbook of Water Resources Management: Discourses, Concepts and Examples. Cham: Springer Nature.

Bolan, N., Hoang, S. A., Tanveer, M., Wang, L., Bolan, S., Sooriyakumar, P., Robinson, B., Wijesekara, H., Wijesooriya, M., Keerthanan, S., Vithanage, M., Markert, B., Fränzle, S., Wünschmann, S., Sarkar, B., Vinu, A., Kirkham, M. B., Siddique, K. H. M. and Rinklebe, J. (2021): From mine to mind and mobiles – Lithium contamination and its risk management. Environmental Pollution 290, 118067. https://www.doi.org/10.1016/j.envpol.2021.118067.

Bolch, T., Shea, J. M., Liu, S., Azam, F. M., Gao, Y., Gruber, S., Immerzeel, W. W., Kulkarni, A., Li, H., Tahir, A. A., Zhang, G. and Zhang, Y. (2019): Status and Change of the Cryosphere in the Extended Hindu Kush Himalaya Region. In: Wester, P., Mishra, A., Mukherji, A. and Shrestha, A. B. (Hrsg.): The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People. Cham: Springer Nature, 209–255. https://doi.org/10.1007/978-3-319-92288-1_7.

Bonet, B., Chaudhary, A., Krause, S., Hoellein, T., Mitrano, D. M. and Lynch, I. (2023): Editorial: Exploring the combined effect of climate change and pollution on freshwater ecosystems. Frontiers in Environmental Science 11, 1293169. https://www.doi.org/10.3389/fenvs.2023.1293169.

Bonn, A., Brink, W., Hecker, S., Herrmann, T. M., Liedtke, C., Premke-Kraus, M., Voigt-Heucke, S., Gönner, J. v., Altmann, C. and Bauhus, W. (2022): White Paper Citizen Science Strategy 2030 for Germany. Leipzig, Berlin: Helmholtz Association, Leibniz Association, Fraunhofer Society.

Borchardt, D., Bogardi, J. J. and Ibisch, R. B. (2016): Integrated Water Resources Management: Concept, Research and Implementation. Basel: Springer Cham. https://doi.org/10.1007/978-3-319-25071-7.

Bosmans, J., Wanders, N., Bierkens, M. F., Huijbregts, M. A., Schipper, A. M. and Barbarossa, V. (2022): FutureStreams, a global dataset of future streamflow and water temperature. Scientific data 9, 307. https://doi.org/10.1038/s41597-022-01410-6.

Bosson, J. B., Huss, M., Cauvy-Fraunie, S., Clement, J. C., Costes, G., Fischer, M., Poulenard, J. and Arthaud, F. (2023): Future emergence of new ecosystems caused by glacial retreat. Nature 620 (7974), 562–569. https://www.doi.org/10.1038/s41586-023-06302-2.

Bostic, D., Mendez-Barrientos, L., Pauloo, R., Dobbin, K. and MacClements, V. (2023): Thousands of domestic and public supply wells face failure despite groundwater sustainability reform in California's Central Valley. Scientific Reports 13 (1), 14797. https://doi.org/10.1038/s41598-023-41379-9.

Boyd, D., Pathak, M., van Diemen, R. and Skea, J. (2022): Mitigation co-benefits of climate change adaptation: A case-study analysis of eight cities. Sustainable Cities and Society 77, 103563. https://doi.org/10.1016/j.scs.2021.103563.

Brás, T. A., Seixas, J., Carvalhais, N. and Jägermeyr, J. (2021): Severity of drought and heatwave crop losses tripled over the last five decades in Europe. Environmental Research Letters 16 (6), 065012. https://www.doi.org/10.1088/1748-9326/abf004.

Brauman, K. A., Garibaldi, L. A., Polasky, S., Aumeeruddy-Thomas, Y., Brancalion, P. H. S., DeClerck, F., Jacob, U., Mastrangelo, M. E., Nkongolo, N. V., Palang, H., Pérez-Méndez, N., Shannon, L. J., Shrestha, U. B., Strombom, E. and Verma, M. (2020): Global trends in nature's contributions to people. Proceedings of the National Academy of Sciences 117 (51), 32799–32805. https://www.doi.org/10.1073/pnas.2010473117.

Breuer, R. and Gärditz, K. F. (2017): Einleitung and Überblick. In: Breuer, R. and Gärditz, K. F. (Hrsg.): Öffentliches and privates Wasserrecht. Munich: C.H. Beck, Rn. 134, 135.

Bring, A., Thorslund, J., Rosén, L., Tonderski, K., Åberg, C., Envall, I. and Laudon, H. (2022): Effects on groundwater storage of restoring, constructing or draining wetlands in temperate and boreal climates: a systematic review. Environmental Evidence 11 (38), 1–29. https://www.doi.org/10.1186/s13750-022-00289-5.

Brown, A. G., Lespez, L., Sear, D. A., Macaire, J.-J., Houben, P., Klimek, K., Brazier, R. E., Van Oost, K. and Pears, B. (2018): Natural vs anthropogenic streams in Europe: History, ecology and implications for restoration, river-rewilding and riverine ecosystem services. Earth-Science Reviews 180, 185–205. https://doi.org/10.1016/j.earscirev.2018.02.001.

Brown, C. (2011): Decision-scaling for robust planning and policy under climate uncertainty. Washington, D.C.: World Bank.

Brown, C., Werick, W., Leger, W. and Fay, D. (2011): A decision-analytic approach to managing climate risks: Application to the upper great lakes 1. JAWRA Journal of the American Water Resources Association 47 (3), 524–534. https://doi.org/10.1111/j.1752-1688.2011.00552.x.

Brown, C., Ghile, Y., Laverty, M. and Li, K. (2012): Decision scaling: Linking bottom-up vulnerability analysis with climate projections in the water sector. Water Resources Research 48 (9), 1–12. https://doi.org/10.1029/2011WR011212.

Brudler, S., Arnbjerg-Nielsen, K., Hauschild, M. Z. and Rygaard, M. (2016): Life cycle assessment of stormwater management in the context of climate change adaptation. Water Research 106, 394–404. https://doi.org/10.1016/j.watres.2016.10.024.

Brunnée, J. (2007): Common Areas, Common Heritage, and Common Concern. In: Bodansky, D., Brunnée, J. and Hey, E. (Hrsg.): The Oxford Handbook of International Enviromental Law. Oxford: Oxford University Press, 550–573. https://www.doi.org/10.1093/oxfordhb/9780199552153.013.0023.

Buchert, M., Dolega, P. and Degreif, S. (2020): Ökologische and sozio-ökonomische Herausforderungen in Batterie-Lieferketten: Graphit and Lithium. Darmstadt: Öko-Institut e.V. https://www.oeko.de/publikationen/p-details/oekologische-and-sozio-oekonomische-herausforderungen-in-batterie-lieferketten-graphit-und-lithium.

Budding Polo-Ballinas, M., Arumugam, P., Verstand, D., Siegmund-Schultze, M., Keesstra, S., García Chávez, L., de Boer, R. and van Eldik, I. V. (2022): Nature-based Solutions in Food Systems. Review of Nature-based Solutions towards more sustainable agriculture and food production. Discussion Paper. Wageningen: Wageningen Environmental Research.

BUKEA – Behörde für Umwelt, Klima, Energie and Agrarwirtschaft, (2024): Gründachförderung. Auf die Dächer – fertig – grün! Hamburg: BUKEA. https://www.hamburg.de/foerderung/4364756/gruendachfoerderung/, accessed on 5.06.2024.

Bullock, A. and Acreman, M. (2003): The role of wetlands in the hydrological cycle. Hydrology and Earth System Sciences 7 (3), 358–389. https://www.doi.org/10.5194/hess-7-358-2003.

BUMV – Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit and Verbraucherschutz (2024): Exportinitiative Umweltschutz. Berlin: BUMV. https://www.exportinitiative-umweltschutz.de/, accessed on 18.06.2024.

BUND – Bund für Umwelt and Naturschutz Deutschland (2019): Die Wasserentnahmeentgelte der Länder. Berlin: BUND.

Bundschuh, J., Kaczmarczyk, M., Ghaffour, N. and Tomaszewska, B. (2021): State-of-the-art of renewable energy sources used in water desalination: Present and future prospects. Desalination 508, 115035. https://www.doi.org/10.1016/j.desal.2021.115035.

Buras, A., Rammig, A. and Zang, C. S. (2020): Quantifying impacts of the 2018 drought on European ecosystems in comparison to 2003. Biogeosciences 17 (6), 1655–1672. https://www.doi.org/10.5194/bg-17-1655-2020.

Burchi, F. and Malerba, D. (2023): Are women poorer? A cross-country analysis of gender differentials in multidimensional poverty. In: Wagle, U. (Hrsg.): Research Handbook on Poverty and Inequality. Cheltenham, UK: Edward Elgar Publishing, 103–117. https://doi.org/10.4337/9781800882300.00014.

Burls, N. J., Blamey, R. C., Cash, B. A., Swenson, E. T., Fahad, A. a., Bopape, M.-J. M., Straus, D. M. and Reason, C. J. (2019): The Cape Town "day zero" drought and Hadley cell expansion. Npj Climate and Atmospheric Science 2 (1), 27. https://doi.org/10.1038/s41612-019-0084-6.

Calliari, E., Castellari, S., Davis, M., Linnerooth-Bayer, J., Martin, J., Mysiak, J., Pastor, T., Ramieri, E., Scolobig, A. and Sterk, M. (2022): Building climate resilience through nature-based solutions in Europe: A review of enabling knowledge, finance and governance frameworks. Climate Risk Management 37, 100450. https://doi.org/10.1016/j.crm.2022.100450.

Calow, R. and Mason, N. (2014): The real water crisis: inequality in a fast-changing world. London: Overseas Development Institute (ODI). https://cdn.odi.org/media/documents/8953.pdf.

Canadell, J. G., Monteiro, P. M. S., Costa, M. H., Cotrim da Cunha, L., Cox, P. M., Eliseev, A. V., Henson, S., Ishii, M., Jaccard, S., Koven, C., Lohila, A., Patra, P. K., Piao, S., Rogelj, J., Syampungani, S., Zaehle, S. and Zickfeld, K. (2021): Global Carbon and other Biogeochemical Cycles and Feedbacks Supplementary Material. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Pēan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B. (Hrsg.): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press, 673–816. https://www.doi.org/10.1017/9781009157896.007.

Canas, N. (2024): Europäische Kommission legt Wasserstrategie auf Eis. Berlin: Euractiv. https://www.euractiv.de/section/energie-and-umwelt/news/europaeische-kommission-legt-wasserstrategie-auf-eis/, published on 17.02.2024.

Cantelon, J. A., Guimond, J. A., Robinson, C. E., Michael, H. A. and Kurylyk, B. L. (2022): Vertical Saltwater Intrusion in Coastal Aquifers Driven by Episodic Flooding: A Review. Water Resources Research 58 (11), e2022WR032614. https://www.doi.org/10.1029/2022wr032614.

Capon, S. J., Chambers, L. E., Mac Nally, R., Naiman, R. J., Davies, P., Marshall, N., Pittock, J., Reid, M., Capon, T., Douglas, M., Catford, J., Baldwin, D. S., Stewardson, M., Roberts, J., Parsons, M. and Williams, S. E. (2013): Riparian Ecosystems in the 21st Century: Hotspots for Climate Change Adaptation? Ecosystems 16 (3), 359–381. https://www.doi.org/10.1007/s10021-013-9656-1.

Capon, S. J., Stewart-Koster, B. and Bunn, S. E. (2021): Future of freshwater ecosystems in a 1.5 C warmer world. Frontiers in Environmental Science 9, 784642. https://doi.org/10.3389/fenvs.2021.784642.

Caretta, M. A., Mukherji, A., Arfanuzzaman, M., Betts, R. A., Gelfan, A., Hirabayashi, Y., Lissner, T. K., Liu, J., Lopez Gunn, E., Morgan, R., Mwanga, S. and Supratid, S. (2022): Water. In: Pörtner, H.-O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A. and Rama, B. (Hrsg.): Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press, 551–712. https://www.doi.org/10.1017/9781009325844.006.

Caruso, G. D. (2017): The legacy of natural disasters: The intergenerational impact of 100 years of disasters in Latin America. Journal of Development Economics 127, 209–233. https://doi.org/10.1016/j.jdeveco.2017.03.007.

Casanova, M. T., Bachmann, M., Bagella, S., Bester, A., Lloyd, L. and Farnsworth, L. (2023): Just Add Water? Wetland and Riparian Restoration. In: Florentine, S., Gibson-Roy, P., Dixon, K. W. and Broadhurst, L. (Hrsg.): Ecological Restoration. Cham: Springer, 195–239. https://doi.org/10.1007/978-3-031-25412-3_6.

Castaño, S., de la Losa, A., Martínez-Santos, P., Mediavilla, R. and Santisteban, J. I. (2018): Long-term effects of aquifer overdraft and recovery on groundwater quality in a Ramsar wetland: Las Tablas de Daimiel National Park, Spain. Hydrological Processes 32 (18), 2863–2873. https://www.doi.org/10.1002/hyp.13225.

Castellar, J. A., Torrens, A., Buttiglieri, G., Monclus, H., Arias, C. A., Carvalho, P. N., Galvao, A. and Comas, J. (2022): Nature-based solutions coupled with advanced technologies: An opportunity for decentralized water reuse in cities. Journal of Cleaner Production 340, 130660. https://doi.org/10.1016/j.jclepro.2022.130660.

Castillo-Zacarías, C., Barocio, M. E., Hidalgo-Vázquez, E., Sosa-Hernández, J. E., Parra-Arroyo, L., López-Pacheco, I. Y., Barceló, D., Iqbal, H. N. M. and Parra-Saldívar, R. (2021): Antidepressant drugs as emerging contaminants: Occurrence in urban and non-urban waters and analytical methods for their detection. Science of The Total Environment 757, 143722. https://doi.org/10.1016/j.scitotenv.2020.143722.

Cauvy-Fraunie, S. and Dangles, O. (2019): A global synthesis of biodiversity responses to glacier retreat. Nature Ecology & Evolution 3 (12), 1675–1685. https://www.doi.org/10.1038/s41559-019-1042-8.

CBD – Convention on Biological Diversity (2023): Water and Biodiversity: Relevance of water and water-related ecosystems to the Goals and Targets of the Kunming-Montreal Global Biodiversity Framework. Montreal: CBD. https://www.cbd.int/sites/default/files/2023-03/gbf-water-implications-cbd-march2023.pdf.

CBD – Convention on Biological Diversity (2024): 2030 Targets (with Guidance Notes). Montreal: CBD. https://www.cbd.int/gbf/targets, accessed on 4.06.2024.

CBI – Climate Bonds Initiative (2024): Global State of the Market 2023. London: CBI. https://www.climatebonds.net/files/reports/cbi_sotm23_02e.pdf.

CDC – Centers for Disease Control and Prevention (2024): Harmful Algal Blooms: Contributing Factors and Impacts. Druid Hills, USA: CDC. https://www.cdc.gov/harmful-algal-blooms/about/harmful-algal-blooms-contributing-factors-and-impacts.html?CDC_AAref_Val=https://www.cdc.gov/habs/environment.html, accessed on 8.07.2024.

CDP – Carbon Disclosure Project (2021): A Wave of Change: The role of companies in building a water-secure world. CDP Global Water Report 2020. London: CDP.

CDP – Carbon Disclosure Project and Planet Tracker (2022): High and dry: How water issues are stranding assets. London: CDP.

Chakravarty, A. (2023): Ensuring Water Security in the Brahmaputra basin: shift from conflict to cooperation. In: Casado Pérez, V. and Larson, R. (Hrsg.): A Research Agenda for Water Law. Cheltenham: Edward Elgar, 33–58.

Chaplin-Kramer, R., Sharp, R. P., Weil, C., Bennett, E. M., Pascual, U., Arkema, K. K., Brauman, K. A., Bryant, B. P., Guerry, A. D. and Haddad, N. M. (2019): Global modeling of nature's contributions to people. Science 366 (6462), 255–258. https://doi.org/10.1126/science.aaw3372.

Chappelle, C., Collins, J. and Hanak, E. (2021): Access to Safe Drinking Water in California. San Francisco, California: Public Policy Institute of California (PPIC).

Chappelle, C. and Hanak, E. (2021): Water Affordability in California. San Francisco, California: Public Policy Institute of California (PPIC).

Chávez García Silva, R., Reinecke, R., Copty, N. K., Barry, D. A., Heggy, E., Labat, D., Roggero, P. P., Borchardt, D., Rode, M., Gómez-Hernández, J. J. and Jomaa, S. (2024): Multi-decadal groundwater observations reveal surprisingly stable levels in southwestern Europe. Communications Earth & Environment 5 (1), 387. https://doi.org/10.1038/s43247-024-01554-w.

Cheng, D., Ngo, H. H., Guo, W., Chang, S. W., Nguyen, D. D., Liu, Y., Wei, Q. and Wei, D. (2020): A critical review on antibiotics and hormones in swine wastewater: Water pollution problems and control approaches. Journal of Hazardous Materials 387, 121682. https://doi.org/10.1016/j.jhazmat.2019.121682.

Chevalier, N., Guillou, P., Viguié, C., Fini, J.-B., Sachs, L. M., Michel-Caillet, C. and Mhaouty-Kodja, S. (2024): Lithium and endocrine disruption: A concern for human health? Environment International, 108861. https://doi.org/10.1016/j.envint.2024.108861.

Chihanga, T. (2019): Social and behaviour change for sustainable WASH interventions in Zimbabwe. Loughborough: Loughborough University. https://hdl.handle.net/2134/35650.

Chinkin, C. (2000): Normative Development in the International Legal System. In: Shelton, D. (Hrsg.): Commitment and Compliance. The Role of Non-Binding Norms in the International Legal System. Oxford: Oxford University Press, 21–42.

Choi, H.-B., Ryu, J.-S., Shin, W.-J. and Vigier, N. (2019): The impact of anthropogenic inputs on lithium content in river and tap water. Nature Communications 10, 5371. https://doi.org/10.1038/s41467-019-13376-y.

Chowdhury, S., Mazumder, M. A. J., Al-Attas, O. and Husain, T. (2016): Heavy metals in drinking water: Occurrences, implications, and future needs in developing countries. Science of The Total Environment 569–570, 476–488. https://doi.org/10.1016/j.scitotenv.2016.06.166.

Christ, M. and Sommer, B. (2023): Weltrettungskompetenz? Überlegungen zu BNE aus der Perspektive der sozial-ökologischen Transformationsforschung. Zeitschrift für internationale Bildungsforschung and Entwicklungspädagogik (ZEP) 46 (2), 25–30. https://doi.org/10.31244/zep.2023.02.0.

Christian, J. I., Basara, J. B., Hunt, E. D., Otkin, J. A., Furtado, J. C., Mishra, V., Xiao, X. and Randall, R. M. (2021): Global distribution, trends, and drivers of flash drought occurrence. Nature communications 12, 6330. https://doi.org/10.1038/s41467-021-26692-z.

Cid, N., Er-s, T., Heino, J., Singer, G., Jähnig, S. C., Cañedo-Argüelles, M., Bonada, N., Sarremejane, R., Mykrä, H., Sandin, L., Paloniemi, R., Varumo, L. and Datry, T. (2022): From meta-system theory to the sustainable management of rivers in the Anthropocene. Frontiers in Ecology and the Environment 20 (1), 49–57. https://doi.org/10.1002/fee.2417.

Cissé, G., McLeman, R., Adams, H., Aldunce, P., Bowen, K., Campbell-Lendrum, D., Clayton, S., Ebi, K. L., Hess, J., Huang, C., Liu, Q., McGregor, G., Semenza, J. and Tirado, M. C. (2022): Health, Wellbeing and the Changing Structure of Communities. In: Pörtner, H.-O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A. and Rama, B. (Hrsg.): Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press, 1041–1170.

Civic, M. (1998): A comparative analysis of the Israeli and Arab water law traditions and insights for modern water sharing agreements. Denver Journal of International Law and Policy 26 (3), 437–452.

civity Management Consultants (2018): Kosten and verursachungsgerechte Finanzierung einer vierten Reinigungsstufe in Kläranlagen. Berlin: Bundesverband der Energie- and Wasserwirtschaft e. V. (BDEW).

CNRA – California Natural Resources Agency (2022): California's Water Supply Strategy: Adapting to a Hotter, Drier Future. Sacramento, California: CNRA. https://resources.ca.gov/-/media/CNRA-Website/Files/Initiatives/Water-Resilience/CA-Water-Supply-Strategy.pdf.

CNRA – California Natural Resources Agency (2023): California's Groundwater Conditions: Semi-Annual Update October 2023 Fall Bulletin. Sacramento, California: CNRA.

Convergence – Global Network for Blended Finance (2024): Blended Finance. Toronto: Convergence. https://www.convergence.finance/blended-finance, accessed on 11.03.2024.

Cooper, M. W., Brown, M. E., Hochrainer-Stigler, S., Pflug, G., McCallum, I., Fritz, S., Silva, J. and Zvoleff, A. (2019): Mapping the effects of drought on child stunting. Proceedings of the National Academy of Sciences 116 (35), 17219–17224. https://doi.org/10.1073/pnas.190522811.

Cornwall, W. (2023): After the flood. Science 382 (6668), 254–259. https://doi.org/10.1126/science.adl4035.

Costello, M. J., Vale, M. M., Kiessling, W., Maharaj, S., Price, J. and Talukdar, G. H. (2022): Cross-Chapter Paper 1: Biodiversity Hotspots. In: Pörtner, H.-O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A. and Rama, B. (Hrsg.): Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press, 2123–2161. https://www.doi.org/10.1017/9781009325844.018.

Cottier, T., Aerni, P., Karapinar, B., Matteotti, S., de Sépibus, J. and Shingal, A. (2014): The Principle of Common Concern and Climate Change. Archiv des Völkerrechts 52, 293–324. https://www.doi.org/10.1628/000389214X14186502494027.

Cousins, I. T., DeWitt, J. C., Glüge, J., Goldenman, G., Herzke, D., Lohmann, R., Ng, C. A., Scheringer, M. and Wang, Z. (2020): The high persistence of PFAS is sufficient for their management as a chemical class. Environmental Science: Processes & Impacts 22 (12), 2307–2312. https://www.doi.org/10.1039/D0EM00355G.

Crate, S. A. and Nuttall, M. (2009): Anthropology and Climate Change: From Encounters to Actions. New York: Routledge.

Cremades, R., Sanchez-Plaza, A., Hewitt, R. J., Mitter, H., Baggio, J. A., Olazabal, M., Broekman, A., Kropf, B. and Tudose, N. C. (2021): Guiding cities under increased droughts: The limits to sustainable urban futures. Ecological Economics 189, 107140. https://doi.org/10.1016/j.ecolecon.2021.107140.

Cressey, D. (2017): Climate change is making algal blooms worse. Nature, 1–2. https://www.doi.org/10.1038/nature.2017.21884.

Cui, T., Li, Y., Yang, L., Nan, Y., Li, K., Tudaji, M., Hu, H., Long, D., Shahid, M., Mubeen, A., He, Z., Yong, B., Lu, H., Li, C., Ni, G., Hu, C. and Tian, F. (2023): Non-monotonic changes in Asian Water Towers' streamflow at increasing warming levels. Nature Communications 14, 1176. https://www.doi.org/10.1038/s41467-023-36804-6.

Cullet, P. and Koonan, S. (2017) (Hrsg.): Water Law in India: An Introduction to Legal Instruments. Oxford, UK: Oxford University Press.

Cushing, L. J., Ju, Y., Kulp, S., Depsky, N., Karasaki, S., Jaeger, J., Raval, A., Strauss, B. and Morello-Frosch, R. (2023): Toxic Tides and Environmental Injustice: Social Vulnerability to Sea Level Rise and Flooding of Hazardous Sites in Coastal California. Environmental Science & Technology 57 (19), 7370–7381. https://www.doi.org/10.1021/acs.est.2c07481.

CWIS – Citywide Inclusive Sanitation Initiative, BMGF – The Bill & Melinda Gates Foundation and Athena Infonomics (2021): Lusaka CWIS City Snapshot. Washington D.C: CWIS.

d'Odorico, P., Carr, J., Dalin, C., Dell'Angelo, J., Konar, M., Laio, F., Ridolfi, L., Rosa, L., Suweis, S. and Tamea, S. (2019): Global virtual water trade and the hydrological cycle: patterns, drivers, and socio-environmental impacts. Environmental Research Letters 14 (5), 053001. https://doi.org/10.1088/1748-9326/ab05f4.

da Silva, J. P., Sousa, R., Goncalves, D. V., Miranda, R., Reis, J., Teixeira, A., Varandas, S., Lopes-Lima, M. and Filipe, A. F. (2023): Streams in the Mediterranean Region are not for mussels: Predicting extinctions and range contractions under future climate change. Science of The Total Environment 883, 163689. https://www.doi.org/10.1016/j.scitotenv.2023.163689.

Dakyaga, F., Ahmed, A. and Sillim, M. L. (2021): Governing ourselves for sustainability: Everyday ingenuities in the governance of water infrastructure in the informal settlements of Dar es Salaam. Urban Forum 32, 111–129. https://doi.org/10.1007/s12132-020-09412-6.

Daly-Hassen, H., Annabi, M. and King-Okumu, C. (2019): Social and Private Profitability of Tree-Based Adaptation Options to Climate Change in a Dryland Area of Tunisia. New Medit 18 (2), 89–104. https://www.doi.org/10.30682/nm1902f.

Damania, R. (2020): The economics of water scarcity and variability. Oxford Review of Economic Policy 36 (1), 24–44. https://doi.org/10.1016/j.jpolmod.2017.10.003.

Dang, Q. and Konar, M. (2018): Trade openness and domestic water use. Water Resources Research 54 (1), 4–18. https://doi.org/10.1002/2017WR021102.

Daniels, A. (2021): São Paulo in poverty: improving life in the slums. Bournemouth: BUzz Bournemouth. https://buzz.bournemouth.ac.uk/2021/01/nearly-20-of-residents-in-sao-paulo-live-in-poverty/, published on 21.01.2021.

Danske Vandværker (2024): About us: The Association of Waterworks in Denmark. Solrød Strand: Danske Vandværker. https://danskevv.dk/om-os/about-us/, accessed on 5.03.2024.

Das, S., Fuchs, H., Philip, R. and Rao, P. (2022): A review of water valuation metrics: Supporting sustainable water use in manufacturing. Water Resources and Industry 29, 100199. https://www.doi.org/10.1016/j.wri.2022.100199.

Davenport, C. (2023): Strawberry Case Study: What if Farmers Had to Pay for Water? New York: New York Times. https://www.nytimes.com/interactive/2023/12/29/climate/california-farmers-water-tax.html, published on 22.01.2024.

Davidson, N. C., van Dam, A. A., Finlayson, C. M. and McInnes, R. J. (2019): Worth of wetlands: revised global monetary values of coastal and inland wetland ecosystem services. Marine and Freshwater Research 70 (8), https://www.doi.org/10.1071/mf18391.

Davies, I. (2017): Women's Economic Empowerment and Care (WE-Care)-Oxfam: Phase 2 Interim Report. Oxford: Oxfam.

de Graaf, I. E., van Beek, R. L., Gleeson, T., Moosdorf, N., Schmitz, O., Sutanudjaja, E. H. and Bierkens, M. F. (2017): A global-scale two-layer transient groundwater model: Development and application to groundwater depletion. Advances in water Resources 102, 53–67. https://doi.org/10.1016/j.advwatres.2017.01.011.

de Ruyter van Steveninck, E., Arrieta, L., Lloyd, G., Ashipala, J., Gallo, I. and Fenni, Y. (2018): Climate Change Adaptation and Integrated Water Resources Management. Stockholm: International Capacity Development Network for Sustainable Water Management (Cap-Net). https://www.doi.org/10.13140/RG.2.2.29264.66560.

De Stefano, L., Hernández-Mora, N., Gómez-Limón, J. and Calatrava, J. (2016): Los mercados informales de aguas en españa: una visión de conjunto. In: Gômez-Limón, J. A. and Calatrava, J. (Hrsg.): Los mercados de agua en España: presente y perspectivas. Barcelona: Fundación Cajamar, 95–121.

Dean, L., Njelesani, J., Smith, H. and Bates, I. (2015): Promoting sustainable research partnerships: a mixed-method evaluation of a United Kingdom-Africa capacity strengthening award scheme. Health Research Policy and Systems 13, 81. https://www.doi.org/10.1186/s12961-015-0071-2.

Deane, B. M. D., Brian (2021): The Alliance of Community-Owned Water Services in Europe: Opportunities and Challenges Based on the Irish Perspective. Water 13 (22), 3181. https://doi.org/10.3390/w13223181.

DeBerry, D. A. and Hunter, D. M. (2024): Impacts of Invasive Plants on Native Vegetation Communities in Wetland and Stream Mitigation. Biology (Basel) 13 (4), 275. https://www.doi.org/10.3390/biology13040275.

Delevingne, L., Glazener, W., Grégoir, L. and Henderson, K. (2020): Climate risk and decarbonization: What every mining CEO needs to know. New York: McKinsey & Company. https://www.mckinsey.com/capabilities/sustainability/our-insights/climate-risk-and-decarbonization-what-every-mining-ceo-needs-to-know#/, published on 28.01.2020.

Dellapenna, J. W. and Gupta, J. (2009) (Hrsg.): The evolution of the law and politics of water. Berlin, Heidelberg: Springer.

Dellapenna, J. W., Gupta, J., Li, W. J. and Schmidt, F. (2013): Thinking about the Future of Global Water Governance. Ecology and Society 18 (3), 28. https://www.doi.org/10.5751/Es-05657-180328.

Deng, C., Zhang, G., Liu, Y., Nie, X., Li, Z., Liu, J. and Zhu, D. (2021): Advantages and disadvantages of terracing: A comprehensive review. International Soil and Water Conservation Research 9 (3), 344–359. https://www.doi.org/10.1016/j.iswcr.2021.03.002.

Deng, G., Gao, J., Jiang, H., Li, D., Wang, X., Wen, Y., Sheng, L. and He, C. (2022): Response of vegetation variation to climate change and human activities in semi-arid swamps. Frontiers in Plant Science 13, 990592. https://www.doi.org/10.3389/fpls.2022.990592.

Depietri, Y. and McPhearson, T. (2017): Integrating the Grey, Green, and Blue in Cities: Nature-Based Solutions for Climate Change Adaptation and Risk Reduction. In: Kabisch, N., Korn, H., Stadler, J. and Bonn, A. (Hrsg.): Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice. Cham: Spinger Nature, 91–109. https://doi.org/10.1007/978-3-319-56091-5_6.

DFG – Deutsche Forschungsgemeinschaft (2023): MAK-and BAT-Werte-Liste 2023. Ständige Senatskommission zur Prüfung gesundheitsschädlicher Arbeitsstoffe. Mitteilung 59. Bonn: DFG. https://www.doi.org/10.34865/mbwl_2023_deu.

DFI BCF – DFI Working Group on Blended Concessional Finance for Private Sector Projects (2023): Joint report, March 2023 Update. Washington, D.C.: International Finance Corporation (IFC).

DG ENV – Directorate-General for Environment (2023): The Road to Green 5: Restoring European rivers - a win-win scenario for humans and nature. Brussels: EU. https://environment.ec.europa.eu/news/restoring-european-rivers-win-win-scenario-humans-and-nature-2023-10-18_en, published on 18.10.2023.

DGE – Deutsche Gesellschaft für Ernährung (2024): Gut essen and trinken – die DGE-Empfehlungen. Bonn: DGE. https://www.dge.de/gesunde-ernaehrung/gut-essen-and-trinken/dge-empfehlungen/, accessed on 12.07.2024.

Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R. T., Molnár, Z., Hill, R., Chan, K. M. A., Baste, I. A., Brauman, K. A., Polasky, S., Church, A., Lonsdale, M., Larigauderie, A., Leadley, P. W., van Oudenhoven, A. P. E., van der Plaat, F., Schröter, M., Lavorel, S., Aumeeruddy-Thomas, Y., Bukvareva, E., Davies, K., Demissew, S., Erpul, G., Failler, P., Guerra, C. A., Hewitt, C. L., Keune, H., Lindley, S. and Shirayama, Y. (2018): Assessing nature's contributions to people. Science 359 (6373), 270–272. https://www.doi.org/10.1126/science.aap8826.

Di Marco, A. (2023): Water democracy under European Union law: Requiring participatory services management. Utilities Policy 84, 101648. https://doi.org/10.1016/j.jup.2023.101648.

DIN – Deutsches Institut für Normung (1994): Hydrologie - Teil 3: Begriffe zur quantitativen Hydrologie (DIN 4049-3). DIN: Berlin. https://www.din.de/de/mitwirken/normenausschuesse/naw/wdc-beuth:din21:2387598, accessed on 20.11.2024.

Distefano, T. and Kelly, S. (2017): Are we in deep water? Water scarcity and its limits to economic growth. Ecological Economics 142, 130–147. https://doi.org/10.1016/j.ecolecon.2017.06.019.

Distefano, T., Laio, F., Ridolfi, L. and Schiavo, S. (2018): Shock transmission in the international food trade network. PloS one 13 (8), e0200639. https://doi.org/10.1371/journal.pone.0200639.

Ditlevsen, P. and Ditlevsen, S. (2023): Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. Nature Communications 14, 4254. https://www.doi.org/10.1038/s41467-023-39810-w.

Dixson-Decleve, S., Gaffney, O., Ghosh, J., Randers, J., Rockstrom, J. and Stoknes, P. E. (2022): Earth for All: A Survival Guide for Humanity. Gabriola Island, Canada: New Society Publishers.

Dombrowsky, I., Hagemann, N. and Houdret, A. (2014): The river basin as a new scale for water governance in transition countries? A comparative study of Mongolia and Ukraine. Environmental Earth Sciences 72, 4705–4726. https://doi.org/10.1007/s12665-014-3308-4.

Dombrowsky, I., Hägele, R., Behrenbeck, L., Bollwein, T., Köder, M., Oberhauser, D., Schamberger, R., Al-Naber, M., Al-Raggad, M. and Salameh, E. (2022a): Natural resource governance in light of the 2030 agenda: The case of competition for groundwater in Azraq, Jordan (IDOS Studies 106). Bonn: German Institute of Development and Sustainability (IDOS). https://doi.org/10.23661/is106.2022.

Dombrowsky, I., Lenschow, A., Meergans, F., Schütze, N., Lukat, E., Stein, U. and Yousefi, A. (2022b): Effects of policy and functional (in)coherence on coordination – A comparative analysis of cross-sectoral water management problems. Environmental Science & Policy 131, 118–127. https://doi.org/10.1016/j.envsci.2022.01.019.

Dörendahl, E. and Aich, P. (2021): Integrating EbA and IWRM for climate-resilient water management. Bonn: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

Dottori, F., Szewczyk, W., Ciscar, J.-C., Zhao, F., Alfieri, L., Hirabayashi, Y., Bianchi, A., Mongelli, I., Frieler, K., Betts, R. A. and Feyen, L. (2018): Increased human and economic losses from river flooding with anthropogenic warming. Nature Climate Change 8 (9), 781–786. https://www.doi.org/10.1038/s41558-018-0257-z.

Douville, H., Raghavan, K., Renwick, J., Allan, R. P., Arias, P. A., Barlow, M., Cerezo-Mota, R., Cherchi, A., Gan, T. Y., Gergis, J., Jiang, D., Khan, A., Pokam Mba, W., Rosenfeld, D., Tierney, J. and Zolin, O. (2021): Water Cycle Changes. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B. (Hrsg.): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge Universtiy Press, 1055–1210. https://www.doi.org/10.1017/9781009157896.010.

Doyle, M. W., Stanley, E. H., Orr, C. H., Selle, A. R., Sethi, S. A. and Harbor, J. M. (2005): Stream ecosystem response to small dam removal: Lessons from the Heartland. Geomorphology 71 (1), 227–244. https://www.doi.org/10.1016/j.geomorph.2004.04.011.

Drewes, J. (2024): Projekt Nutzwasser - Nutzwasser als alternative Wasserressource. Garching/Munich: Technische Universität München, Lehrstuhl für Siedlungswasserwirtschaft. https://www.nutzwasser.org/, accessed on 17.09.2024.

Drewes, J. E. and Horstmeyer, N. (2016): Recent Developments in Potable Water Reuse. In: Fatta-Kassinos, D., Dionysiou, D. D. and Kümmerer, K. (Hrsg.): Advanced Treatment Technologies for Urban Wastewater Reuse. Cham: Springer International Publishing, 269–290. https://www.doi.org/10.1007/698_2015_341.

Droste, N., Schröter-Schlaack, C., Hansjürgens, B. and Zimmermann, H. (2017): Implementing nature-based solutions in urban areas: financing and governance aspects. In: Kabisch, N., Korn, H., Stadler, J. and Bonn, A. (Hrsg.): Nature-based solutions to climate change adaptation in urban areas: linkages between science, policy and practice. Cham: Springer Nature, 307–321.

Duarte, B., Gameiro, C., Matos, A. R., Figueiredo, A., Silva, M. S., Cordeiro, C., Caçador, I., Reis-Santos, P., Fonseca, V. and Cabrita, M. T. (2021): First screening of biocides, persistent organic pollutants, pharmaceutical and personal care products in Antarctic phytoplankton from Deception Island by FT-ICR-MS. Chemosphere 274, 129860. https://doi.org/10.1016/j.chemosphere.2021.129860.

DuChanois, R. M., Cooper, N. J., Lee, B., Patel, S. K., Mazurowski, L., Graedel, T. E. and Elimelech, M. (2023): Prospects of metal recovery from wastewater and brine. Nature Water 1, 37–46. https://www.doi.org/10.1038/s44221-022-00006-z.

Duda, J. J. and Bellmore, J. R. (2022): Dam Removal and River Restoration. In: Mehner, T. and Tockner, K. (Hrsg.): Encyclopedia of Inland Waters (Second Edition). Oxford: Elsevier, 576–585. https://www.sciencedirect.com/science/article/pii/B9780128191668001018.

Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z., Knowler, D. J., Leveque, C., Naiman, R. J., Prieur-Richard, A. H., Soto, D., Stiassny, M. L. and Sullivan, C. A. (2006): Freshwater biodiversity: importance, threats, status and conservation challenges. Biological reviews of the Cambridge Philosophical Society 81 (2), 163–182. https://www.doi.org/10.1017/S1464793105006950.

Dudgeon, D. (2019): Multiple threats imperil freshwater biodiversity in the Anthropocene. Curr Biol 29 (19), R960–R967. https://www.doi.org/10.1016/j.cub.2019.08.002.

Duffus, J. H. (2022): „Heavy metals" a meaningless term? (IUPAC Technical Report). Pure and Applied Chemistry 74 (5), 793–807. https://www.doi.org/10.1351/pac200274050793.

DUK – Deutsche UNESCO Kommission (2024): Gleichberechtigte Wissenschaftskooperation weltweit – Positionspapier der Deutschen UNESCO-Kommission. Bonn: Deutsche UNESCO-Kommission e. V.

Duong, K. and Saphores, J.-D. M. (2015): Obstacles to wastewater reuse: an overview. WIREs Water 2 (3), 199–214. https://doi.org/10.1002/wat2.1074.

Dupuy, J.-l., Fargeon, H., Martin-StPaul, N., Pimont, F., Ruffault, J., Guijarro, M., Hernando, C., Madrigal, J. and Fernandes, P. (2020): Climate change impact on future wildfire danger and activity in southern Europe: a review. Annals of Forest Science 77 (2), 35. https://www.doi.org/10.1007/s13595-020-00933-5.

Durner, W. and Ludwig, R. (2008): Paradigmenwechsel in der europäischen Umweltrechtsetzung? Überlegungen zu Bedeutung and Grundstrukturen des Instruments der Maßnahmenplanung im neueren Umweltrecht der Gemeinschaft. Natur and Recht 30, 457–467. https://www.doi.org/10.1007/s10357-008-1496-y.

Durner, W. (2019): Das "Verschlechterungsverbot" and das "Verbesserungsgebot" im Wasserwirtschaftsrecht. Natur and Recht 41 (1), 1–14. https://www.doi.org/10.1007/s10357-018-3458-3.

Durner, W. (2021): Infrastrukturverwaltung. In: Kahl, W. and Ludwigs, M. (Hrsg.): Handbuch des Verwaltungsrechts Band I Grundstrukturen des deutschen Verwaltungsrechts. Munich: C.F. Müller, 807–846.

Dusaucy, J., Gateuille, D., Perrette, Y. and Naffrechoux, E. (2021): Microplastic pollution of worldwide lakes. Environmental Pollution 284, 117075. https://www.doi.org/10.1016/j.envpol.2021.117075.

Dutta, D., Arya, S. and Kumar, S. (2021): Industrial wastewater treatment: Current trends, bottlenecks, and best practices. Chemosphere 285, 131245. https://www.doi.org/10.1016/j.chemosphere.2021.131245.

DWD – Deutsche Wetterdienst (2024): Wetter- and Klimalexikon: Kryosphäre. Offenbach: DWD. https://www.dwd.de/DE/service/lexikon/Functions/glossar.html?lv3=101508&lv2=101334, accessed on 20.11.2024.

DWR – California Department of Water Resources (2023): DWR Captures and Stores Water from Record-Breaking Snowpack. Sacramento, California: DWR. https://water.ca.gov/News/Blog/2023/July-23/DWR-Captures-and-Stores-Water-from-Record-Breaking-Snowpack?utm_medium=email&utm_source=govdelivery, published on 19.07.2023.

Eales, J., Bethel, A., Galloway, T., Hopkinson, P., Morrissey, K., Short, R. E. and Garside, R. (2022): Human health impacts of exposure to phthalate plasticizers: An overview of reviews. Environment International 158, 106903. https://doi.org/10.1016/j.envint.2021.106903.

ECB – European Central Bank (2021): Climate-related risk and financial stability. Frankfurt am Main: ECB. https://www.ecb.europa.eu/pub/pdf/other/ecb.climateriskfinancialstability202107~87822fae81.en.pdf.

ECB – European Central Bank (2022): Walking the talk - Banks gearing up to manage risks from climate change and environmental degradation: Results of the 2022 thematic review on climate-related and environmental risks. Frankfurt am Main: ECB.

Edegbene, A. O. and Akamagwuna, F. C. (2022): Insights from the Niger Delta Region, Nigeria on the impacts of urban pollution on the functional organisation of Afrotropical macroinvertebrates. Scientific Reports 12 (1), 22551. https://doi.org/10.1038/s41598-022-26659-0.

EEA – European Environment Agency (2015): Proportion of classified water bodies in different RBDs affected by pollution pressures, for rivers and lakes. Copenhagen: EEA. https://www.eea.europa.eu/data-and-maps/figures/proportion-of-classified-water-bodies-4, published on 16.06.2015.

EEA – European Environment Agency (2021): Ecological status of surface waters in Europe. Copenhagen: EEA. https://www.eea.europa.eu/en/analysis/indicators/ecological-status-of-surface-waters?activeAccordion=546a7c35-9188-4d23-94ee-005d97c26f2b, published on 18.11.2021.

EEA – European Environment Agency (2022): Beyond water quality — Sewage treatment in a circular economy. Copenhagen: EEA. https://www.doi.org/10.2800/897113.

EEA – European Environment Agency (2023): Economic losses from weather- and climate-related extremes in Europe. Copenhagen: EEA. https://www.eea.europa.eu/en/analysis/indicators/economic-losses-from-climate-related, published on 6.10.2023.

EEA – European Environment Agency (2024a): Climate-ADAPT: Conducting a cost-benefit analysis of adaptation measures. Copenhagen: EEA. https://climate-adapt.eea.europa.eu/en/knowledge/tools/urban-ast/step-4-2, published on 7.07.2016.

EEA – European Environment Agency (2024b): Water glossary. Copenhagen: EEA. https://www.eea.europa.eu/themes/water/glossary, accessed on 20.11.2024.

EESC – European Economic and Social Committee (2023): Declaration for an EU Blue Deal. Brussels: EESC. https://www.eesc.europa.eu/de/initiatives/eu-blue-deal.

EFRAG – European Financial Reporting Advisory Group (2022): Draft European Sustsinability Reporting Standards, Appendix IV - TCFD Recommendations and ESRS Reconciliation Table. Brussels: EFRAG.

EFSA – European Food Safety Authority, Carrasco Cabrera, L., Di Piazza, G., Dujardin, B., Marchese, E. and Medina Pastor, P. (2024): The 2022 European Union report on pesticide residues in food. EFSA Journal 22 (4), e8753. https://doi.org/10.2903/j.efsa.2024.8753.

EIB — Europäische Investitionsbank (2023a): Investing in nature-based solutions - State-of-play and way forward for public and private financial measures in Europe. Luxemburg: EIB.

EIB — Europäische Investitionsbank (2023b): Orientierung der EIB für Finanzierungen im Wassersektor, Aufbau klimaresilienter Wassersysteme. Luxemburg: EIB.

Elevitch, C. R., Mazaroli, D. N. and Ragone, D. (2018): Agroforestry Standards for Regenerative Agriculture. Sustainability 10 (9), https://www.doi.org/10.3390/su10093337.

Elliott, J., Deryng, D., Muller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Florke, M., Wada, Y., Best, N., Eisner, S., Fekete, B. M., Folberth, C., Foster, I., Gosling, S. N., Haddeland, I., Khabarov, N., Ludwig, F., Masaki, Y., Olin, S., Rosenzweig, C., Ruane, A. C., Satoh, Y., Schmid, E., Stacke, T., Tang, Q. and Wisser, D. (2014): Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proceedings of the National Academy of Sciences of the United States of America 111 (9), 3239–3244. https://doi.org/10.1073/pnas.1222474110.

Emmons, C. V. (2020): International Organizations: Enablers or Impediments for Authoritarian International Law? AJIL Unbound 114, 226–231. https://www.doi.org/10.1017/aju.2020.45.

Engel, J., Kokas, D., Lopez-Acevedo, G. and Maliszewska, M. (2021): The distributional impacts of trade: Empirical innovations, analytical tools, and policy responses. Washington, D.C.: World Bank Group.

EPA – United States Environmental Protection Agency (2023): Technical Fact Sheet: Lithium in Drinking Water. Washington, D.C.: EPA. https://www.epa.gov/system/files/documents/2023-11/ucmr5-technical-fact-sheet-lithium-in-drinking-water.pdf.

EPA – United States Environmental Protection Agency (2024): Frequent Questions about Water Quality Trading. Washington, D.C.: EPA. https://www.epa.gov/npdes/frequent-questions-about-water-quality-trading, accessed on 15.07.2024.

Eriksen, S., Schipper, E. L. F., Scoville-Simonds, M., Vincent, K., Adam, H. N., Brooks, N., Harding, B., Khatri, D., Lenaerts, L., Liverman, D., Mills-Novoa, M., Mosberg, M., Movik, S., Muok, B., Nightingale, A., Ojha, H., Sygna, L., Taylor, M., Vogel, C. and West, J. J. (2021): Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? World Development 141, 105383. https://doi.org/10.1016/j.worlddev.2020.105383.

Erwin, A., Ma, Z., Popovici, R., Salas O'Brien, E. P., Zanotti, L., Zeballos Zeballos, E., Bauchet, J., Ramirez Calderón, N. and Arce Larrea, G. R. (2021): Intersectionality shapes adaptation to social-ecological change. World Development 138, 105282. https://doi.org/10.1016/j.worlddev.2020.105282.

Escher, B., Neale, P. and Leusch, F. (2021): Bioanalytical tools in water quality assessment. London: IWA Publishing.

Escher, B. I., Altenburger, R., Bluher, M., Colbourne, J. K., Ebinghaus, R., Fantke, P., Hein, M., Kock, W., Kummerer, K., Leipold, S., Li, X., Scheringer, M., Scholz, S., Schloter, M., Schweizer, P. J., Tal, T., Tetko, I., Traidl-Hoffmann, C., Wick, L. Y. and Fenner, K. (2023): Modernizing persistence-bioaccumulation-toxicity (PBT) assessment with high throughput animal-free methods. Archives of Toxicology 97 (5), 1267–1283. https://doi.org/10.1007/s00204-023-03485-5.

Escriva-Bou, A., Medellín-Azuara, J., Hanak, E., Abatzoglou, J. and Viers, J. (2022a): Drought and California's Agriculture. San Francisco, California: Public Policy Institute of California (PPIC).

Escriva-Bou, A., Rosser, A. and Hanak, E. (2022b): How Are California's Cities Managing the Drought? San Francisco, California: Public Policy Institute of California (PPIC). https://www.ppic.org/blog/how-are-californias-cities-managing-the-drought/, published on 31.10.2022.

Etongo, D., Djenontin, I., Kanninen, M. and Fobissie, K. (2015): Smallholders' Tree Planting Activity in the Ziro Province, Southern Burkina Faso: Impacts on Livelihood and Policy Implications. Forests 6 (12), 2655–2677. https://www.doi.org/10.3390/f6082655.

EU – Europäische Union (2020): Verordnung (EU) 2020/852 des Europäischen Parlaments and des Rates vom 18. Juni 2020 über die Einrichtung eines Rahmens zur Erleichterung nachhaltiger Investitionen and zur Änderung der Verordnung (EU) 2019/2088. Amtsblatt der Europäischen Union Nr. L 198 vom 22.06.2020. Brussels: EU.

EU – Europäische Union (2023): Verordnung (EU) 2023/2859 des Europäischen Parlaments and des Rates vom 13. Dezember 2023 zur Einrichtung eines zentralen europäischen Zugangsportals für den zentralisierten Zugriff auf öffentlich verfügbare, für Finanzdienstleistungen, Kapitalmärkte and Nachhaltigkeit relevante Informationen. Amtsblatt der Europäischen Union Nr. L 2859 vom 20.12.2023. Brussels: EU.

EU Blue Economy Observatory (2024): Desalination. Brussels: EU. https://blue-economy-observatory.ec.europa.eu/eu-blue-economy-sectors/desalination_en#6, accessed on 8.07.2024.

EuGH – Europäischer Gerichtshof (2015): Urteil des Gerichtshofs (Große Kammer) vom 1. Juli 2015 in der Rechtssache C-416/13 (Weservertiefung). Luxemburg: EuGH.

EuGH – Europäischer Gerichtshof (2020): Urteil des Gerichtshofs (Erste Kammer) vom 28. Mai 2020 in der Rechtssache C-535/18. Luxemburg: EuGH.

Europäische Kommission (2016): 10 benefits of Economic Partnership Agreements (EPAs). Brussels: EU.

Europäische Kommission (2018): Aktionsplan: Finanzierung nachhaltigen Wachstums. COM(2018) 97 final. Brussels: EU.

Europäische Kommission (2020a): Mitteilung der Kommission an das Europäische Parlament and den Rat, den Europäischen Wirtschafts- nd Sozialausschuss and den Ausschuss der Regionen. Ein neuer Aktionsplan für die Kreislaufwirtschaft. Für ein saubereres and wettbewerbsfähigeres Europa. COM(2020) 98 final. Brussels: EU.

Europäische Kommission (2020b): Critical raw materials for strategic technologies and sectors in the EU: a foresight study. Brussels: EU. https://www.doi.org/10.2873/865242.

Europäische Kommission (2021a): Strategy for Financing the Transition to a Sustainable Economy. COM(2021) 390 final. Brussels: EU. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0390.

Europäische Kommission (2021b): Bericht der Kommission an den Rat and das Europäische Parlament ber die Umsetzung der Wasserrahmenrichtlinie (2000/60/EG), der Richtlinie über Umweltqualitätsnormen (2008/105/EG, geändert durch die Richtlinie 2013/39/EU) and der Hochwasserrichtlinie (2007/60/EG). COM(2021) 970 final. Brussels: EU. https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:52021DC0970.

Europäische Kommission (2023a): EU Aid for Trade Progress Report 2023. Brussels: EU. https://www.developmentaid.org/api/frontend/cms/file/2024/04/eu-aid-for-trade-MN0323474ENN.pdf.

Europäische Kommission (2023b): Delegierte Verordnung (EU) 2023/2486 der Kommission zur Ergänzung der Verordnung (EU) 2020/852 des Europäischen Parlaments and des Rates durch Festlegung der technischen Bewertungskriterien, anhand deren bestimmt wird, unter welchen Bedingungen davon auszugehen ist, dass eine Wirtschaftstätigkeit einen wesentlichen Beitrag zur nachhaltigen Nutzung and zum Schutz von Wasser- and Meeresressourcen, zum Übergang zu einer Kreislaufwirtschaft, zur Vermeidung and Verminderung der Umweltverschmutzung oder zum Schutz and zur Wiederherstellung der Biodiversität and der Ökosysteme leistet, and anhand deren bestimmt wird, ob diese Wirtschaftstätigkeit erhebliche Beeinträchtigungen eines der übrigen Umweltziele vermeidet, and zur Änderung der Delegierten Verordnung (EU) 2021/2178 der Kommission in Bezug auf besondere Offenlegungspflichten für diese Wirtschaftstätigkeiten. Amtsblatt der Europäischen Union Nr. L 198/13 vom 21.11.2023. Brussels: EU. https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=OJ:L_202302486.

Europäische Kommission (2024a): Mitteilung der Kommission. Leitkriterien and Grundsätze für das Konzept der wesentlichen Verwendung in EU-Rechtsvorschriften, die Chemikalien betreffen. C/2024/2894. Brussels: EU. https://eur-lex.europa.eu/eli/C/2024/2894/oj.

Europäische Kommission (2024b): Supporting companies in applying the European Sustainability Reporting Standards. Dokumentation eines Expertendialogs am 16. Mai 2024. Brussels: EU. https://finance.ec.europa.eu/events/supporting-companies-applying-european-sustainability-reporting-standards-2024-05-16_en, accessed on 7.06.2024.

Europäischer Rat (2024): Proposal for a directive of the European Parliament and of the Council concerning urban wastewater treatment (recast). Brussels: EU.

Europäisches Parlament and Committee on the Environment, Public Health and Food Safety (2023): Draft Report on the proposal for a regulation of the European Parliament and of the Council on the sustainable use of plant protection products and amending Regulation (EU) 2021/2115 (COM(2022)0305 – C9-0207/2022 – 2022/0196(COD)). Brussels: EU.

Europäisches Parlament (2024a): Initiative for water resilience in "A European Green Deal". Brussels: EU. https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-water-resilience.

Europäisches Parlament (2024b): Legislative Entschließung des Europäischen Parlaments vom 10.4.2024 zu dem Vorschlag für eine Richtlinie des Europäischen Parlaments and des Rates über die Behandlung von kommunalem Abwasser (Neufassung) (COM(2022)0541 – C9-0363/2022 – 2022/0345(COD)), P9_TA(2024)0222. Brussels: EU. https://www.europarl.europa.eu/doceo/document/TA-9-2024-0222_EN.pdf.

EuroStat – Statistisches Amt der Europäischen Union (2023): Environmental tax statistics. Luxemburg: EuroStat. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Environmental_tax_statistics#Environmental_taxes_in_the_EU, published on 26.09.2023.

Eyl-Mazzega, M.-A. and Cassignol, É. (2022): The Geopolitics of Seawater Desalination. Paris: Institut français des relations internationales (IFRI).

Fahimi, A., Ducoli, S., Federici, S., Ye, G., Mousa, E., Frontera, P. and Bontempi, E. (2022): Evaluation of the sustainability of technologies to recycle spent lithium-ion batteries, based on embodied energy and carbon footprint. Journal of Cleaner Production 338, 130493. https://www.doi.org/10.1016/j.jclepro.2022.130493.

Falkenmark, M. and Rockström, J. (2004): Balancing Water for Humans and Nature: The New Approach in Ecohydrology. London, Sterling: Earthscan.

Falkenmark, M. and Rockström, J. (2006): The new blue and green water paradigm: Breaking new ground for water resources planning and management. Journal of Water Resources Planning and Management-Asce 132 (3), 129–132. https://doi.org/10.1061/(ASCE)0733-9496(2006)132:3(129).

Falkenmark, M., Wang-Erlandsson, L. and Rockström, J. (2019): Understanding of water resilience in the Anthropocene. Journal of Hydrology X 2, 100009. https://www.doi.org/10.1016/j.hydroa.2018.100009.

FAO – Food and Agriculture Organization and IWMI – International Water Management Institute (2018): More people, more food, worse water? a global review of water pollution from agriculture. Rome: FAO, IWMI.

FAO – Food and Agriculture Organization and UNDP – United Nations Development Programm (2018): Cost-benefit analysis for climate change adaptation policies and investments in the agriculture sectors. Rome, New York: FAO, UNDP.

FAO – Food and Agriculture Organization (2019): Proactive Approaches to Drought Preparedness: Where are we now and where do we go from here. White Paper Proactive Approaches to Drought Preparedness. Rome: FAO. http://www.fao.org/3/ca5794en/ca5794en.pdf.

FAO – Food and Agriculture Organization (2020a): The State of Food and Agriculture 2020. Overcoming water challenges in agriculture. Rome: FAO.

FAO – Food and Agriculture Organization (2020b): Unpacking water tenure for improved food security and sustainable development. Land and Water Discussion Papers. Rome: FAO. https://doi.org/10.4060/cb1230en.

FAO – Food and Agriculture Organization, IUCN – International Union for Conservation of Nature and SER – Society for Ecological Restoration (2021): Principles for Ecosystem Restoration to Guide the United Nations Decade 2021–2030. Rome: FAO.

FAO – Food and Agriculture Organization and UN Water – United Nations Water (2021): Progress on Level of Water Stress – 2021 Update. Global Status and acceleration needs for SDG indicator 6.4.2. Rome: FAO, UN Water. https://doi.org/10.4060/cb6241en.

FAO – Food and Agriculture Organization (2022a): Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security. Rome: FAO. https://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/416990/.

FAO – Food and Agriculture Organization (2022b): The State of the World's Land and Water Resources for Food and Agriculture – Systems at breaking point. Main report. Rome: FAO. https://doi.org/10.4060/cb9910en.

FAO – Food and Agriculture Organization (2024a): Soil Conservation / World Overview of Conservation Approaches and Techniques (WOCAT). Rome: FAO. https://www.fao.org/soils-portal/soil-management/soil-conservation/en/, accessed on 1.07.2024.

FAO – Food and Agriculture Organization (2024b): Global Dialogue on Water Tenure. Rome: FAO. https://sdgs.un.org/partnerships/global-dialogue-water-tenure, accessed on 25.06.2024.

Farmer, M., Benson, A., McMahon, G., Principe, J. and Middleton, M. (2015): Unintended Consequences of Involving Stakeholders Too Late: Case Study in Multi-Objective Management. Journal of Water Resources Planning and Management 141 (10), 1–8. https://www.doi.org/10.1061/(ASCE)WR.1943-5452.0000512.

Faunt, C. C., Sneed, M., Traum, J. and Brandt, J. T. (2016): Water availability and land subsidence in the Central Valley, California, USA. Hydrogeology Journal 24 (3), 675–684. https://www.doi.org/10.1007/s10040-015-1339-x.

Faysse, N. (2015): The rationale of the Green Morocco Plan: missing links between goals and implementation. The Journal of North African Studies 20 (4), 622–634. https://www.doi.org/10.1080/13629387.2015.1053112.

Fearnside, P. M. (2021): Lessons from Brazil's São Paulo droughts (commentary). Menlo Park, USA: Mongabay. https://news.mongabay.com/2021/07/lessons-from-brazils-sao-paulo-droughts-commentary/, published on 30.07.2021.

Filho, W. L., Wolf, F., Totin, E., Zvobgo, L., Simpson, N. P., Musiyiwa, K., Kalangu, J. W., Sanni, M., Adelekan, I., Efitre, J., Donkor, F. K., Balogun, A. L., Mucova, S. A. R. and Ayal, D. Y. (2023): Is indigenous knowledge serving climate adaptation? Evidence from various African regions. Development Policy Review 41 (2), e12664. https://doi.org/10.1111/dpr.12664.

Finck Stiftung (2024a): Projekte & Partner: Praktische Beispiele für unsere Arbeit. Briesen (Mark): Finck Stiftung. https://finck-stiftung.org/projekte-partner/, accessed on 1.07.2024.

Finck Stiftung (2024b): Das Reallabor für regenerative ökologische Landnutzung. Briesen (Mark): Finck Stiftung. https://finck-stiftung.org/, accessed on 1.07.2024.

Finkelman, R. B., Wolfe, A. and Hendryx, M. S. (2021): The future environmental and health impacts of coal. Energy Geoscience 2, 99–112. https://www.doi.org/10.1016/j.engeos.2020.11.001.

Finlayson, C. M. (2016): Freshwater Marshes and Swamps. In: Finlayson, C., Milton, G., Prentice, R. and Davidson, N. (Hrsg.): The Wetland Book. Dordrecht: Springer, 1–14.

Finogenova, N., Dolganova, I., Berger, M., Núñez, M., Blizniukova, D., Müller-Frank, A. and Finkbeiner, M. (2019): Water footprint of German agricultural imports: Local impacts due to global trade flows in a fifteen-year perspective. Science of the Total Environment 662, 521–529. https://doi.org/10.1016/j.scitotenv.2019.01.264.

Fleischmann, N. and Dworak, T. (2022): Abhschlussbericht: Evaluierung Dialogprozess „Nationaler Wasserdialog" (2018 – 2020). Dessau-Roßlau: Umweltbundesamt (UBA). https://www.umweltbundesamt.de/publikationen/evaluierung-dialogprozess-nationaler-wasserdialog.

Fleming, A., Agrawal, S., Dinomika, Fransisca, Y., Graham, L., Lestari, S., Mendham, D., O'Connell, D., Paul, B., Po, M., Rawluk, A., Sakuntaladewi, N., Winarno, B. and Yuwati, T. W. (2021): Reflections on integrated research from community engagement in peatland restoration. Humanities and Social Sciences Communications 8 (1), 199. https://www.doi.org/10.1057/s41599-021-00878-8.

Flörke, M., Schneider, C. and McDonald, R. I. (2018): Water competition between cities and agriculture driven by climate change and urban growth. Nature Sustainability 1, 51–58. https://www.doi.org/10.1038/s41893-017-0006-8.

Flörke, M., Onigkeit, J. and Oppel, H. (2021): Water Resources as important factors in the Energy Transition at local and global scale. Final Report of the joint project WANDEL. Bochum: Ruhr-Universität Bochum.

Foley, M. M., Bellmore, J. R., O'Connor, J. E., Duda, J. J., East, A. E., Grant, G. E., Anderson, C. W., Bountry, J. A., Collins, M. J., Connolly, P. J., Craig, L. S., Evans, J. E., Greene, S. L., Magilligan, F. J., Magirl, C. S., Major, J. J., Pess, G. R., Randle, T. J., Shafroth, P. B., Torgersen, C. E., Tullos, D. and Wilcox, A. C. (2017): Dam removal: Listening in. Water Resources Research 53 (7), 5229–5246. https://doi.org/10.1002/2017WR020457.

Fowler, H. J., Wasko, C. and Prein, A. F. (2021): Intensification of short-duration rainfall extremes and implications for flood risk: current state of the art and future directions. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 379 (2195), 20190541. https://www.doi.org/10.1098/rsta.2019.0541.

Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., Golledge, N. R., Hemer, M., Kopp, R. E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I. S., Ruiz, L., Sallée, J.-B., Slangen, A. B. A. and Yu, Y. (2021): Ocean, Cryosphere and Sea Level Change. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B. (Hrsg.): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press, 1211–1362. https://www.doi.org/10.1017/9781009157896.011.

Foyle, L., Burnett, M., Creaser, A., Hens, R., Keough, J., Madin, L., Price, R., Smith, H., Stone, S. and Kinobe, R. T. (2023): Prevalence and distribution of antimicrobial resistance in effluent wastewater from animal slaughter facilities: A systematic review. Environmental Pollution 318, 120848. https://doi.org/10.1016/j.envpol.2022.120848.

Freyburg, T. (2012): The two sides of functional cooperation with authoritarian regimes: a multi-level perspective on the conflict of objectives between political stability and democratic change. Democratization 19 (3), 575–601. https://doi.org/10.1080/13510347.2012.674363.

Frimpong, F., Asante, M. D., Peprah, C. O., Amankwaa-Yeboah, P., Danquah, E. O., Ribeiro, P. F., Aidoo, A. K., Agyeman, K., Asante, M. O. O., Keteku, A. and Botey, H. M. (2023): Water-smart farming: review of strategies, technologies, and practices for sustainable agricultural water management in a changing climate in West Africa. Frontiers in Sustainable Food Systems 7, 1110179. https://www.doi.org/10.3389/fsufs.2023.1110179.

Fröhlich, C., Gioli, G., Cremades, R. and Myrttinen, H. (2018) (Hrsg.): Water Security Across the Gender Divide. Cham: Springer.

Fu, Z., Ciais, P., Wigneron, J.-P., Gentine, P., Feldman, A. F., Makowski, D., Viovy, N., Kemanian, A. R., Goll, D. S., Stoy, P. C., Prentice, I. C., Yakir, D., Liu, L., Ma, H., Li, X., Huang, Y., Yu, K., Zhu, P., Li, X., Zhu, Z., Lian, J. and Smith, W. K. (2024): Global critical soil moisture thresholds of plant water stress. Nature Communications 15 (1), 4826. https://doi.org/10.1038/s41467-024-49244-7.

Fuente, D., Allaire, M., Jeuland, M. and Whittington, D. (2020): Forecasts of mortality and economic losses from poor water and sanitation in sub-Saharan Africa. PloS one 15 (3), e0227611. https://doi.org/10.1371/journal.pone.0227611.

Fukuyama, T. and Tajiki-Nishino, R. (2020): Pesticide and Immunotoxicology. In: Otsuki, T., Di Gioacchino, M. and Petrarca, C. (Hrsg.): Allergy and Immunotoxicology in Occupational Health - The Next Step. Singapore: Springer Singapore, 183–195. https://doi.org/10.1007/978-981-15-4735-5_12.

G7 – Gruppe der Sieben (2024): G7 Water Coalition. Savelletri: G7.

G20 Water Platform (2024): Water Dialogue. https://g20waterplatform.org.sa/en/Researches/Pages/WaterDialogue.aspx, accessed on 3.07.2024.

Gallardo-Albarrán, D. (2020): Sanitary infrastructures and the decline of mortality in Germany, 1877–1913. The Economic History Review 73 (3), 730–757. https://doi.org/10.1111/ehr.12942.

Galloway, D., Jones, D. R. and Ingebritsen, S. (1999): Land Subsidence in the United States. Reston, Virginia: Geological Survey (USGS).

Gambrill, M., Gilsdorf, R. J. and Kotwal, N. (2020): Citywide inclusive sanitation—business as unusual: shifting the paradigm by shifting minds. Frontiers in Environmental Science 7, 201. https://doi.org/10.3389/fenvs.2019.00201.

Gangemi, S., Gofita, E., Costa, C., Teodoro, M., Briguglio, G., Nikitovic, D., Tzanakakis, G., Tsatsakis, A. M., Wilks, M. F., Spandidos, D. A. and Fenga, C. (2016): Occupational and environmental exposure to pesticides and cytokine pathways in chronic diseases (Review). International Journal of Molecular Medicine 38 (4), 1012–1020. https://www.doi.org/10.3892/ijmm.2016.2728.

Gatis, N., Benaud, P., Anderson, K., Ashe, J., Grand-Clement, E., Luscombe, D. J., Puttock, A. and Brazier, R. E. (2023): Peatland restoration increases water storage and attenuates downstream stormflow but does not guarantee an immediate reversal of long-term ecohydrological degradation. Scientific Reports 13 (1), 15865. https://www.doi.org/10.1038/s41598-023-40285-4.

GCA – Global Commission on Adaptation (2019): Adapt Now: A Global Call for Leadership on Climate Resilience. Rotterdam, Washington, D.C.: Global Center on Adaptation, World Resources Institute (WRI).

GCEW – Global Commission on the Economics of Water (2023a): The What, Why and How of the World Water Crisis: Global Commission on the Economics of Water – Phase 1 Review and Finding. Paris: GCEW.

GCEW – Global Commission on the Economics of Water (2023b): Turning the Tide – A Call to Collective Action. Paris: Organisation for Economic Co-operation and Development (OECD).

Geertsma, R., Wilschut, L. I. and Kauffman, J. H. (2009): Baseline Review of the Upper Tana, Kenya. Green Water Credits Report 8. Wageningen: World Soil Information (ISRIC).

Gerenday, S., Perrone, D., Clark, J. and Ulibarri, N. (2023): Recycled water could recharge aquifers in the Central Valley. California Agriculture, 1–10. https://www.doi.org/10.3733/ca.2023a0005.

Gerlitz, J.-Y., Apablaza, M., Hoermann, B., Hunzai, K. and Bennett, L. (2015): A Multidimensional Poverty Measure for the Hindu Kush–Himalayas, Applied to Selected Districts in Nepal. Mountain Research and Development 35 (3), 278–288. https://doi.org/10.1659/MRD-JOURNAL-D-14-00027.1.

Gerten, D. (2018): Wasser: Knappheit, Klimawandel, Welternährung. Munich: C.H. Beck.

Gething, P. W., Ayling, S., Mugabi, J., Muximpua, O. D., Kagulura, S. S. and Joseph, G. (2023): Cholera risk in Lusaka: A geospatial analysis to inform improved water and sanitation provision. PLOS Water 2 (8), e0000163. https://doi.org/10.1371/journal.pwat.0000163.

Getirana, A., Libonati, R. and Cataldi, M. (2021): Brazil is in water crisis - it needs a drought plan. Nature 600, 218–220. https://doi.org/10.1038/d41586-021-03625-w.

Giller, K. E., Witter, E., Corbeels, M. and Tittonell, P. (2009): Conservation agriculture and smallholder farming in Africa: The heretics' view. Field Crops Research 114 (1), 23–34. https://www.doi.org/10.1016/j.fcr.2009.06.017.

Giller, K. E., Hijbeek, R., Andersson, J. A. and Sumberg, J. (2021): Regenerative Agriculture: An agronomic perspective. Outlook on Agriculture 50 (1), 13–25. https://www.doi.org/10.1177/0030727021998063.

Ginbo, T., Di Corato, L. and Hoffmann, R. (2021): Investing in climate change adaptation and mitigation: A methodological review of real-options studies. Ambio 50 (1), 229–241. https://doi.org/10.1007/s13280-020-01342-8.

Ginzky, H. (2009): Die Pflicht zur Minderung von Schadstoffeinträgen in Oberflächengewässer – Vorgaben der Wasserrahmenrichtlinie and der Richtlinie Prioritäre Stoffe. Zeitschrift für Umweltrecht 5, 242–249.

Girard, C., Pulido-Velazquez, M., Rinaudo, J.-D., Pagé, C. and Caballero, Y. (2015): Integrating top–down and bottom–up approaches to design global change adaptation at the river basin scale. Global Environmental Change 34, 132–146. https://doi.org/10.1016/j.gloenvcha.2015.07.002.

Giupponi, C. and Gain, A. K. (2017): Integrated water resources management (IWRM) for climate change adaptation. Regional Environmental Change 17 (7), 1865–1867. https://www.doi.org/10.1007/s10113-017-1173-x.

Gladstone, F., Liverman, D., Rodríguez, R. A. S. and Santos, A. E. M. (2021): NAFTA and environment after 25 years: A retrospective analysis of the US-Mexico border. Environmental Science & Policy 119, 18–33. https://doi.org/10.1016/j.envsci.2020.10.017.

Gleick, P. H. (2014): Water, Drought, Climate Change, and Conflict in Syria. Weather, Climate, and Society 6 (3), 331–340. https://www.doi.org/10.1175/wcas-d-13-00059.1.

Glibert, P. M. (2020): Harmful algae at the complex nexus of eutrophication and climate change. Harmful Algae 91, 101583. https://www.doi.org/10.1016/j.hal.2019.03.001.

Goldstein, J. E., Neimark, B., Garvey, B. and Phelps, J. (2023): Unlocking „lock-in" and path dependency: A review across disciplines and socio-environmental contexts. World Development 161, 1–15. https://doi.org/10.1016/j.worlddev.2022.106116.

Gomes, I. B., Maillard, J.-Y., Simões, L. C. and Simões, M. (2020): Emerging contaminants affect the microbiome of water systems—strategies for their mitigation. npj Clean Water 3 (39), 1–11. https://www.doi.org/10.1038/s41545-020-00086-y.

González-Gaya, B., Lopez-Herguedas, N., Bilbao, D., Mijangos, L., Iker, A. M., Etxebarria, N., Irazola, M., Prieto, A., Olivares, M. and Zuloaga, O. (2021): Suspect and non-target screening: the last frontier in environmental analysis. Analytical Methods 13 (16), 1876–1904. https://www.doi.org/10.1039/D1AY00111F.

Gouel, C. and Laborde, D. (2021): The crucial role of domestic and international market-mediated adaptation to climate change. Journal of Environmental Economics and Management 106, 102408. https://doi.org/10.1016/j.jeem.2020.102408.

Gozzo, L. F., Drumond, A., Pampuch, L. A., Ambrizzi, T., Crespo, N. M., Reboita, M. S., Bier, A. A., Carpenedo, C. B., Bueno, P. G., Pinheiro, H. R., Custodio, M. d. S., Kuki, C. A. C., Tomaziello, A. C. N., Gomes, H. B., da Rocha, R. P., Coelho, C. A. S. and Pimentel, R. d. M. (2022): Intraseasonal Drivers of the 2018 Drought Over São Paulo, Brazil. Frontiers in Climate 4, 1–19. https://www.doi.org/10.3389/fclim.2022.852824.

Grafton, R., Manero, A., Chu, L. and Wyrwoll, P. (2023): The Price and Value of Water: An Economic Review. Cambridge Prisms: Water 1 (e3), 1–39. https://www.doi.org/10.1017/wat.2023.2.

Grafton, R. Q., Williams, J., Perry, C. J., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S. A., Wang, Y., Garrick, D. and Allen, R. G. (2018): The paradox of irrigation efficiency. Science 361 (6404), 748–750. https://www.doi.org/10.1126/science.aat9314.

Graham, N. T., Hejazi, M. I., Chen, M., Davies, E. G., Edmonds, J. A., Kim, S. H., Turner, S. W., Li, X., Vernon, C. R. and Calvin, K. (2020a): Humans drive future water scarcity changes across all Shared Socioeconomic Pathways. Environmental Research Letters 15 (1), 014007. https://doi.org/10.1088/1748-9326/ab639b.

Graham, N. T., Hejazi, M. I., Kim, S. H., Davies, E. G., Edmonds, J. A. and Miralles-Wilhelm, F. (2020b): Future changes in the trading of virtual water. Nature communications 11, 3632. https://doi.org/10.1038/s41467-020-17400-4.

Gramlich, A., Stoll, S., Stamm, C., Walter, T. and Prasuhn, V. (2018): Effects of artificial land drainage on hydrology, nutrient and pesticide fluxes from agricultural fields – A review. Agriculture, Ecosystems & Environment 266, 84–99. https://www.doi.org/10.1016/j.agee.2018.04.005.

Grant, L., Vanderkelen, I., Gudmundsson, L., Tan, Z., Perroud, M., Stepanenko, V. M., Debolskiy, A. V., Droppers, B., Janssen, A. B. G., Woolway, R. I., Choulga, M., Balsamo, G., Kirillin, G., Schewe, J., Zhao, F., del Valle, I. V., Golub, M., Pierson, D., Marcé, R., Seneviratne, S. I. and Thiery, W. (2021): Attribution of global lake systems change to anthropogenic forcing. Nature Geoscience 14 (11), 849–854. https://www.doi.org/10.1038/s41561-021-00833-x.

Grebot, B., Illes, A., Madzharova, G., Scarlat, A., Anderson, N. and Fribourg-Blanc, B. (2019): Urban Waste Water – Non-Connected Dwellings. Final Report. Copenhagen: European Environment Agency (EEA).

Grech-Madin, C., Döring, S., Kim, K. and Swain, A. (2018): Negotiating water across levels: A peace and conflict „Toolbox" for water diplomacy. Journal of Hydrology 559, 100–109. https://www.doi.org/10.1016/j.jhydrol.2018.02.008.

Greif, A. (2006): Institutions and the path to the modern economy: Lessons from medieval trade. New York, USA: Cambridge University Press.

Grieger, R., Capon, S. J., Hadwen, W. L. and Mackey, B. (2020): Between a bog and a hard place: a global review of climate change effects on coastal freshwater wetlands. Climatic Change 163 (1), 161–179. https://www.doi.org/10.1007/s10584-020-02815-1.

Griffith, A. W. and Gobler, C. J. (2020): Harmful algal blooms: A climate change co-stressor in marine and freshwater ecosystems. Harmful Algae 91, 101590. https://www.doi.org/10.1016/j.hal.2019.03.008.

Grigoratos, T. and Martini, G. (2015): Brake wear particle emissions: a review. Environmental Science and Pollution Research 22 (4), 2491–2504. https://www.doi.org/10.1007/s11356-014-3696-8.

Grimm, P. Y., Oliver, S., Merten, S., Han, W. W. and Wyss, K. (2022): Enhancing the Understanding of Resilience in Health Systems of Low- and Middle-Income Countries: A Qualitative Evidence Synthesis. International Journal of Health Policy and Management 11 (7), 899–911. https://www.doi.org/10.34172/ijhpm.2020.261.

Große Hüttmann, M. (2020): Deliberation. Europalexikon. Bonn: Bundeszentrale für politische Bildung (bpb). https://www.bpb.de/kurz-knapp/lexika/das-europalexikon/176777/deliberation/, accessed on 14.05.2024.

Gumbricht, T., Roman-Cuesta, R. M., Verchot, L., Herold, M., Wittmann, F., Householder, E., Herold, N. and Murdiyarso, D. (2017): An expert system model for mapping tropical wetlands and peatlands reveals South America as the largest contributor. Global Change Biology 23 (9), 3581–3599. https://www.doi.org/10.1111/gcb.13689.

Gupta, J., Liverman, D., Prodani, K., Aldunce, P., Bai, X., Broadgate, W., Ciobanu, D., Gifford, L., Gordon, C., Hurlbert, M., Inoue, C. Y. A., Jacobson, L., Kanie, N., Lade, S. J., Lenton, T. M., Obura, D., Okereke, C., Otto, I. M., Pereira, L., Rockström, J., Scholtens, J., Rocha, J., Stewart-Koster, B., David Tàbara, J., Rammelt, C. and Verburg, P. H. (2023): Earth system justice needed to identify and live within Earth system boundaries. Nature Sustainability 6 (6), 630–638. https://www.doi.org/10.1038/s41893-023-01064-1.

Gurreck, M. (2023): Informelle Administrativnormen im Unionsrecht. Baden-Baden: Nomos. https://doi.org/10.5771/9783748917724.

Gut and Bösel (2024): Unserere Arbeit. Briesen (Mark): Gut and Bösel,. https://www.gutundboesel.org/arbeiten/, accessed on 1.07.2024.

Gutiérrez, J. S., moore, J. N., Donnelly, J. P., Dorador, C., Navedo, J. G. and Senner, N. R. (2022): Climate change and lithium mining influence flamingo abundance in the Lithium Triangle. Proceedings of the Royal Society B: Biological Sciences 289 (1970), 20212388. https://www.doi.org/10.1098/rspb.2021.2388.

GWP – Global Water Partnership (1996): Dublin-Rio Principles. Stockholm: GWP.

GWP – Global Water Partnership (2019): Addressing Water in Na tional Adaptation Plans: Water Supplement to the UNFCCC NAP Technical Guidelines. Stockholm: GWP.

GWP – Global Water Partnership (2024a): What is the WEFE Nexus? Stockholm: GWP. https://www.gwp.org/en/sdg6support/iwrm-support/themes/water--energy--food--ecosystems-nexus/what-is-the-wefe-nexus/, accessed on 4.6.2024.

GWP – Global Water Partnership (2024b): National IWRM Plans. Stockholm: GWP. https://iwrmactionhub.org/fr/node/56, accessed on 3.07.2024.

H-BRS – Hochschule Bonn-Rhein-Sieg (2019): CitizenLab: Wieviel Wasser speichert mein Boden? H-BRS: Sankt Augustin. https://www.h-brs.de/de/news/citizenlab-wieviel-wasser-speichert-mein-boden, accessed on 10.05.2024.

Haapalehto, T. O., Vasander, H., Jauhiainen, S., Tahvanainen, T. and Kotiaho, J. S. (2011): The Effects of Peatland Restoration on Water-Table Depth, Elemental Concentrations, and Vegetation: 10 Years of Changes. Restoration Ecology 19 (5), 587–598. https://www.doi.org/10.1111/j.1526-100X.2010.00704.x.

Habel, M., Mechkin, K., Podgorska, K., Saunes, M., Babi-ski, Z., Chalov, S., Absalon, D., Podgórski, Z. and Obolewski, K. (2020): Dam and reservoir removal projects: a mix of social-ecological trends and cost-cutting attitudes. Scientific Reports 10 (1), 19210. https://doi.org/10.1038/s41598-020-76158-3.

Habermas, J. (1992): Faktizität and Geltung. Beiträge zur Diskurstheorie des Rechts and des demokratischen Rechtsstaats. Frankfurt am Main: Suhrkamp.

Hachfeld, D., Terhorst, P. and Hoedeman, O. (2009): Progressive Public Water Management in Europe. In search of exemplary cases. Amsterdam, Brussels: Transnational Institute (TNI), Corporate Europe Observatory (CEO). https://www.epsu.org/article/progressive-public-water-management-europe-search-exemplary-cases.

Hack, J., Siegel, K., Disse, M., Evers, M., Taft, L., Heinz, I., Schulte, A., Reinhardt-Imjela, C., Krois, J. and Breuer, L. (2017): Aktuelle Forschungsfragen and Herausforderungen bei der Umsetzung des Integrierten Wasserresourcenmanagements unter Wasserknappheit. Hydrologie and Wasserbewirtschaftung: HyWa 61 (3), 195–206. https://doi.org/10.26083/tuprints-00019877.

Haerdle, B. (2018): Durstiges Europa. Umwelt Perspektiven 725. Leipzig: Helmholtz-Zentrum für Umweltforschung (UFZ). http://www.schattenblick.de/infopool/umwelt/klima/uklfo725.html.

Haines, A. and Frumkin, H. (2021): Planetary health: safeguarding human health and the environment in the Anthropocene. Cambridge: Cambridge University Press.

Hajat, S., Proestos, Y., Araya-Lopez, J. L., Economou, T. and Lelieveld, J. (2023): Current and future trends in heat-related mortality in the MENA region: a health impact assessment with bias-adjusted statistically downscaled CMIP6 (SSP-based) data and Bayesian inference. Lancet Planet Health 7 (4), e282–e290. https://www.doi.org/10.1016/s2542-5196(23)00045-1.

Halkes, R. T., Hughes, A., Wall, F., Petavratzi, E., Pell, R. and Lindsay, J. J. (2024): Life cycle assessment and water use impacts of lithium production from salar deposits: Challenges and opportunities. Resources, Conservation & Recycling 207, 107554. https://www.doi.org/10.1016/j.resconrec.2024.107554.

Hall, N. (2024): Surviving Scarcity: Water and the Future of the Middle East. Washington, D.C.: Center for Strategic and International Studies (CSIS). https://features.csis.org/surviving-scarcity-water-and-the-future-of-the-middle-east/?trk=feed_main-feed-card_reshare_feed-article-content, published on 22.03.2024.

Hallegatte, S., Shah, A., Brown, C., Lempert, R. and Gill, S. (2012): Investment decision making under deep uncertainty--application to climate change. Washington, D.C.: World Bank. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2143067.

Hamadeh, N., van Rompaey, C., Metreau, E. and Eapen, S. G. (2022): New World Bank country classifications by income level: 2022-2023. World Bank: Washington, DC. https://blogs.worldbank.org/opendata/new-world-bank-country-classifications-income-level-2022-2023, accessed on 10.03.2023.

Hamidov, A., Kasymov, U., Djumaboev, K. and Paul, C. (2022): Rebound Effects in Irrigated Agriculture in Uzbekistan: A Stakeholder-Based Assessment. Sustainability 14 (14), 8375. https://www.doi.org/10.3390/su14148375.

Hammond, W. M., Williams, A. P., Abatzoglou, J. T., Adams, H. D., Klein, T., Lopez, R., Saenz-Romero, C., Hartmann, H., Breshears, D. D. and Allen, C. D. (2022): Global field observations of tree die-off reveal hotter-drought fingerprint for Earth's forests. Nature Communications 13 (1), 1761. https://www.doi.org/10.1038/s41467-022-29289-2.

Han, J., Wang, C., Deng, S. and Lichtfouse, E. (2023): China's sponge cities alleviate urban flooding and water shortage: a review. Environmental Chemistry Letters 21 (3), 1297–1314. https://doi.org/10.1007/s10311-022-01559-x.

Harlan, T. and Hennig, T. (2022): From mountains to megaregions: A powershed analysis of the Third Pole hydropower boom. Global Environmental Change 73, 102483. https://www.doi.org/10.1016/j.gloenvcha.2022.102483.

Harvey, G. L. and Henshaw, A. J. (2023): Rewilding and the water cycle. WIREs Water 10 (6), e1686. https://www.doi.org/10.1002/wat2.1686.

Haygarth, P. M., Condron, L. M., Heathwaite, A. L., Turner, B. L. and Harris, G. P. (2005): The phosphorus transfer continuum: Linking source to impact with an interdisciplinary and multi-scaled approach. Science of The Total Environment 344 (1), 5–14. https://doi.org/10.1016/j.scitotenv.2005.02.001.

HBS – Heinrich-Böll-Stiftung (2023): Wasser für die Landwirtschaft. HBS: Dresden. https://weiterdenken.de/de/2023/03/11/wasser-fuer-die-landwirtschaft, published on 11.03.2023.

He, C., Liu, Z., Wu, J., Pan, X., Fang, Z., Li, J. and Bryan, B. A. (2021): Future global urban water scarcity and potential solutions. Nature Communications 12, 4667. https://www.doi.org/10.1038/s41467-021-25026-3.

Heck, K., Blumstein, S. and Johnso, F. (2022): Promoting Water Tenure for Food Security, Climate Resilience and Equity. Berlin: adelphi research gGmbH. https://adelphi.de/system/files/mediathek/bilder/WT%20Workshop%20Report_final.pdf.

Heiberg, J. and Truffer, B. (2022): The emergence of a global innovation system – A case study from the urban water sector. Environmental Innovation and Societal Transitions 43, 270–288. https://doi.org/10.1016/j.eist.2022.04.007.

Heidler, A., Nesi, M., Nikiema, J. and Lüthi, C. (2023): Multilateral development banks investment behaviour in water and sanitation: findings and lessons from 60 years of investment projects in Africa and Asia. Journal of Water, Sanitation and Hygiene for Development 13 (5), 362–374. https://doi.org/10.2166/washdev.2023.004.

Helbig, M., Waddington, J. M., Alekseychik, P., Amiro, B. D., Aurela, M., Barr, A. G., Black, T. A., Blanken, P. D., Carey, S. K., Chen, J., Chi, J., Desai, A. R., Dunn, A., Euskirchen, E. S., Flanagan, L. B., Forbrich, I., Friborg, T., Grelle, A., Harder, S., Heliasz, M., Humphreys, E. R., Ikawa, H., Isabelle, P.-E., Iwata, H., Jassal, R., Korkiakoski, M., Kurbatova, J., Kutzbach, L., Lindroth, A., Löfvenius, M. O., Lohila, A., Mammarella, I., Marsh, P., Maximov, T., Melton, J. R., Moore, P. A., Nadeau, D. F., Nicholls, E. M., Nilsson, M. B., Ohta, T., Peichl, M., Petrone, R. M., Petrov, R., Prokushkin, A., Quinton, W. L., Reed, D. E., Roulet, N. T., Runkle, B. R. K., Sonnentag, O., Strachan, I. B., Taillardat, P., Tuittila, E.-S., Tuovinen, J.-P., Turner, J., Ueyama, M., Varlagin, A., Wilmking, M., Wofsy, S. C. and Zyrianov, V. (2020): Increasing contribution of peatlands to boreal evapotranspiration in a warming climate. Nature Climate Change 10 (6), 555–560. https://www.doi.org/10.1038/s41558-020-0763-7.

Heldt, S., Rodríguez-de-Francisco, J. C., Dombrowsky, I., Feld, C. K. and Karthe, D. (2017): Is the EU WFD suitable to support IWRM planning in non-European countries? Lessons learnt from the introduction of IWRM and River Basin Management in Mongolia. Environmental Science & Policy 75, 28–37. https://doi.org/10.1016/j.envsci.2017.05.009.

Heller, L., Karunananthan, M., Zwarteveen, M., Hall, D., Manahan, M. A. and Diouf, F. (2023): What water will the UN Conference carry forward: a fundamental human right or a commodity? The Lancet 402 (10404), 757–759. https://doi.org/10.1016/S0140-6736(23)01430-7.

Helmke, G. and Levitsky, S. (2004): Informal institutions and comparative politics: A research agenda. Perspectives on Politics 2 (4), 725–740. https://www.jstor.org/stable/3688540.

Helmrich, A., Chester, M., Miller, T. R. and Allenby, B. (2023): Lock-in: origination and significance within infrastructure systems. Environmental Research: Infrastructure and Sustainability 3 (3), 032001. https://www.doi.org/10.1088/2634-4505/acf7e6.

Hendryx, M., Zullig, K. J. and Luo, J. (2020): Impacts of Coal Use on Health. Annual Review of Public Health 41, 397–415. https://www.doi.org/10.1146/annurev-publhealth-040119-094104.

Henson, B. and Masters, J. (2023): The Libya floods: a climate and infrastructure catastrophe. New Haven, USA: Yale Climate Connections. https://yaleclimateconnections.org/2023/09/the-libya-floods-a-climate-and-infrastructure-catastrophe/, published on 13.09.2023.

Herbers, H. (2006): Handlungsmacht and Handlungsvermögen im Transformationsprozess : Schlussfolgerungen aus der Privatisierung der Landwirtschaft in Tadschikistan. Geographica Helvetica 61 (1), 13–20. https://doi.org/10.5194/gh-61-13-2006.

Herbert, C. and Döll, P. (2019): Global assessment of current and future groundwater stress with a focus on transboundary aquifers. Water Resources Research 55 (6), 4760–4784. https://doi.org/10.1029/2018WR023321.

Herman, F., De Doncker, F., Delaney, I., Prasicek, G. and Koppes, M. (2021): The impact of glaciers on mountain erosion. Nature Reviews Earth & Environment 2 (6), 422–435. https://www.doi.org/10.1038/s43017-021-00165-9.

Herrera-Garcia, G., Ezquerro, P., Tomas, R., Bejar-Pizarro, M., Lopez-Vinielles, J., Rossi, M., Mateos, R. M., Carreon-Freyre, D., Lambert, J., Teatini, P., Cabral-Cano, E., Erkens, G., Galloway, D., Hung, W. C., Kakar, N., Sneed, M., Tosi, L., Wang, H. and Ye, S. (2021): Mapping the global threat of land subsidence. Science 371 (6524), 34–36. https://www.doi.org/10.1126/science.abb8549.

Herrfahrdt-Pähle, E. (2010): South African water governance between administrative and hydrological boundaries. Climate and Development 2 (2), 111–127. https://www.doi.org/10.3763/cdev.2010.0038.

Herrfahrdt-Pähle, E., Scheumann, W., Houdret, A. and Dombrowsky, I. (2019): Freshwater as a Global Commons. International Governance and the Role of Germany. Bonn: Deutsches Institut für Entwicklungspolitik (DIE).

High Court of South Africa (2008): Mazibuko and Others v. City of Johannesburg and Others. Case No. 06/13865. Urteil vom 30.5.2008. Johannesburg: High Court of South Africa. https://www.saflii.org/za/cases/ZAGPHC/2008/491.pdf.

Hill-Lewis, G. (2023): Cape Town: Lessons from managing water scarcity. Washington, D.C.: Brookings Institution. https://www.brookings.edu/articles/cape-town-lessons-from-managing-water-scarcity/, published on 22.03.2023.

Hiller, C. X., Hübner, U., Fajnorova, S., Schwartz, T. and Drewes, J. E. (2019): Antibiotic microbial resistance (AMR) removal efficiencies by conventional and advanced wastewater treatment processes: A review. Science of the Total Environment 685, 596–608. https://doi.org/10.1016/j.scitotenv.2019.05.315.

Ho, J., Ahmadi, J., Schweikart, C., Hübner, U., Schwaller, C., Tiehm, A. and Drewes, J. E. (2024): Assuring reclaimed water quality using a multi-barrier treatment train according to the new EU non-potable water reuse regulation. Water Research, 122429. https://doi.org/10.1016/j.watres.2024.122429.

Hobbs, R. J., Higgs, E. and Harris, J. A. (2009): Novel ecosystems: implications for conservation and restoration. Trends in Ecology & Evolution 24 (11), 599–605. https://doi.org/10.1016/j.tree.2009.05.012.

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B. and Steltzer, H. (2019): High Mountain Areas. In: Pörtner, H.-O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B. and Weyer, N. M. (Hrsg.): IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge: Cambridge University Press, 131–202. https://www.doi.org/10.1017/9781009157964.004.

Hodgson, G. M. (2006): What are institutions? Journal of economic issues 40 (1), 1–25. https://doi.org/10.1080/00213624.2006.11506879.

Hoekstra, A. Y. and Hung, P. Q. (2002): Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade. Value of Water: Research Report Series 11. Delft, Niederlande: IHE Delft Institute for Water Education. https://www.waterfootprint.org/resources/Report11.pdf.

Hoekstra, A. Y., Chapagain, A., Aldaya, M. M. and Mekonnen, M. (2011): The water footprint assessment manual : setting the global standard. London, Washington, D.C: Routhledge.

Hoekstra, A. Y. and Mekonnen, M. M. (2012): The water footprint of humanity. Proceedings of the National Academy of Sciences (PNAS) 109 (9), 3232–3237. https://doi.org/10.1073/pnas.1109936109.

Horlemann, L. and Dombrowsky, I. (2012): Institutionalising IWRM in developing and transition countries: the case of Mongolia. Environmental Earth Sciences 65, 1547–1559. https://doi.org/10.1007/s12665-011-1213-7.

Hornidge, A.-K. and Scholtes, F. (2009): Waiting for the water to come? Poverty reduction in times of global climate change. Bonn: CARE Deutschland-Luxemburg e.V., Zentrum für Entwicklungsforschung (ZEF). https://nbn-resolving.org/urn:nbn:de:0168-ssoar-323148.

Hornidge, A.-K., Oberkircher, L., Tischbein, B., Schorcht, G., Bhaduri, A. and Manschadi, A. M. (2011): Reconceptualizing water management in Khorezm, Uzbekistan. Natural Resources Forum 35 (4), 251–268. https://doi.org/10.1111/j.1477-8947.2011.01391.x.

Hornidge, A.-K. and Scholtes, F. (2011): Climate Change and Everyday Life in Toineke Village, West Timor: Uncertainties, Knowledge and Adaptation. Sociologus 61 (2), 151–175. https://www.jstor.org/stable/43645696.

Hornidge, A.-K., Oberkircher, L. and Kudryavtseva, A. (2013): Boundary management and the discursive sphere–Negotiating 'realities' in Khorezm, Uzbekistan. Geoforum 45, 266–274. https://doi.org/10.1016/j.geoforum.2012.11.014.

Hornidge, A.-K., Oberkircher, L., Tischbein, B., Schorcht, G., Bhaduri, A., Awan, U. K. and Manschadi, A. M. (2016): Reconceptualising Water Management in Khorezm, Uzbekistan. In: Borchardt, D., Bogardi, J. J. and Ibisch, R. B. (Hrsg.): Integrated Water Resources Management: Concept, Research and Implementation. Basel: Springer Cham, 569–602. https://doi.org/10.1007/978-3-319-25071-7_22.

Hornidge, A.-K., McDonald-Bärtl, A. J. and Pieterse, E. (2023): Science and Digitalization for a Better Future. Issue Paper Think7 Advisory Process (Japan). Bonn: Deutsches Institut für Entwicklungspolitik (DIE).

Houdret, A. (2012): The Water Connection: Irrigation, Water Grabbing and Politics in Southern Morocco. Water Alternatives 5 (2), 284–303.

Houdret, A., Dombrowsky, I. and Horlemann, L. (2014): The institutionalization of River Basin Management as politics of scale–Insights from Mongolia. Journal of Hydrology 519, 2392–2404. https://doi.org/10.1016/j.jhydrol.2013.11.037.

Houdret, A. (2021): How Can Water Sector Cooperation Support Democratic Governance? Insights from Morocco. Middle East Law and Governance 13 (1), 72–97. https://doi.org/10.1163/18763375-13010004.

Houdret, A. and Amichi, H. (2022): The rural social contract in Morocco and Algeria: reshaping through economic liberalisation and new rules and practices. The Journal of North African Studies 27 (4), 641–662. https://doi.org/10.1080/13629387.2020.1848560.

Houdret, A. and Heinz, R. (2022): Groundwater governance through institutional bricolage? Participation in Morocco's Chtouka aquifer contract. Water International 47 (4), 565–582. https://doi.org/10.1080/02508060.2022.2049545.

Houdret, A. and von Lossow, T. (2023): Water crises – water opportunities: Promoting water cooperation in the Middle East. Clingendael Report. Den Haag: The Netherlands Institute of International Relations (Clingendael).

Hu, F. and Tan, D. (2018): No Water, No Growth – Does Asia have enough water to develop? Hong Kong: China Water Risk (CWR).

Huang, A.-J. (2022): Disclosable Restructuring Paper - Lusaka Sanitation Project - P149091 (English). Washington, D.C.: World Bank Group.

Hubbard, S. C., Meltzer, M. I., Kim, S., Malambo, W., Thornton, A. T., Shankar, M. B., Adhikari, B. B., Jeon, S., Bampoe, V. D. and Cunningham, L. C. (2020): Household illness and associated water and sanitation factors in peri-urban Lusaka, Zambia, 2016–2017. NPJ Clean Water 3 (1), 26. https://doi.org/10.1038/s41545-020-0076-4.

Huggins, X., Gleeson, T., Kummu, M., Zipper, S. C., Wada, Y., Troy, T. J. and Famiglietti, J. S. (2022): Hotspots for social and ecological impacts from freshwater stress and storage loss. Nature Communications 13 (1), 439. https://www.doi.org/10.1038/s41467-022-28029-w.

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., Brun, F. and Kääb, A. (2021): Accelerated global glacier mass loss in the early twenty-first century. Nature 592 (7856), 726–731. https://www.doi.org/10.1038/s41586-021-03436-z.

Hugron, S., Guêné-Nanchen, M., Roux, N., LeBlanc, M.-C. and Rochefort, L. (2020): Plant reintroduction in restored peatlands: 80 % successfully transferred – Does the remaining 20 % matter? Global Ecology and Conservation 22, e01000. https://www.doi.org/10.1016/j.gecco.2020.e01000.

Huinink, J. (2022): Messung von sozialer Ungleichheit. In: Baur, N. and Blasius, J. (Hrsg.): Handbuch Methoden der empirischen Sozialforschung. Wiesbaden: Springer, 1037–1049. https://doi.org/10.1007/978-3-531-18939-0_82.

Huitema, D. and Meijerink, S. V. (2017): The politics of river basin organisations: coalitions, institutional design choices and consequences. Ecology and Society 22 (2), 42. http://www.jstor.org/stable/26270064.

Hunzai, K., Gerlitz, J. and Hoermann, B. (2011): Understanding mountain poverty in the Hindu Kush-Himalayas: Regional report for Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan. Kathmandu, Nepal: International Centre for Integrated Mountain Development (ICIMOD). https://doi.org/10.53055/ICIMOD.553.

Huss, M. and Hock, R. (2018): Global-scale hydrological response to future glacier mass loss. Nature Climate Change 8 (2), 135–140. https://www.doi.org/10.1038/s41558-017-0049-x.

Hutton, G. and Varughese, M. C. (2016): The Costs of Meeting the 2030 Sustainable Development Goal Targets on Drinking Water Sanitation, and Hygiene. Water and Sanitation Program: Technical Paper 103171. Washington, D.C.: World Bank Group.

Ibisch, R. B., Bogardi, J. J. and Borchardt, D. (2016a): Integrated Water Resources Management: Concept, Research and Implementation. In: Borchardt, D., Bogardi, J. J. and Ibisch, R. B. (Hrsg.): Integrated Water Resources Management: Concept, Research and Implementation. Cham: Springer, 3–32. https://doi.org/10.1007/978-3-319-25071-7_1.

Ibisch, R. B., Leidel, M., Niemann, S., Hornidge, A.-K. and Goedert, R. (2016b): Capacity Development for Integrated Water Resources Management: Lessons Learned from Applied Research Projects. In: Borchardt, D., Bogardi, J. J. and Ibisch, R. B. (Hrsg.): Integrated Water Resources Management: Concept, Research and Implementation. Cham: Springer, 335–373. https://doi.org/10.1007/978-3-319-25071-7_14.

Iceland, C. and Black, C. (2023): UN Water Conference 2023: Not Enough Game-changing Commitments. Washington, D.C.: World Resources Institute (WRI). https://www.wri.org/insights/un-water-conference-2023-needed-outcomes, published on 30.03.2023.

ICIMOD – International Centre for Integrated Mountain Development (2023): Water, ice, society, and ecosystems in the Hindu Kush Himalaya: An outlook. [Wester, P., Chaudhary, S., Chettri, N., Jackson, M., Maharjan, A., Nepal, S. and Steiner, J. F. (eds.)]. Kathmandu, Nepal: ICIMOD. https://doi.org/10.53055/ICIMOD.1028.

ICJ – International Court of Justice (1997): GabCikovo-Nagymaros Project (Hungary/Slovakia), Judgment, I.C.J. Reports 1997, p. 7. Den Haag: ICJ. https://www.icj-cij.org/sites/default/files/case-related/92/092-19970925-JUD-01-00-EN.pdf.

IEEP - Institute for European Environmental Policy, Trinomics, IVM – Institute for Environmental Studies and UNEP-WCMC – United Nations Environment Programme World Conservation Monitoring Centre (2021): Methodology for assessing the impacts of trade agreements on biodiversity and ecosystems. Service contract for the European Commission (No 07.0202/2019/812941/SER/ENV.D.2). Brussels/London: IEEP. https://environment.ec.europa.eu/document/download/af910298-f32d-4c52-beb1-e7236a91d359_en?filename=Methodology-for-assessing-the-impacts-of-trade-agreements-on-biodiversity-and-ecosystems.pdf.

IFRS – International Financial Reporting Standards (2023): IFRS S2 Climate-related Disclosures with the TCFD Recommendations. London: IFRS. https://www.ifrs.org/content/dam/ifrs/supporting-implementation/ifrs-s2/ifrs-s2-comparison-tcfd-july2023.pdf.

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., Nepal, S., Pacheco, P., Painter, T. H., Pellicciotti, F., Rajaram, H., Rupper, S., Sinisalo, A., Shrestha, A. B., Viviroli, D., Wada, Y., Xiao, C., Yao, T. and Baillie, J. E. M. (2020): Importance and vulnerability of the world's water towers. Nature 577 (7790), 364–369. https://www.doi.org/10.1038/s41586-019-1822-y.

IPBES – Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2018a): The IPBES assessment report on land degradation and restoration. [Montanarella, L., Scholes, R., and Brainich, A. (eds.)]. Bonn: IPBES secretariat.

IPBES – Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2018b): The IPBES regional assessment report on biodiversity and ecosystem services for Europe and Central Asia [Rounsevell, M., Fischer, M., Torre-Marin Rando, A., Mader, A. (eds.)]. Bonn: IPBES secretariat.

IPBES – Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019a): Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Service [Brondízio, E. S., Settele, J., Díaz, S., Ngo, H. T (eds.)]. Bonn: IPBES secretariat. https://doi.org/10.5281/zenodo.3831673.

IPBES – Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019b): Zusammenfassung für politische Entscheidungsträger des globalen Assessments der biologischen Vielfalt and Ökosystemleistungen der Zwischenstaatlichen Plattform für Biodiversität and Ökosystemleistungen. In: Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Guèze, M., Agard, J., Arneth, A., Balvanera, P., Brauman, K. A., Butchart, S. H. M., Chan, K. M. A., Garibaldi, L. A., Ichii, K., Liu, J., Subramanian, S. M., Midgley, G. F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., Polasky, S., Purvis, A., Razzaque, J., Reyers, B., Roy Chowdhury, R., Shin, Y. J., Visseren-Hamakers, I. J., Willis, K. J. and Zayas, C. N. (Hrsg.): Globaler Bewertungsbericht über die biologische Vielfalt and Ökosystemleistungen. Bonn: IPBES secretariat, 1–56.

IPCC – Intergovernmental Panel on Climate Change (2019a): IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B. and Weyer, N.M. (eds.)]. Cambridge, UK and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157964.

IPCC – Intergovernmental Panel on Climate Change (2019b): Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D. C., Zhai, R. Slade, P., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M. and Malley, J. (eds.)]. Cambridge, UK and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157988.

IPCC – Intergovernmental Panel on Climate Change (2021a): Technical Summary. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B. (Hrsg.): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 33–144. https://www.doi.org/10.1017/9781009157896.002.

IPCC – Intergovernmental Panel on Climate Change (2021b): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B. (eds.)]. Cambridge, UK and New York, NY, USA: Cambridge University Press. https://www.doi.org/10.1017/9781009157896.

IPCC – Intergovernmental Panel on Climate Change (2021c): Summary for Policymakers. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B. (Hrsg.): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, 3–32. https://www.doi.org/10.1017/9781009157896.001.

IPCC – Intergovernmental Panel on Climate Change (2022a): Technical Summary. In: Pörtner, H.-O., Roberts, D. C., Poloczanska, E. S., Mintenbeck, K., Tignor, M., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A. and Rama, B. (Hrsg.): Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 37–118. https://www.doi.org/10.1017/9781009325844.002.

IPCC – Intergovernmental Panel on Climate Change (2022b): Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S. and Malley, J. (eds.)]. Cambridge, UK and New York, NY, USA: Cambridge University Press. https://www.doi.org/10.1017/9781009157926.

IPCC – Intergovernmental Panel on Climate Change (2022c): Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A. and Rama, B. (eds.)]. Cambridge, UK and New York, NY, USA: Cambridge University Press. https://www.doi.org/10.1017/9781009325844.

IPCC – Intergovernmental Panel on Climate Change (2023a): Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Lee, H. and Romero, J. (eds.)]. Geneva: IPCC. https://www.doi.org/10.59327/IPCC/AR6-9789291691647.

IPCC – Intergovernmental Panel on Climate Change (2023b): Summary for Policymakers. In: Lee, H. and Romero, J. (Hrsg.): Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: IPCC, 1–34. https://www.doi.org/10.59327/IPCC/AR6-9789291691647.001.

IPSF – International Platform on Sustainable Finance (2023): Annual Report 2023. https://finance.ec.europa.eu/document/download/cb307a8e-8b9a-4360-8dff-64110a6187d9_en?filename=231204-ipsf-annual-report_en.pdf.

ISC – International Science Council (2021): Unleashing Science: Delivering Missions for Sustainability. Paris: ISC. https://www.doi.org/10.24948/2021.04.

ISRIC – World Soil Information (2024): Green Water Credits (GWC). Wageningen: ISRIC. https://www.isric.org/projects/green-water-credits-gwc, accessed on 4.06.2024.

IUCN – International Union for Conservation of Nature (2021): Peatlands and Climate change. Gland, Schweiz: IUCN. https://www.iucn.org/sites/default/files/2022-04/iucn_issues_brief_peatlands_and_climate_change_final_nov21.pdf.

IWA – International Water Association (2022): Lessons Learnt: Regulating for Citywide Inclusive Sanitation. London: IWA.

IWMI – International Water Management Institute (2024): IWMI in Middle East and North Africa. Colombo, Sri Lanka: IWMI. https://www.iwmi.cgiar.org/about/where-we-work/iwmi-in-the-middle-east-and-north-africa/, accessed on 25.06.2024.

Jackson, M., Azam, M. F., Baral, P., Benestad, R., Brun, F., Muhammad, S., Pradhananga, S., Shrestha, F., Steiner, J. F. and Thapa, A. (2023): Consequences of climate change for the cryosphere in the Hindu Kush Himalaya. In: ICIMOD – International Centre for Integrated Mountain Development, Wester, P., Chaudhary, S., Chettri, N., Jackson, M., Maharjan, A., Nepal, S. and Steiner, J. F. (Hrsg.): Water, ice, society, and ecosystems in the Hindu Kush Himalaya: An outlook. Kathmandu, Nepal: ICIMOD, 17–71. https://doi.org/10.53055/ICIMOD.1030.

Jacobsen, D., Milner, A. M., Brown, L. E. and Dangles, O. (2012): Biodiversity under threat in glacier-fed river systems. Nature Climate Change 2 (5), 361–364. https://www.doi.org/10.1038/nclimate1435.

Jane, S. F., Hansen, G. J. A., Kraemer, B. M., Leavitt, P. R., Mincer, J. L., North, R. L., Pilla, R. M., Stetler, J. T., Williamson, C. E., Woolway, R. I., Arvola, L., Chandra, S., DeGasperi, C. L., Diemer, L., Dunalska, J., Erina, O., Flaim, G., Grossart, H. P., Hambright, K. D., Hein, C., Hejzlar, J., Janus, L. L., Jenny, J. P., Jones, J. R., Knoll, L. B., Leoni, B., Mackay, E., Matsuzaki, S. S., McBride, C., Muller-Navarra, D. C., Paterson, A. M., Pierson, D., Rogora, M., Rusak, J. A., Sadro, S., Saulnier-Talbot, E., Schmid, M., Sommaruga, R., Thiery, W., Verburg, P., Weathers, K. C., Weyhenmeyer, G. A., Yokota, K. and Rose, K. C. (2021): Widespread deoxygenation of temperate lakes. Nature 594 (7861), 66–70. https://www.doi.org/10.1038/s41586-021-03550-y.

Jasechko, S., Seybold, H., Perrone, D., Fan, Y., Shamsudduha, M., Taylor, R. G., Fallatah, O. and Kirchner, J. W. (2024): Rapid groundwater decline and some cases of recovery in aquifers globally. Nature 625, 715–721. https://www.doi.org/10.1038/s41586-023-06879-8.

Jeppesen, E., Beklio-lu, M. and Zadereev, E. (2023): The Effects of Global Climate Change on Water Level and Salinity: Causes and Effects. Water 15 (15), 2853. https://www.doi.org/10.3390/w15152853.

Jequier, E. and Constant, F. (2010): Water as an essential nutrient: the physiological basis of hydration. European Journal of Clinical Nutrition 64 (2), 115–123. https://www.doi.org/10.1038/ejcn.2009.111.

Jimenez, A. and Bray, B. (2022): Blending Water Management and Climate Change Adaptation Approaches. Copenhagen: UNEP-DHI Centre on Water and Environment.

Jin, H., Huang, Y., Bense, V. F., Ma, Q., Marchenko, S. S., Shepelev, V. V., Hu, Y., Liang, S., Spektor, V. V., Jin, X., Li, X. and Li, X. (2022): Permafrost Degradation and Its Hydrogeological Impacts. Water 14 (3), 372. https://www.doi.org/10.3390/w14030372.

Jin, Y., Behrens, P., Tukker, A. and Scherer, L. (2019a): Supplementary information: Water use of electricity technologies: A global meta-analysis. Renewable and Sustainable Energy Reviews 115, 1–41. https://www.doi.org/10.1016/j.rser.2019.109391.

Jin, Y., Behrens, P., Tukker, A. and Scherer, L. (2019b): Water use of electricity technologies: A global meta-analysis. Renewable and Sustainable Energy Reviews 115, 109391. https://www.doi.org/10.1016/j.rser.2019.109391.

Jin, Y., Hu, S., Ziegler, A. D., Gibson, L., Campbell, J. E., Xu, R., Chen, D., Zhu, K., Zheng, Y., Ye, B., Ye, F. and Zeng, Z. (2023): Energy production and water savings from floating solar photovoltaics on global reservoirs. Nature Sustainability 6 (7), 865–874. https://www.doi.org/10.1038/s41893-023-01089-6.

Jones, E. R., Bierkens, M. F., van Puijenbroek, P. J., van Beek, L. P., Wanders, N., Sutanudjaja, E. H. and van Vliet, M. T. (2023): Sub-Saharan Africa will increasingly become the dominant hotspot of surface water pollution. Nature Water 1, 602–613. https://doi.org/10.1038/s44221-023-00105-5.

Kačergytė, I., Arlt, D., Berg, Å., Żmihorski, M., Knape, J., Rosin, Z. M. and Pärt, T. (2021): Evaluating created wetlands for bird diversity and reproductive success. Biological Conservation 257, 109084. https://www.doi.org/10.1016/j.biocon.2021.109084.

Kagohashi, K., Tsurumi, T. and Managi, S. (2015): The effects of international trade on water use. PloS one 10 (7), e0132133. https://doi.org/10.1371/journal.pone.0132133.

Kahle, M. and Nöh, I. (2009): Biozide in Gewässern: Eintragspfade and Informationen zur Belastungssituation and deren Auswirkungen. UBA-Texte 09/2009. Dessau-Roßlau: Umweltbundesamt (UBA). https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/3811.pdf.

Kairigo, P., Ngumba, E., Sundberg, L.-R., Gachanja, A. and Tuhkanen, T. (2020): Contamination of Surface Water and River Sediments by Antibiotic and Antiretroviral Drug Cocktails in Low and Middle-Income Countries: Occurrence, Risk and Mitigation Strategies. Water 12 (5), 1376. https://www.doi.org/10.3390/w12051376.

Kalia, B. (2020): Water Crisis in Cities: The Case of 'Day Zero' in Chennai, India. Berlin: Technische Universität Berlin, International Conference on Sustainable Development 2020. https://ic-sd.org/wp-content/uploads/2020/11/Bhrigu-Kalia.pdf.

Kalisz, S., Kibort, K., Mioduska, J., Lieder, M. and Małachowska, A. (2022): Waste management in the mining industry of metals ores, coal, oil and natural gas - A review. Journal of Environmental Management 304, 114239. https://www.doi.org/10.1016/j.jenvman.2021.114239.

Karakurt, S., Schmid, L., Hübner, U. and Drewes, J. E. (2019): Dynamics of Wastewater Effluent Contributions in Streams and Impacts on Drinking Water Supply via Riverbank Filtration in Germany—A National Reconnaissance. Environmental Science & Technology 53 (11), 6154–6161. https://www.doi.org/10.1021/acs.est.8b07216.

Karakurt-Fischer, S., Sanz-Prat, A., Greskowiak, J., Ergh, M., Gerdes, H., Massmann, G., Ederer, J., Regnery, J., Hübner, U. and Drewes, J. E. (2020): Developing a novel biofiltration treatment system by coupling high-rate infiltration trench technology with a plug-flow porous-media bioreactor. Science of The Total Environment 722, 137890. https://doi.org/10.1016/j.scitotenv.2020.137890.

Karakurt-Fischer, S., Rien, C., Sanz-Prat, A., Szewzyk, R., Hübner, U., Drewes, J. E. and Selinka, H.-C. (2021): Fate and Transport of Viruses within a High-Rate Plug-Flow Biofilter Designed for Non-Membrane-Based Indirect Potable Reuse Applications. ACS ES&T Water 1 (5), 1229–1239. https://www.doi.org/10.1021/acsestwater.0c00305.

Karakurt-Fischer, S., Johnson, D. R., Fenner, K. and Hafner, J. (2023): Making waves: Enhancing pollutant biodegradation via rational engineering of microbial consortia. Water Res 247, 120756. https://www.doi.org/10.1016/j.watres.2023.120756.

Kaushal, S. S., Gold, A. J. and Mayer, P. M. (2017): Land Use, Climate, and Water Resources-Global Stages of Interaction. Water 9 (10), 815. https://www.doi.org/10.3390/w9100815.

Kaushal, S. S., Likens, G. E., Pace, M. L., Reimer, J. E., Maas, C. M., Galella, J. G., Utz, R. M., Duan, S., Kryger, J. R. and Yaculak, A. M. (2021): Freshwater salinization syndrome: From emerging global problem to managing risks. Biogeochemistry 154, 255–292. https://doi.org/10.1007/s10533-021-00784-w.

Kaushal, S. S., Likens, G. E., Mayer, P. M., Shatkay, R. R., Shelton, S. A., Grant, S. B., Utz, R. M., Yaculak, A. M., Maas, C. M., Reimer, J. E., Bhide, S. V., Malin, J. T. and Rippy, M. A. (2023): The anthropogenic salt cycle. Nature Reviews Earth & Environment 4 (11), 770–784. https://www.doi.org/10.1038/s43017-023-00485-y.

Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G., Nel, J. L., Mac Nally, R., Gregr, E. J., Watermeyer, K. E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C. E. R., Etter, A., Roux, D. J., Stark, J. S., Rowland, J. A., Brummitt, N. A., Fernandez-Arcaya, U. C., Suthers, I. M., Wiser, S. K., Donohue, I., Jackson, L. J., Pennington, R. T., Iliffe, T. M., Gerovasileiou, V., Giller, P., Robson, B. J., Pettorelli, N., Andrade, A., Lindgaard, A., Tahvanainen, T., Terauds, A., Chadwick, M. A., Murray, N. J., Moat, J., Pliscoff, P., Zager, I. and Kingsford, R. T. (2022): A function-based typology for Earth's ecosystems - Appendix S4. The IUCN Global Ecosystem Typology v2.1: Descriptive profile for Biomes and Ecosystem Functional Groups. Content version: v2.1, updated 2022-04-06. Nature, 513–518. https://www.doi.org/10.1038/s41586-022-05318-4.

Kelly, J. C., Wang, M., Dai, Q. and Winjobi, O. (2021): Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries. Resources, Conservation & Recycling 174, 105762. https://www.doi.org/10.1016/j.resconrec.2021.105762.

Kendzia, N. (2020): Bewässern nach Regeln - Wasserbedarf urbaner Grünflächen. Freising: Arbeitsgemeinschaft Landtechnik and Landwirtschaftliches Bauwesen in Bayern e.V. (ALB).

Keremane, B. and Mckay, B. (2007): Self-created Rules and Conflict Management Processes: The Case of Water Users' Associations on Waghad Canal in Maharashtra, India. International Journal of Water Resources Development 22 (4), 543–559. https://doi.org/10.1080/07900620600779673.

Keynoush, B. (2022): Severe sand and dust storms are an underrated risk in the Gulf region, despite mitigation measures. Washington, D.C.: Middle East Institute. https://www.mei.edu/publications/severe-sand-and-dust-storms-are-underrated-risk-gulf-region-despite-mitigation, published on 14.03.2022.

Khemka, R., Lopez, P. and Jensen, O. (2023): Scaling Up Finance for Water: A WBG Strategic Framework and Roadmap for Action. Washington, D.C.: World Bank Group.

Kim, E. A. and Hornidge, A.-K. (2016): IWRM in Uzbekistan: a global concept with local consequences. In: Ibisch, R. B., Bogardi, J. J. and Borchardt, D. (Hrsg.): Integrated Water Resources Management: Concept, Research and Implementation. Cham: Springer Nature, 201–219. https://doi.org/10.1007/978-3-319-25071-7_9.

King-Okumu, C. (2021): A rapid review of drought risk mitigation measures – Integrated drought management. Rome: Food and Agriculture Organization (FAO). https://doi.org/10.4060/cb7085en.

Kinna, R. and Rieu-Clarke, A. (2017): The Governance Regime of the Mekong River Basin. Can the Global Water Conventions Strengthen the 1995 Mekong Agreement? International Water Law 2 (1), 1–84. https://www.doi.org/10.1163/23529369-12340005.

Kirrane, E. F., Luben, T. J., Benson, A., Owens, E. O., Sacks, J. D., Dutton, S. J., Madden, M. and Nichols, J. L. (2019): A systematic review of cardiovascular responses associated with ambient black carbon and fine particulate matter. Environment International 127, 305–316. https://doi.org/10.1016/j.envint.2019.02.027.

Kirschner, A. (2020): Grenzüberschreitende Implikationen eines Menschenrechts auf Wasser? Heidelberg: Springer. https://doi.org/10.1007/978-3-662-60773-2.

Kittikhoun, A. and Staubli, D. M. (2018): Water diplomacy and conflict management in the Mekong: From rivalries to cooperation. Journal of Hydrology 567, 654–667. https://www.doi.org/10.1016/j.jhydrol.2018.09.059.

Klassen, S. and Evans, D. (2020): Top-down and bottom-up water management: A diachronic model of changing water management strategies at Angkor, Cambodia. Journal of Anthropological Archaeology 58, 101166. https://doi.org/10.1016/j.jaa.2020.101166.

Klinger, M., Gueye, A., Sherpa, A. M. and Strande, L. (2019): Scoping study: faecal sludge treatment plants in South-Asia and sub-Saharan Africa. Gates Open Res 3, 1716. https://doi.org/10.21955/gatesopenres.1116557.1.

Kloepfer, M. and Durner, W. (2020): Umweltschutzrecht. Munich: C.H. Beck.

Kloke-Lesch, A. and Hornidge, A.-K. (2023): Embrace Multipolarity: Germany Must Act European for the Global Common Good. Berlin: 49security. https://fourninesecurity.de/2023/01/26/embrace-multipolarity-germany-must-act-european-for-the-global-common-good, published on 25.01.2023.

Koelmans, A. A., Nor, N. H. M., Hermsen, E., Kooi, M., Mintenig, S. M. and De France, J. (2019): Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. Water Research 155, 410–422. https://www.doi.org/10.1016/j.watres.2019.02.054.

Kohler, C., Breninek, P. and Hasenauer, C. (2023): Wasserentnahmen in Bayern: Wie ahnungslos die Behörden sind. Munich: Bayerischer Rundfunk. https://www.br.de/nachrichten/bayern/wasserentnahmen-in-bayern-so-ahnungslos-sind-die-behoerden,TeRVVWD, published on 20.05.2023.

Komives, K., Foster, V., Halpern, J. and Wodon, Q. (2005): Water, electricity, and the poor: Who benefits from utility subsidies? Washington, D.C.: World Bank Publications. https://documents1.worldbank.org/curated/en/606521468136796984/pdf/343340REPLACEM10082136342501PUBLIC1.pdf.

Konapala, G., Mishra, A. K., Wada, Y. and Mann, M. E. (2020): Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. Nature Communications 11, 3044. https://www.doi.org/10.1038/s41467-020-16757-w.

Kosmowski, F. (2018): Soil water management practices (terraces) helped to mitigate the 2015 drought in Ethiopia. Agricultural Water Management 204, 11–16. https://www.doi.org/10.1016/j.agwat.2018.02.025.

Koutroulis, A., Papadimitriou, L., Grillakis, M., Tsanis, I., Warren, R. and Betts, R. (2019): Global water availability under high-end climate change: A vulnerability based assessment. Global and Planetary Change 175, 52–63. https://doi.org/10.1016/j.gloplacha.2019.01.013.

Kowarsch, M. (2012): Wie sollte die Nutzung des knappen Gutes Süßwasser geregelt werden? In: Maring, M. (Hrsg.): Globale öffentliche Güter in interdisziplinären Perspektiven. Band 5. Karlsruhe: Karlsruher Institut für Technologie (KIT), 161–178.

Kraaijenbrink, P. D., Stigter, E. E., Yao, T. and Immerzeel, W. W. (2021): Climate change decisive for Asia's snow meltwater supply. Nature Climate Change 11 (7), 591–597. https://doi.org/10.1038/s41558-021-01074-x.

Kraemer, B. M., Pilla, R. M., Woolway, R. I., Anneville, O., Ban, S., Colom-Montero, W., Devlin, S. P., Dokulil, M. T., Gaiser, E. E., Hambright, K. D., Hessen, D. O., Higgins, S. N., Jöhnk, K. D., Keller, W., Knoll, L. B., Leavitt, P. R., Lepori, F., Luger, M. S., Maberly, S. C., Müller-Navarra, D. C., Paterson, A. M., Pierson, D. C., Richardson, D. C., Rogora, M., Rusak, J. A., Sadro, S., Salmaso, N., Schmid, M., Silow, E. A., Sommaruga, R., Stelzer, J. A. A., Straile, D., Thiery, W., Timofeyev, M. A., Verburg, P., Weyhenmeyer, G. A. and Adrian, R. (2021): Climate change drives widespread shifts in lake thermal habitat. Nature Climate Change 11 (6), 521–529. https://www.doi.org/10.1038/s41558-021-01060-3.

Kreyling, J., Tanneberger, F., Jansen, F., van der Linden, S., Aggenbach, C., Blüml, V., Couwenberg, J., Emsens, W. J., Joosten, H., Klimkowska, A., Kotowski, W., Kozub, L., Lennartz, B., Liczner, Y., Liu, H., Michaelis, D., Oehmke, C., Parakenings, K., Pleyl, E., Poyda, A., Raabe, S., Röhl, M., Rücker, K., Schneider, A., Schrautzer, J., Schröder, C., Schug, F., Seeber, E., Thiel, F., Thiele, S., Tiemeyer, B., Timmermann, T., Urich, T., van Diggelen, R., Vegelin, K., Verbruggen, E., Wilmking, M., Wrage-Mönnig, N., Wołejko, L., Zak, D. and Jurasinski, G. (2021): Rewetting does not return drained fen peatlands to their old selves. Nature Communications 12 (1), 5693. https://www.doi.org/10.1038/s41467-021-25619-y.

Krishnamurthy, L., Krishnamurthy, P. K., Rajagopal, I. and Peralta Solares, A. (2019): Can agroforestry systems thrive in the drylands? Characteristics of successful agroforestry systems in the arid and semi-arid regions of Latin America. Agroforestry Systems 93 (2), 503–513. https://www.doi.org/10.1007/s10457-017-0143-0.

Kruk, M. E., Ling, E. J., Bitton, A., Cammett, M., Cavanaugh, K., Chopra, M., el-Jardali, F., Macauley, R. J., Muraguri, M. K., Konuma, S., Marten, R., Martineau, F., Myers, M., Rasanathan, K., Ruelas, E., Soucat, A., Sugihantono, A. and Warnken, H. (2017): Building resilient health systems: a proposal for a resilience index. BMJ 357, j2323. https://www.doi.org/10.1136/bmj.j2323.

Kumar, A., Kumar, A., Chaturvedi, A. K., Joshi, N., Mondal, R. and Malyan, S. K. (2023a): Greenhouse gas emissions from hydroelectric reservoirs: mechanistic understanding of influencing factors and future prospect. Environmental Science and Pollution Research, 1–18. https://www.doi.org/10.1007/s11356-023-25717-y.

Kumar, V., Singh, E., Singh, S., Pandey, A. and Bhargava, P. C. (2023b): Micro- and nano-plastics (MNPs) as emerging pollutant in ground water: Environmental impact, potential risks, limitations and way forward towards sustainable management. Chemical Engineering Journal 459, 141568. https://www.doi.org/10.1016/j.cej.2023.141568.

Kumar, V., Parihar, R. D., Sharma, A., Bakshi, P., Singh Sidhu, G. P., Bali, A. S., Karaouzas, I., Bhardwaj, R., Thukral, A. K., Gyasi-Agyei, Y. and Rodrigo-Comino, J. (2019): Global evaluation of heavy metal content in surface water bodies: A meta-analysis using heavy metal pollution indices and multivariate statistical analyses. Chemosphere 236, 124364. https://doi.org/10.1016/j.chemosphere.2019.124364.

Kumari, M. and Pulimi, M. (2023): Phthalate esters: occurrence, toxicity, bioremediation, and advanced oxidation processes. Water Science and Technology 87 (9), 2090–2115. https://www.doi.org/10.2166/wst.2023.119.

Kundzewicz, Z. W. (2008): Climate change impacts on the hydrological cycle. Ecohydrology & Hydrobiology 8 (2–4), 195–203. https://www.doi.org/10.2478/v10104-009-0015-y.

Kurian, M. (2017): The water-energy-food nexus: trade-offs, thresholds and transdisciplinary approaches to sustainable development. Environmental Science & Policy 68, 97–106. https://doi.org/10.1016/j.envsci.2016.11.006.

Kuzma, S., Saccoccia, L. and Chertock, M. (2023): 25 Countries, Housing One-quarter of the Population, Face Extremely High Water Stress. Washington, D.C.: World Resources Institute (WRI). https://www.wri.org/insights/highest-water-stressed-countries, published on 16.08.2023.

LADWP – Los Angeles Department of Water and Power (2024): Water System. Los Angeles: LADWP. https://www.ladwp.com/who-we-are/water-system, accessed on 20.06.2024.

Lafrenière, M. J. and Lamoureux, S. F. (2019): Effects of changing permafrost conditions on hydrological processes and fluvial fluxes. Earth-Science Reviews 191, 212–223. https://www.doi.org/10.1016/j.earscirev.2019.02.018.

Laghari, A. N., Abbasi, H. U., Aziz, A. and Kanasro, N. A. (2015): Impact analyses of upstream water infrastructure development schemes on downstream flow and sediment discharge and subsequent effect on Deltaic region. Sindh University Research Journal-SURJ (Science Series) 47 (4), 805–808.

Langer, M., von Deimling, T. S., Westermann, S., Rolph, R., Rutte, R., Antonova, S., Rachold, V., Schultz, M., Oehme, A. and Grosse, G. (2023): Thawing permafrost poses environmental threat to thousands of sites with legacy industrial contamination. Nature Communications 14 (1), 1721. https://www.doi.org/10.1038/s41467-023-37276-4.

Lardoux de Pazzis, A. and Muret, A. (2021): The role of intermediaries to facilitate water-related investment. OECD Environment Working Papers No. 180. Paris: Organisation for Economic Co-operation and Development (OECD). https://doi.org/10.1787/19970900.

Larsson, D. G. J. and Flach, C.-F. (2022): Antibiotic resistance in the environment. Nature Reviews Microbiology 20 (5), 257–269. https://www.doi.org/10.1038/s41579-021-00649-x.

Laskowski, S. R. (2010): Das Menschenrecht auf Wasser. Tübingen: Mohr Siebeck.

Lau, S. C. Y., Wilson, N. G., Golledge, N. R., Naish, T. R., Watts, P. C., Silva, C. N. S., Cooke, I. R., Allcock, A. L., Mark, F. C., Linse, K. and Strugnell, J. M. (2023): Genomic evidence for West Antarctic Ice Sheet collapse during the Last Interglacial. Science 382 (6677), 1384–1389. https://www.doi.org/10.1126/science.ade0664.

Laubenstein, H., Connor, R., Leflaive, X., Smythe, H., Dhot, N., Austin, M., Kjellén, M., Saleh, A. and Trombitcaia, I. (2023): Chapter 12: Financing. In: UNESCO – United Nations Educational Scientific and Cultural Organization (Hrsg.): The United Nations World Water Development Report 2023: Partnerships and cooperation for water. Paris: UNESCO, 162–171.

Lavenex, S. (2014): The power of functionalist extension: how EU rules travel. Journal of European Public Policy 21 (6), 885–903. https://www.doi.org/10.1080/13501763.2014.910818.

Laville, S., Leach, A. and Aguilar García, C. (2023): In charts: how privatisation drained Thames Water's coffers. London: The Guardian. https://www.theguardian.com/business/2023/jun/30/in-charts-how-privatisation-drained-thames-waters-coffers, published on 30.06.2023.

Law, A., Gaywood, M. J., Jones, K. C., Ramsay, P. and Willby, N. J. (2017): Using ecosystem engineers as tools in habitat restoration and rewilding: beaver and wetlands. Science of The Total Environment 605–606, 1021–1030. https://www.doi.org/10.1016/j.scitotenv.2017.06.173.

LAWA – Bund/Länder-Arbeitsgemeinschaft Wasser (2021): Auf dem Weg zur wassersensiblen Stadtentwicklung: Erfordernisse aus Sicht der Wasserwirtschaft. Berlin: Senatsverwaltung für Umwelt, Mobilität, Verbraucher- and Klimaschutz von Berlin.

LAWA – Bund/Länder-Arbeitsgemeinschaft Wasser (2022): Umgang mit Zielkonflikten bei der Anpassung der Wasserwirtschaft an den Klimawandel. Berlin: LAWA.

Lee, D., Gibson, J. M., Brown, J., Habtewold, J. and Murphy, H. M. (2023): Burden of disease from contaminated drinking water in countries with high access to safely managed water: A systematic review. Water Research 242, 120244. https://doi.org/10.1016/j.watres.2023.120244.

Lees, M., Knight, R. and Smith, R. (2022): Development and Application of a 1D Compaction Model to Understand 65 Years of Subsidence in the San Joaquin Valley. Water Resources Research 58 (6), e2021WR031390. https://www.doi.org/10.1029/2021WR031390.

Lepenies, P. and Sieler, S. (2010): Die Messung der mehrdimensionalen Armut – Was kann der neue Index? KFW-Development Research. Fokus Entwicklungspolitik Nr. 9. Frankfurt am Main: KfW Entwicklungsbank. https://www.kfw-entwicklungsbank.de/Download-Center/PDF-Dokumente-Development-Research/2010_11_FE_Lepenies-Messung-mehrdimensionale-Armut_D.pdf.

Levy, W., Pandelova, M., Henkelmann, B., Bernhöft, S., Fischer, N., Antritter, F. and Schramm, K.-W. (2017): Persistent organic pollutants in shallow percolated water of the Alps Karst system (Zugspitze summit, Germany). Science of The Total Environment 579, 1269–1281. https://doi.org/10.1016/j.scitotenv.2016.11.113.

LfU Bayern – Bayrisches Landesamt für Umwelt (2024): Wasser: Trinkwasserschutzgebiete - Kooperation mit Landwirten. Augsburg: LfU Bayern. https://www.lfu.bayern.de/wasser/trinkwasserschutzgebiete/kooperation_mit_landwirten/index.htm, accessed on 1.07.2024.

Li, C., Busquets, R. and Campos, L. C. (2020): Assessment of microplastics in freshwater systems: A review. Science of The Total Environment 707, 135578. https://www.doi.org/10.1016/j.scitotenv.2019.135578.

Libanda, B., Rand, E., Gyang, G. N., Sindano, C. T., Simwanza, L. and Chongo, M. (2024): Recent and future exposure of water, sanitation, and hygiene systems to climate-related hazards in Zambia. Journal of Water and Climate Change 15 (3), 958–977. https://doi.org/10.2166/wcc.2024.392.

Liess, M., Böhme, A., Gröning, J., Liebmann, L., Lück, M., Reemtsma, T., Römerscheid, M., Schade, U., Schwarz, B., Vormeier, P. and O., W. (2023): Belastung von kleinen Gewässern in der Agrarlandschaft mit Pflanzenschutzmittel-Rückständen – TV1 Datenanalyse zur Pilotstudie Kleingewässermonitoring 2018/2019. Dessau-Roßlau: Umweltbundesamt (UBA). https://www.umweltbundesamt.de/publikationen/belastung-von-kleinen-gewaessern-in-der-0.

Lima de Miranda, K. and Snower, D. J. (2020): Recoupling Economic and Social Prosperity. Global Perspectives 1 (1), 11867. https://doi.org/10.1525/001c.11867.

Lipp, H. P. and Lipp, A. (2022): Arzneimittelrückstände in Gewässern. Die Urologie 61 (11), 1208–1216. https://www.doi.org/10.1007/s00120-022-01934-0.

Liu, J., Yang, H., Cudennec, C., Gain, A. K., Hoff, H., Lawford, R., Qi, J., Strasser, L. d., Yillia, P. T. and Zheng, C. (2017): Challenges in operationalizing the water–energy–food nexus. Hydrological Sciences Journal 62 (11), 1714–1720. https://doi.org/10.1080/02626667.2017.1353695.

Liu, J., Mao, G., Hoekstra, A. Y., Wang, H., Wang, J., Zheng, C., van Vliet, M. T. H., Wu, M., Ruddell, B. and Yan, J. (2018): Managing the energy-water-food nexus for sustainable development. Applied Energy 210, 377–381. https://doi.org/10.1016/j.apenergy.2017.10.064.

Liu, L., Wang, W., Yan, X., Shen, M. and Chen, H. (2023): The cascade influence of grain trade shocks on countries in the context of the Russia-Ukraine conflict. Humanities and Social Sciences Communications 10, 449. https://www.doi.org/10.1057/s41599-023-01944-z.

Liu, P.-W., Famiglietti, J. S., Purdy, A. J., Adams, K. H., McEvoy, A. L., Reager, J. T., Bindlish, R., Wiese, D. N., David, C. H. and Rodell, M. (2022): Groundwater depletion in California's Central Valley accelerates during megadrought. Nature Communications 13 (1), 7825. https://doi.org/10.1038/s41467-022-35582-x.

Llamas, M. R. and Martínez-Santos, P. (2005): Intensive groundwater use:: Silent revolution and potential source of social conflicts. Journal of Water Resources Planning and Management 131 (5), 337–341. https://doi.org/10.1061/(ASCE)0733-9496(2005)131:5(337).

Lohrmann, A., Farfan, J., Lohrmann, C., Kölbel, J. F. and Pettersson, F. (2023): Troubled waters: Estimating the role of the power sector in future water scarcity crises. Energy 282, 128820. https://www.doi.org/10.1016/j.energy.2023.128820.

Loisel, J. and Gallego-Sala, A. (2022): Ecological resilience of restored peatlands to climate change. Communications Earth & Environment 3 (1), 208. https://www.doi.org/10.1038/s43247-022-00547-x.

Lone, S. A., Jeelani, G., Deshpande, R. D., Mukherjee, A., Jasechko, S. and Lone, A. (2021): Meltwaters dominate groundwater recharge in cold arid desert of Upper Indus River Basin (UIRB), western Himalayas. Science of The Total Environment 786, 147514. https://doi.org/10.1016/j.scitotenv.2021.147514.

Lötters-Viehof, S., Hilbrich, S., Berensmann, K., Artmann, G., Ashman, S., Herbold, T., Monti, A., Paffhausen, F., Roigk, S. and Steenkamp, L.-A. (2023): The Implementation of Sustainable Finance Taxonomies: Learning from South African Experiences. Bonn: German Institute of Development and Sustainability (IDOS). https://doi.org/10.23661/ipb20.2023.

Love, H. (2024): Fostering inclusive and sustainable agricultural innovation in California's Central Valley,. Washington, D.C.: Brookings Institution. https://www.brookings.edu/articles/fostering-inclusive-and-sustainable-agricultural-innovation-in-californias-central-valley/, published on 21.05.2024.

Ludwig, F., van Slobbe, E. and Cofino, W. (2014): Climate change adaptation and Integrated Water Resource Management in the water sector. Journal of Hydrology 518, 235–242. https://doi.org/10.1016/j.jhydrol.2013.08.010.

Lührmann, A. and Lindberg, S. I. (2019): A third wave of autocratization is here: what is new about it? Democratization 26 (7), 1095–1113. https://www.doi.org/10.1080/13510347.2019.1582029.

Lukat, E., Lenschow, A., Dombrowsky, I., Meergans, F., Schütze, N., Stein, U. and Pahl-Wostl, C. (2023): Governance towards coordination for water resources management: The effect of governance modes. Environmental Science & Policy 141, 50–60. https://doi.org/10.1016/j.envsci.2022.12.016.

Lüthi, C., Willetts, J. and Hoffmann, S. (2020): Editorial: City-Wide Sanitation: The Urban Sustainability Challenge. Frontiers in Environmental Science 8, 585418. https://doi.org/10.3389/fenvs.2020.585418.

Lutz, A. F., Immerzeel, W. W., Shrestha, A. B. and Bierkens, M. F. P. (2014): Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. Nature Climate Change 4 (7), 587–592. https://www.doi.org/10.1038/nclimate2237.

Luukkonen, H. (2013): Vesiosuuskunnat, kuntien vesihuoltolaitokset ja kunnat. (Water cooperatives, municipal water utilities and municipalities). Helsinki: Kuntaliiton verkkojulkaisu.

Lynch, A. J., Cooke, S. J., Arthington, A. H., Baigun, C., Bossenbroek, L., Dickens, C., Harrison, I., Kimirei, I., Langhans, S. D., Murchie, K. J., Olden, J. D., Ormerod, S. J., Owuor, M., Raghavan, R., Samways, M. J., Schinegger, R., Sharma, S., Tachamo-Shah, R. D., Tickner, D., Tweddle, D., Young, N. and Jähnig, S. C. (2023): People need freshwater biodiversity. WIREs Water 10 (3), e1633. https://www.doi.org/10.1002/wat2.1633.

Madaka, H., Babbitt, C. W. and Ryen, E. G. (2022): Opportunities for reducing the supply chain water footprint of metals used in consumer electronics. Resources, Conservation and Recycling 176, 105926. https://www.doi.org/10.1016/j.resconrec.2021.105926.

Madhav, R. (2009): Law and policy reforms for irrigation. In: Cullet, P., Gowlland Gualtieri, A., Madhav, R. and Ramanathan, U. (Hrsg.): Water Law for the Twenty-First Century. National and International Aspects of Water Law Reform in India. London, New York: Taylor and Francis, 205–234.

Mager, U. (2015): International Water Law: Global Developments and Regional Examples. Heidelberg: Jedermann-Verlag GmbH.

Magilligan, F. J., Nislow, K. H., Dietrich, J. T., Doyle, H. and Kynard, B. (2021): Transient versus sustained biophysical responses to dam removal. Geomorphology 389, 107836. https://doi.org/10.1016/j.geomorph.2021.107836.

Maharjan, A., McDowell, G., Pandey, A., Pasakhala, B., Shrestha, M. and Wang, X. (2023): Cryospheric change, adaptation, and sustainable development in the mountain societies of the Hindu Kush Himalaya. In: ICIMOD – International Centre for Integrated Mountain Development, Wester, P., Chaudhary, S., Chettri, N., Jackson, M., Maharjan, A., Nepal, S. and Steiner, J. F. (Hrsg.): Water, ice, society, and ecosystems in the Hindu Kush Himalaya: An outlook. Kathmandu, Nepal: ICIMOD, 165–217. https://doi.org/10.53055/ICIMOD.1033.

Makate, C., Wang, R., Makate, M. and Mango, N. (2017): Impact of drought tolerant maize adoption on maize productivity, sales and consumption in rural Zimbabwe. Agrekon 56 (1), 67–81. https://doi.org/10.1080/03031853.2017.1283241.

Makate, C. (2020): Local institutions and indigenous knowledge in adoption and scaling of climate-smart agricultural innovations among sub-Saharan smallholder farmers. International Journal of Climate Change Strategies and Management 12 (2), 270–287. https://doi.org/10.1108/IJCCSM-07-2018-0055.

Maleki, S., Soffianian, A. R., Koupaei, S. S., Pourmanafi, S. and Saatchi, S. (2018): Wetland restoration prioritizing, a tool to reduce negative effects of drought; An application of multicriteria-spatial decision support system (MC-SDSS). Ecological Engineering 112, 132–139. https://www.doi.org/10.1016/j.ecoleng.2017.12.031.

Manteca Vilanova, X., De Briyne, N., Beaver, B. and Turner, P. V. (2019): Horse Welfare During Equine Chorionic Gonadotropin (eCG) Production. Animals 9 (12), 1053. https://www.doi.org/10.3390/ani9121053x.

Markowska, J., Szalinska, W., Dabrowska, J. and Brzakala, M. (2020): The concept of a participatory approach to water management on a reservoir in response to wicked problems. Journal of Environmental Management 259, 109626. https://www.doi.org/10.1016/j.jenvman.2019.109626.

Maroufpoor, S., Bozorg-Haddad, O., Maroufpoor, E., Gerbens-Leenes, W., Loaiciga, H., Savic, D. and Singh, V. (2021): Optimal virtual water flows for improved food security in water-scarce countries. Scientific Reports 11, 1–18. https://www.doi.org/10.1038/s41598-021-00500-6.

Marston, L., Konar, M., Cai, X. and Troy, T. J. (2015): Virtual groundwater transfers from overexploited aquifers in the United States. Proceedings of the National Academy of Sciences 112 (28), 8561–8566. https://doi.org/10.1073/pnas.1500457112.

Martens, H. R., Laage, K., Eickmanns, M., Drexler, A., Heinsohn, V., Wegner, N., Muster, C., Diekmann, M., Seeber, E., Kreyling, J., Michalik, P. and Tanneberger, F. (2023): Paludiculture can support biodiversity conservation in rewetted fen peatlands. Scientific Reports 13, 18091. https://doi.org/10.1038/s41598-023-44481-0.

Martin-Ortega, J. (2023): We cannot address global water challenges without social sciences. Nature Water 1 (1), 2–3. https://doi.org/10.1038/s44221-022-00013-0.

Martínez-Santos, P., De Stefano, L., Llamas, M. R. and Martínez-Alfaro, P. E. (2008): Wetland Restoration in the Mancha Occidental Aquifer, Spain: A Critical Perspective on Water, Agricultural, and Environmental Policies. Restoration Ecology 16 (3), 511–521. https://www.doi.org/10.1111/j.1526-100X.2008.00410.x.

Martius, C., Froebrich, J. and Nuppenau, E.-A. (2009): Water Resource Management for Improving Environmental Security and Rural Livelihoods in the Irrigated Amu Darya Lowlands. In: Brauch, H. G., Spring, Ú. O., Grin, J., Mesjasz, C., Kameri-Mbote, P., Behera, N. C., Chourou, B. and Krummenacher, H. (Hrsg.): Facing Global Environmental Change: Environmental, Human, Energy, Food, Health and Water Security Concepts. Berlin, Heidelberg: Springer, 749–761. https://doi.org/10.1007/978-3-540-68488-6_57.

Masood, N., Hudson-Edwards, K. and Farooqi, A. (2020): True cost of coal: Coal mining industry and its associated environmental impacts on water resource development. Journal of Sustainable Mining 19 (3), 1–17. https://www.doi.org/10.46873/2300-3960.1012.

Matanzima, J. and Mosuoe-Tsietsi, T. (2023): Dam removal blind spots: debating the importance of community engagement in dam decommissioning projects. Frontiers in Water 5, 1–9. https://www.doi.org/10.3389/frwa.2023.1286128.

Mathioudakis, V., Gerbens-Leenes, P. W., Van der Meer, T. H. and Hoekstra, A. Y. (2017): The water footprint of second-generation bioenergy: A comparison of biomass feedstocks and conversion techniques. Journal of Cleaner Production 148, 571–582. https://doi.org/10.1016/j.jclepro.2017.02.032.

Maximilian, S., Alexandra, S., Josef, C., Susanne, B., Susanne, B. and Annette, P. (2023): Impact of Ambient Ultrafine Particles on Cause-Specific Mortality in Three German Cities. American Journal of Respiratory and Critical Care Medicine 207 (10), 1334–1344. https://www.doi.org/10.1164/rccm.202209-1837OC.

Mazhar, S., Pellegrini, E., Contin, M., Bravo, C. and De Nobili, M. (2022): Impacts of salinization caused by sea level rise on the biological processes of coastal soils - A review. Frontiers in Environmental Science 10, 909415. https://www.doi.org/10.3389/fenvs.2022.909415.

Mbengue, M. and Cima, E. (2023): „Giant Steps“: how technology is shaping international water law. In: Casado Pérez, V. and Larson, R. (Hrsg.): A Research Agenda for International Water Law. Cheltenham: Edward Elgar, 9–32. https://www.e-elgar.com/shop/gbp/a-research-agenda-for-water-law-9781802204469.html.

McCaffrey, S. C. and Sinjela, M. (1998): The 1997 United Nations Convention on International Watercourses. American Journal of International Law 92 (1), 97–107. https://www.doi.org/10.2307/2998069.

McDonald, R. I., Weber, K., Padowski, J., Flörke, M., Schneider, C., Green, P. A., Gleeson, T., Eckman, S., Lehner, B., Balk, D., Boucher, T., Grill, G. and Montgomery, M. (2014): Water on an urban planet: Urbanization and the reach of urban water infrastructure. Global Environmental Change 27, 96–105. https://doi.org/10.1016/j.gloenvcha.2014.04.022.

McGonigle, D. F., Harris, R. C., McCamphill, C., Kirk, S., Dils, R., Macdonald, J. and Bailey, S. (2012): Towards a more strategic approach to research to support catchment-based policy approaches to mitigate agricultural water pollution: A UK case-study. Environmental Science & Policy 24, 4–14. https://doi.org/10.1016/j.envsci.2012.07.016.

McKinlay, R., Plant, J. A., Bell, J. N. B. and Voulvoulis, N. (2008): Endocrine disrupting pesticides: Implications for risk assessment. Environment international 34 (2), 168–183. https://www.doi.org/10.1016/j.envint.2007.07.013.

Meehan, K., Mirumachi, N., Loftus, A. and Akhter, M. (2023): Water: A Critical Introduction. Hoboken (USA), Sussex (UK): John Wiley & Sons.

Meinzen-Dick, R. and Zwarteveen, M. (1998): Gendered participation in water management: Issues and illustrations from water users' associations in South Asia. Agriculture and Human Values 15, 337–345. https://doi.org/10.1023/A:1007533018254.

Meisch, S. P. (2019): I Want to Tell You a Story: How Narrative Water Ethics Contributes to Re-theorizing Water Politics. Water 11 (4), 631. https://doi.org/10.3390/w11040631.

Mekonnen, M. M., Gerbens-Leenes, P. W. and Hoekstra, A. Y. (2015): The consumptive water footprint of electricity and heat: a global assessment. Environmental Science: Water Research & Technology 1 (3), 285–297. https://www.doi.org/10.1039/c5ew00026b.

Mekonnen, M. M., Gerbens-Leenes, P. W. and Hoekstra, A. Y. (2016): Future electricity: The challenge of reducing both carbon and water footprint. Sci Total Environ 569–570, 1282–1288. https://www.doi.org/10.1016/j.scitotenv.2016.06.204.

Meldrum, J., Nettles-Anderson, S., Heath, G. and Macknick, J. (2013): Life cycle water use for electricity generation: a review and harmonization of literature estimates. Environmental Research Letters 8, 015031. https://www.doi.org/10.1088/1748-9326/8/1/015031.

Meli, P., Rey Benayas, J. M., Balvanera, P. and Martinez Ramos, M. (2014): Restoration enhances wetland biodiversity and ecosystem service supply, but results are context-dependent: a meta-analysis. PLoS One 9 (4), e93507. https://www.doi.org/10.1371/journal.pone.0093507.

Mendoza, G., Jeuken, A., Matthews, J., Stakhiv, E., Kucharski, J. and Gilroy, K. (2018): Climate Risk Informed Decision Analysis (CRIDA) - Collaborative Water Resources Planning for an Uncertain Future. Paris, Alexandria: United Nations Educational, Scientific and Cultural Organization (UNESCO), International Center for Integrated Water Resources Management (ICIWaRM).

MEP Water Group and EESC – European Economic and Social Committee (2023): Call to Adopt an Ambitious EU Blue Deal. There is no Green without Blue! Brussels: EU.

Meran, G., Siehlow, M. and von Hirschhausen, C. (2021a): Integrated Water Resource Management: Principles and Applications. In: Meran, G., Siehlow, M. and von Hirschhausen, C. (Hrsg.): The Economics of Water: Rules and Institutions. Cham: Springer International Publishing, 23–121. https://doi.org/10.1007/978-3-030-48485-9_3.

Meran, G., Siehlow, M. and von Hirschhausen, C. (2021b): The Economics of Water: Rules and Institutions. Cham: Springer Nature. https://www.doi.org/10.1007/978-3-030-48485-9.

Merz, B., Blöschl, G., Vorogushyn, S., Dottori, F., Aerts, J. C. J. H., Bates, P., Bertola, M., Kemter, M., Kreibich, H., Lall, U. and Macdonald, E. (2021): Causes, impacts and patterns of disastrous river floods. Nature Reviews Earth & Environment 2 (9), 592–609. https://www.doi.org/10.1038/s43017-021-00195-3.

Messager, M. L., Lehner, B., Cockburn, C., Lamouroux, N., Pella, H., Snelder, T., Tockner, K., Trautmann, T., Watt, C. and Datry, T. (2021): Global prevalence of non-perennial rivers and streams. Nature 594 (7863), 391–397. https://www.doi.org/10.1038/s41586-021-03565-5.

Michalak, A. M., Xia, J., Brdjanovic, D., Mbiyozo, A.-N., Sedlak, D., Pradeep, T., Lall, U., Rao, N. and Gupta, J. (2023): The frontiers of water and sanitation. Nature Water 1 (1), 10–18. https://doi.org/10.1038/s44221-022-00020-1.

Mie, A., Rudén, C. and Grandjean, P. (2018): Safety of Safety Evaluation of Pesticides: developmental neurotoxicity of chlorpyrifos and chlorpyrifos-methyl. Environmental Health 17 (1), 77. https://www.doi.org/10.1186/s12940-018-0421-y.

Mielke, K., Schetter, C. and Wilde, A. (2011): Dimensions of social order: Empirical fact, analytical framework and boundary concept. Working Paper Series 78. Bonn: Center for Development Research, University of Bonn.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P. and Stouffer, R. J. (2008): Stationarity Is Dead: Whither Water Management? Science 319 (5863), 573–574. https://www.doi.org/10.1126/science.1151915.

Minckley, T. A., Turner, D. S. and Weinstein, S. R. (2013): The relevance of wetland conservation in arid regions: A re-examination of vanishing communities in the American Southwest. Journal of Arid Environments 88, 213–221. https://www.doi.org/10.1016/j.jaridenv.2012.09.001.

Mirzabaev, A., Wu, J., Evans, J., García-Oliva, F., Hussein, I. A. G., Iqbal, M. H., Kimutai, J., Knowles, T., Meza, F., Nedjraoui, D., Tena, F., Türke-, M., Vázquez, R. J. and Welt, M. (2019): Desertification. In: Shukla, P. R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D. C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M. and Malley, J. (Hrsg.): Climate Change and Land: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Cambridge: Cambridge University Press, 249–344. https://doi.org/10.1017/9781009157988.005.

Mishra, A. K., Singh, J. and Mishra, P. P. (2023): Microplastics in freshwater ecosystem: A serious threat for freshwater environment. International Journal of Environmental Science and Technology 20, 9189–9204. https://www.doi.org/10.1007/s13762-022-04489-x.

Möckel, S., Gawel, E., Liess, M. and Neumeister, L. (2021): Pesticide tax in the EU – Various levy concepts and their impact. Leipzig: Helmholtz Centre for Environmental Research (UFZ). https://www.ufz.de/export/data/global/257265_Study%20Pesticide-Taxes%20(2021).pdf.

Moellenkamp, S., Lamers, M., Huesmann, C., Rotter, S., Pahl-Wostl, C., Speil, K. and Pohl, W. (2010): Informal Participatory Platforms for Adaptive Management. Insights into Niche-finding, Collaborative Design and Outcomes from a Participatory Process in the Rhine Basin. Ecology and Society 15 (4), 41. https://www.jstor.org/stable/26268234.

Mojiri, A., Zhou, J. L., Ohashi, A., Ozaki, N. and Kindaichi, T. (2019): Comprehensive review of polycyclic aromatic hydrocarbons in water sources, their effects and treatments. Science of The Total Environment 696, 133971. https://doi.org/10.1016/j.scitotenv.2019.133971.

Molden, D. J., Shrestha, A. B., Immerzeel, W. W., Maharjan, A., Rasul, G., Wester, P., Wagle, N., Pradhananga, S. and Nepal, S. (2022): The Great Glacier and Snow-Dependent Rivers of Asia and Climate Change: Heading for Troubled Waters. In: Biswas, A. K. and Tortajada, C. (Hrsg.): Water Security Under Climate Change. Singapore: Springer Singapore, 223–250. https://doi.org/10.1007/978-981-16-5493-0_12.

Molle, F. (2009): River-basin planning and management: The social life of a concept. Geoforum 40 (3), 484–494. https://doi.org/10.1016/j.geoforum.2009.03.004.

Mollinga, P. P., Dixit, A. and Athukorala, K. (2006) (Hrsg.): Integrated Water Resources Management: Global Theory, Emerging Practice and Local Needs. New Delhi: SAGE India.

Money, A. (2018): A Typology of Water Infrastructure Investors. WWC White Paper. Marseille: World Water Council (WWC).

Money, A. (2022): Blended Finance in the Water Sector: Challenges and Attributes. Marseille: World Water Council (WWC).

Mora, C., McKenzie, T., Gaw, I. M., Dean, J. M., von Hammerstein, H., Knudson, T. A., Setter, R. O., Smith, C. Z., Webster, K. M., Patz, J. A. and Franklin, E. C. (2022): Over half of known human pathogenic diseases can be aggravated by climate change. Nature Climate Change 12 (9), 869–875. https://www.doi.org/10.1038/s41558-022-01426-1.

Morgan Stanley (2023): 4 Ways to Invest in a Sustainable ‚Blue Economy'. New York: Morgan Stanley. https://www.morganstanley.com/ideas/blue-economy-investing-ocean-priorities, published on 11.04.2023.

Morin, J.-F. (2019): TRade and ENvironment Database (TREND) 2.0. Codebook. Quebec City, Canada: Canada Research Chair in International Political Economy Université Laval. https://www.chaire-epi.ulaval.ca/en/trend.

Mormina, M. (2019): Science, Technology and Innovation as Social Goods for Development: Rethinking Research Capacity Building from Sen's Capabilities Approach. Science and Engineering Ethics 25 (3), 671–692. https://www.doi.org/10.1007/s11948-018-0037-1.

Moss, T. M., Will; Guy, Simon; Marvin, Simon (2009): Organising Water: The Hidden Role of Intermediary Work. Water Alternatives 2 (1), 16–33. https://www.water-alternatives.org/index.php/alldoc/volume2/v2issue1/35-a2-1-2.

Mostert, E., Pahl-Wostl, C., Rees, Y., Searle, B., Tàbara, D. and Tippett, J. (2007): Social learning in European river-basin management: barriers and fostering mechanisms from 10 river basins. Ecology and society 12 (1), 19. https://www.jstor.org/stable/26267838.

MRC – Mekong River Commission (2001): Procedures for Data and Information Exchange and Sharing (PDIES). Phnom Penh, Kambodscha: MRC. https://faolex.fao.org/docs/pdf/mul212072.pdf.

MRC – Mekong River Commission (2021a): Basin Development Strategy for the Mekong River Basin 2021–2030 & MRC Strategic Plan 2021–2025. Phnom Penh, Kambodscha: MRC. https://reliefweb.int/attachments/ab08eed2-d948-31c2-988f-3143c2520108/BDP-2021-2030-SP-2021-2025_Final.pdf.

MRC – Mekong River Commission (2021b): Technical Guidelines on the Implementation of the Procedures for Water Quality. Phnom Penh, Kambodscha: MRC.

MRC – Mekong River Commission (2023): Guidelines for Transboundary Environmental Impact Assessment in the Lower Mekong River Basin (TbEIA). Phnom Penh, Kambodscha: MRC.

Mrozik, W., Rajaeifar, M. A., Heidrich, O. and Christensen, P. (2021): Environmental impacts, pollution sources and pathways of spent lithium-ion batteries. Energy & Environmental Science 14, 6099–6121. https://www.doi.org/10.1039/d1ee00691f.

Mukherjee, K. (2022): Water crisis: a case of Chennai. Journal of Sustainable Science and Transformative Research-Reviews & Letters 1 (2), 39–43.

Müller, S. (2000): Von der Mangel- zur Marktwirtschaft: Analyse der Konsumbedingungen and des Kosumverhaltens in der DDR. Leipzig: Institut für Marktforschung.

Mustapha, J. (2016): La gestion de l'eau agricole par les Associations d'Usagers de l'Eau Agricole (AUEA) et les questions de développement durable: Cas de l'oasis de Mezguita au Maroc. Dossiers de Recherches en Économie et Gestion 5 (1), 47–74. https://doi.org/10.34874/IMIST.PRSM/doreg-v5i1.15225.

NABU – Naturschutzbund Deutschland (2024): ANK – Warum trotz Klimakrise and Hochwasser schon wieder Kürzungen drohen. Berlin: NABU. https://blogs.nabu.de/naturschaetze-retten/ank/, published on 11.06.2024.

Namdar, R., Karami, E. and Keshavarz, M. (2021): Climate Change and Vulnerability: The Case of MENA Countries. ISPRS International Journal of Geo-Information 10 (11), 794. https://www.doi.org/10.3390/ijgi10110794.

Namgay, K., Millar, J. E., Black, R. S. and Samdup, T. (2014): Changes in Transhumant Agro-pastoralism in Bhutan: A Disappearing Livelihood? Human Ecology 42 (5), 779–792. https://doi.org/10.1007/s10745-014-9684-2.

NAP Global Network (2020): The National Adaptation Plan (NAP) Process: Frequently Asked Questions. Winnipeg: International Institute for Sustainable Development (IISD). https://napglobalnetwork.org/2019/12/the-national-adaptation-plan-nap-process-frequently-asked-questions/.

Narayan, A. S., Marks, S. J., Meierhofer, R., Strande, L., Tilley, E., Zurbrügg, C. and Lüthi, C. (2021): Advancements in and integration of water, sanitation, and solid waste for low- and middle-income countries. Annual review of environment and resources 46, 193–219. https://doi.org/10.1146/annurev-environ-030620-042304.

Nathanson, J. A. (2023): The Pollution Problem. Edinburgh: Encyclopædia Britannica, Inc. https://www.britannica.com/explore/savingearth/pollution-overview, accessed on 7.11.2023.

Naturpark NLH – Naturpark Niederlausitzer Heidelandschaft (2024): Landschaftswandel im Auftrag der Wissenschaft. Bad Liebenwerda: Naturpark NLH. https://naturpark-nlh.de/lasswissen, accessed on 10.05.2024.

Naughten, K. A., Holland, P. R. and De Rydt, J. (2023): Unavoidable future increase in West Antarctic ice-shelf melting over the twenty-first century. Nature Climate Change 13 (11), 1222–1228. https://www.doi.org/10.1038/s41558-023-01818-x.

Neef, C., Schmaltz, T. and Thielmann, A. (2021): Recycling von Lithium-Ionen-Batterien: Chancen and Herausforderungen für den Maschinen- and Anlagenbau. Frankfurt: IMPULS Stiftung für den Maschinenbau, den Anlagenbau and die Informationstechnik.

Negrello, M. (2022): Designing with Nature Climate-Resilient Cities: A Lesson from Copenhagen. In: Arbizzani, E., Cangelli, E., Clemente, C., Cumo, F., Giofrè, F., Giovenale, A. M., Palme, M. and Paris, S. (Hrsg.): International Conference on Technological Imagination in the Green and Digital Transition. Cham: Springer, 853–862. https://doi.org/10.1007/978-3-031-29515-7_76.

Nepal, S., Steiner, J. F., Allen, S., Azam, M. F., Bhuchar, S., Biemans, H., Dhakal, M., Khanal, S., Li, D., Lutz, A., Pradhananga, S., Ritzema, R., Stoffel, M. and Stuart-Smith, R. (2023): Consequences of cryospheric change for water resources and hazards in the Hindu Kush Himalaya. In: ICIMOD – International Centre for Integrated Mountain Development, Wester, P., Chaudhary, S., Chettri, N., Jackson, M., Maharjan, A., Nepal, S. and Steiner, J. F. (Hrsg.): Water, ice, society, and ecosystems in the Hindu Kush Himalaya: An outlook. Kathmandu, Nepal: ICIMOD, 73–121. https://doi.org/10.53055/ICIMOD.1031.

Nhim, T. and Richter, A. (2022): Path dependencies and institutional traps in water governance-Evidence from Cambodia. Ecological Economics 196, 107391. https://doi.org/10.1016/j.ecolecon.2022.107391.

Nie, Y., Pritchard, H. D., Liu, Q., Hennig, T., Wang, W., Wang, X., Liu, S., Nepal, S., Samyn, D., Hewitt, K. and Chen, X. (2021): Glacial change and hydrological implications in the Himalaya and Karakoram. Nature Reviews Earth & Environment 2 (2), 91–106. https://www.doi.org/10.1038/s43017-020-00124-w.

Nie, Y., Deng, Q., Pritchard, H. D., Carrivick, J. L., Ahmed, F., Huggel, C., Liu, L., Wang, W., Lesi, M., Wang, J., Zhang, H., Zhang, B., Lu, Q. and Zhang, Y. (2023): Glacial lake outburst floods threaten Asia's infrastructure. Science Bulletin 68 (13), 1361–1365. https://www.doi.org/10.1016/j.scib.2023.05.035.

Nielsen, H. Ø., Konrad, M. T. H., Pedersen, A. B. and Gyldenkærne, S. (2023): Ex-post evaluation of the Danish pesticide tax: A novel and effective tax design. Land Use Policy 126, 106549. https://doi.org/10.1016/j.landusepol.2023.106549.

Niemeijer, D., Puigdefabregas, J., White, R., Lal, R., Winslow, M., Ziedler, J., Prince, S., Archer, E. and King, C. (2005): Dryland Systems. In: Hassan, R., Scholes, R. and Ash, N. (Hrsg.): Ecosystems and Human Well-being: Current State and Trends, Volume 1. Washington, DC: Island Press, 623–662.

Nijnens, J., Behrens, P., Kraan, O., Sprecher, B. and Kleijn, R. (2023): Energy transition will require substantially less mining than the current fossil system. Joule 7 (11), 2408–2413. https://www.doi.org/10.1016/j.joule.2023.10.005.

Nolan, R. H., Anderson, L. O., Poulter, B. and Varner, J. M. (2022): Increasing threat of wildfires: the year 2020 in perspective: A Global Ecology and Biogeography special issue. Global Ecology and Biogeography 31 (10), 1898–1905. https://doi.org/10.1111/geb.13588.

Nord, M., Lundstedt, M., Altman, D., Angiolillo, F., Borella, C., Fernandes, T., Gastaldi, L., Good God, A., Natsika, N. and Lindberg, S. I. (2024): Democracy Report 2024: Democracy Winning and Losing at the Ballot. Göteburg, Schweden: Varieties of Democracy Institute (V-Dem).

North, D. C. (1991): Institutions. Journal of economic perspectives 5 (1), 97–112. https://www.doi.org/10.1257/jep.5.1.97.

Northey, S. A., Mudd, G. M., Werner, T. T., Jowitt, S. M., Haque, N., Yellishetty, M. and Weng, Z. (2017): The exposure of global base metal resources to water criticality, scarcity and climate change. Global Environmental Change 44, 109–124. https://www.doi.org/10.1016/j.gloenvcha.2017.04.004.

Noureddine, G., Eslamian, S. and Katlane, R. (2021): Integrated Water Resources Management and Climate Change. International Journal Water Sciences and Environment Technologies I (1), 89–103.

Nowack, D. and Leininger, J. (2022): Protecting democracy from abroad: democracy aid against attempts to circumvent presidential term limits. Democratization 29 (1), 154–173. https://www.doi.org/10.1080/13510347.2021.1957840.

NRW.Bank – Förderbank für Nordrhein-Westfalen (2024): Grüne Emscher-Lippe. Düsseldorf: NRW.Bank. https://www.nrwbank.de/de/foerderung/foerderprodukte/60014/nrwbank-gruene-emscher-lippe.html, accessed on 16.05.2024.

NWB Bank – Nederlandse Waterschapsbank (2024): About NWB Bank. NWB Bank: dedicated, committed and reliable. Den Haag: NWB Bank. https://nwbbank.com/en/about-nwb-bank, accessed on 1.06.2024.

Oaks, J. L., Gilbert, M., Virani, M. Z., Watson, R. T., Meteyer, C. U., Rideout, B. A., Shivaprasad, H. L., Ahmed, S., Iqbal Chaudhry, M. J., Arshad, M., Mahmood, S., Ali, A. and Ahmed Khan, A. (2004): Diclofenac residues as the cause of vulture population decline in Pakistan. Nature 427, 630–633. https://www.doi.org/10.1038/nature02317.

Obasi, P. N. and Akudinobi, B. B. (2020): Potential health risk and levels of heavy metals in water resources of lead–zinc mining communities of Abakaliki, southeast Nigeria. Applied Water Science 10, 184. https://www.doi.org/10.1007/s13201-020-01233-z.

Oberhauser, D., Hägele, R. and Dombrowsky, I. (2023): Unravelling hidden factors explaining competition for and overuse of groundwater in Azraq, Jordan: digging deeper into a network of action situations. Sustainability Science 18 (1), 235–249. https://doi.org/10.1007/s11625-022-01135-w.

Oberkircher, L. and Hornidge, A.-K. (2011): "Water Is Life"—Farmer Rationales and Water Saving in Khorezm, Uzbekistan: A Lifeworld Analysis. Rural Sociology 76 (3), 394–421. https://doi.org/10.1111/j.1549-0831.2011.00054.x.

OECD – Organisation for Economic Co-operation and Development and WEF – World Economic Forum (2015): Blended Finance Vol. 1: A Primer for Development Finance and Philanthropic Funders: An overview of the strategic use of development finance and philanthropic funds to mobilize private capital for development. Geneva: WEF.

OECD – Organisation for Economic Co-operation and Development (2018): International experience with water abstraction and pollution charge. In: OECD (Hrsg.): Facilitating the Reform of Economic Instruments for Water Management in Georgia. Paris: OECD, 81–86. https://doi.org/10.1787/9789264281776-10-en.

OECD – Organisation for Economic Co-operation and Development (2019a): Making Blended Finance Work for Water and Sanitation: Unlocking Commercial Finance for SDG 6 – Policy Highlights. Paris: OECD.

OECD – Organisation for Economic Co-operation and Development (2019b): Trade and the environment. Paris: OECD. https://issuu.com/oecd.publishing/docs/trade_and_the_environment.

OECD – Organisation for Economic Co-operation and Development (2021): Toolkit for Water Policies and Governance: Converging Towards the OECD Council Recommendation on Water. Paris: OECD. https://doi.org/10.1787/ed1a7936-en.

OECD – Organisation for Economic Co-operation and Development (2022a): Financing a Water Secure Future. OECD Studies on Water. Paris: OECD. https://doi.org/10.1787/a2ecb261-en.

OECD – Organisation for Economic Co-operation and Development (2022b): Global Plastics Outlook: Policy Scenarios to 2060. Paris: OECD. https://www.doi.org/10.1787/aa1edf33-en.

OECD – Organisation for Economic Co-operation and Development (2024): Recommendation of the Council on Countering the Illegal Trade of Pesticides. OECD/LEGAL/0446. Paris: OECD.

Oladele, O. I. and Amara, A. (2024): Farmers' use of Indigenous knowledge on climate change adaptation across farming systems and agroecological zones of Sierra Leone. AlterNative: An International Journal of Indigenous Peoples 0 (0), 1–11. https://www.doi.org/10.1177/11771801241251862.

OÖ Wasser – OÖ Wasser Genossenschaftsverband (2024a): Wassergenossenschaft: Ziel einer Wassergenossenschaft. Linz: OÖ Wasser. https://www.ooewasser.at/de/genossenschaften.html, accessed on 7.02.2024.

OÖ Wasser – OÖ Wasser Genossenschaftsverband (2024b): Daten zur Wassergenossenschaft Gramastetten. Linz: OÖ Wasser. https://www.ooewasser.at/de/wassergenossenschaft/wassergenossenschaft.gramastetten.html, accessed on 5.03.2024.

Oppenheimer, M., Glavovic, B. C., Hinkel, J., van de Wal, R., Magnan, A. K., Abd-Elgawad, A., Cai, R., CifuentesJara, M., DeConto, R. M., Ghosh, T., Hay, J., Isla, F., Marzeion, B., Meyssignac, B. and Sebesvari, Z. (2019): Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: Pörtner, H.-O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B. and Weyer, N. M. (Hrsg.): IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge, UK and New York, NY, USA: Cambridge University Press, 321–445. https://doi.org/10.1017/9781009157964.006.

Osofsky, S. A. and Pongsiri, M. J. (2018): Operationalising planetary health as a game-changing paradigm: health impact assessments are key. The Lancet Planetary Health 2 (2), e54–e55. https://www.doi.org/10.1016/S2542-5196(17)30183-3.

Ostrom, E. and Gardner, R. (1993): Coping with Asymmetries in the Commons: Self-Governing Irrigation Systems Can Work. Journal of Economic Perspectives 7 (4), 93–112. https://www.doi.org/10.1257/jep.7.4.93.

Our World in Data (2023): The global Multidimensional Poverty Index (MPI) 2023. Oxford: Our World in Data, University of Oxford. https://ourworldindata.org/grapher/share-multi-poverty, accessed on 4.07.2024.

Ozment, S. and Feltran-Barbieri, R. (2018): Help for São Paulo's Complex Water Woes: Protect and Restore Forests. Washington, D.C.: World Resources Institute (WRI). https://www.wri.org/insights/help-sao-paulos-complex-water-woes-protect-and-restore-forests, published on 25.09.2018.

Pacific Institute (2023): Water Conflict Chronology. Oakland: Pacific Institute. https://www.worldwater.org/conflict/list/, accessed on 17.02.2024.

Pahl-Wostl, C., Isendahl, N., Möllenkamp, S., Brugnach, M., Jeffrey, P., Medema, W. and Tessa de Vries, T. (2006): Paradigms in Water Management. Deliverable No. 1.12. Osnabrück: NeWater project.

Pahl-Wostl, C. (2007): Transitions towards adaptive management of water facing climate and global change. Water resources management 21, 49–62. https://doi.org/10.1007/s11269-006-9040-4.

Pahl-Wostl, C., Craps, M., Dewulf, A., Mostert, E., Tabara, D. and Taillieu, T. (2007): Social learning and water resources management. Ecology and society 12 (2), 5. http://www.jstor.org/stable/26267868.

Pahl-Wostl, C. (2008): Requirements for adaptive water management. In: Pahl-Wostl, C., Kabat, P. and Möltgen, J. (Hrsg.): Adaptive and integrated water management: Coping with complexity and uncertainty. Berlin, Heidelberg: Springer, 1–22. https://doi.org/10.1007/978-3-540-75941-6_1.

Pahl-Wostl, C. (2019): Governance of the water-energy-food security nexus: A multi-level coordination challenge. Environmental Science & Policy 92, 356–367. https://doi.org/10.1016/j.envsci.2017.07.017.

Pahl-Wostl, C. and Knieper, C. (2023): Pathways towards improved water governance: The role of polycentric governance systems and vertical and horizontal coordination. Environmental Science & Policy 144, 151–161. https://doi.org/10.1016/j.envsci.2023.03.011.

Paisley, K., Weiler, P. and Henshaw, T. (2016): Trans-boundary water governance through the prism of the Mekong River Basin. In: Gray, J., Holley, C. and Rayfuse, R. (Hrsg.): Trans-jurisdictional Water Law and Governance. London: Routledge, 43–61.

Pandit, M. K. and Grumbine, R. E. (2012): Potential effects of ongoing and proposed hydropower development on terrestrial biological diversity in the Indian Himalaya. Conserv Biol 26 (6), 1061–1071. https://www.doi.org/10.1111/j.1523-1739.2012.01918.x.

Pannke, D., Schwan, G., Gerards Iglesias, L., Krabbe, J. and Sabo, K. (2024): Kommunaler Entwicklungsbeirat - Konzept and Praxis. Berlin: Berlin Governance Platform. https://www.governance-platform.org/publikation-entwicklungsbeiraete/.

Parmesan, C., Morecroft, M. D., Trisurat, Y., Adrian, R., Anshari, G. Z., Arneth, A., Gao, Q., Gonzalez, P., Harris, R., Price, J., Stevens, N. and Talukdar, G. H. (2022): Terrestrial and Freshwater Ecosystems and their Services. In: Pörtner, H.-O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A. and Rama, B. (Hrsg.): Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press, 197–377. https://www.doi.org/10.1017/9781009325844.004.

Pascale, S., Kapnick, S. B., Delworth, T. L. and Cooke, W. F. (2020): Increasing risk of another Cape Town "Day Zero" drought in the 21st century. Proceedings of the National Academy of Sciences 117 (47), 29495–29503. https://doi.org/10.1073/pnas.2009144117.

Paszkiewicz, M., Godlewska, K., Lis, H., Caban, M., Białk-Bieli-ska, A. and Stepnowski, P. (2022): Advances in suspect screening and non-target analysis of polar emerging contaminants in the environmental monitoring. TrAC Trends in Analytical Chemistry 154, 116671. https://doi.org/10.1016/j.trac.2022.116671.

Paton, E., Kluge, B. and Nehls, T. (2021): Ein Reallabor für die wassersensible Stadtentwicklung. Projektbericht Hydrologische Notizen. Hydrologie and Wasserwirtschaft 65 (H3), 126–131.

Pattberg, P. and Widerberg, O. (2015): Global environmental governance. In: Pattberg, P. and Zelli, F. (Hrsg.): Encyclopedia of Global Environmental Governance and Politics. Cheltenham: Edward Elgar, 28–35.

Paul, E., Bessière, Y., Dumas, C. and Girbal-Neuhauser, E. (2021): Biopolymers Production from Wastes and Wastewaters by Mixed Microbial Cultures: Strategies for Microbial Selection. Waste Biomass Valor 12, 4213–4237. https://www.doi.org/10.1007/s12649-020-01252-6.

Payne, J., Connor, R. and Chaves Pacheco, S. M. (2024): Energy. In: Nations, U. (Hrsg.): The United Nations World Water Development Report 2024: Water for Prosperity and Peace. Paris: UNESCO, 61–72.

PCA – Permanent Court of Arbitration (2023): PCA Press Release: Proceedings under the Indus Waters Treat (PCA Case No. 2023-01). Den Haag: PCA. https://pca-cpa.org/en/news/pca-press-release-pca-case-no-2023-01-proceedings-under-the-indus-waters-treaty/, published on 6.07.2023.

Pecl, G. T., Araujo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I. C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengard, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., Lenoir, J., Linnetved, H. I., Martin, V. Y., McCormack, P. C., McDonald, J., Mitchell, N. J., Mustonen, T., Pandolfi, J. M., Pettorelli, N., Popova, E., Robinson, S. A., Scheffers, B. R., Shaw, J. D., Sorte, C. J., Strugnell, J. M., Sunday, J. M., Tuanmu, M. N., Verges, A., Villanueva, C., Wernberg, T., Wapstra, E. and Williams, S. E. (2017): Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. Science 355 (6332), 1–9. https://www.doi.org/10.1126/science.aai9214.

Peer, R. A. and Chini, C. M. (2020): An integrated assessment of the global virtual water trade network of energy. Environmental Research Letters 15 (11), 114015. https://doi.org/10.1088/1748-9326/abbbb0.

Pereira, L. B., Sad, C. M. S., Castro, E. V. R., Filgueiras, P. R. and Lacerda Jr., V. (2022): Environmental impacts related to drilling fluid waste and treatment methods: A critical review. Fuel 310, 122301. https://www.doi.org/10.1016/j.fuel.2021.122301.

Perry, C., Steduto, P. and Karajeh, F. (2017): Does improved irrigation technology save water? A review of the evidence. Discussion paper on irrigation and sustainable water resources management in the Near East and North Africa. Kairo: Food and Agriculture Organization (FAO).

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., de Wit, C. A., Diamond, M. L., Fantke, P., Hassellöv, M., MacLeod, M., Ryberg, M. W., Søgaard Jørgensen, P., Villarrubia-Gómez, P., Wang, Z. and Hauschild, M. Z. (2022): Outside the safe operating space of the planetary boundary for novel entities. Environmental Science & Technology 56 (3), 1510–1521. https://doi.org/10.1021/acs.est.1c04158.

Pesa, I. (2021): Between waste and profit: Environmental values on the Central African Copperbelt. The Extractive Industries and Society 8 (4), 100793. https://www.doi.org/10.1016/j.exis.2020.08.004.

Petersen, N. (2024): §7 Laufende Besteuerung. In: Haase, F. and Jachmann-Michel, M. (Hrsg.): Beck'sches Handbuch Immobiliensteuerrecht. Munich: C.H. Beck, Rn. 306–309.

Petersen, T. and Klauer, B. (2014): Öffentlichkeitsbeteiligung, Partizipation and die Verantwortung des Staates in der Umweltpolitik. Leipzig: Helmholtz-Zentrum für Umweltforschung (UFZ).

Pfister, S., Boulay, A.-M., Berger, M., Hadjikakou, M., Motoshita, M., Hess, T., Ridoutt, B., Weinzettel, J., Scherer, L., Döll, P., Manzardo, A., Núñez, M., Verones, F., Humbert, S., Buxmann, K., Harding, K., Benini, L., Oki, T., Finkbeiner, M. and Henderson, A. (2017): Understanding the LCA and ISO water footprint: A response to Hoekstra (2016) "A critique on the water-scarcity weighted water footprint in LCA". Ecological Indicators 72, 352–359. https://doi.org/10.1016/j.ecolind.2016.07.051.

Pierce, G., Chow, N. and DeShazo, J. (2020): The case for state-level drinking water affordability programs: Conceptual and empirical evidence from California. Utilities Policy 63, 101006. https://doi.org/10.1016/j.jup.2020.101006.

Pierson, P. (2000): Increasing returns, path dependence, and the study of politics. American Political Science Review 94 (2), 251–267. https://www.doi.org/10.2307/2586011.

Pietilä, P., Katko, T. and Arvonen, V. (2020): Role of Water Cooperatives in Water Service Production - Lessons from Finland and Denmark. Tampere, Finnland: CIB World Building Congress.

Polazzo, F., Roth, S. K., Hermann, M., Mangold-Doring, A., Rico, A., Sobek, A., Van den Brink, P. J. and Jackson, M. C. (2022): Combined effects of heatwaves and micropollutants on freshwater ecosystems: Towards an integrated assessment of extreme events in multiple stressors research. Global Change Biology 28 (4), 1248–1267. https://www.doi.org/10.1111/gcb.15971.

Polvi, L. E. and Sarneel, J. M. (2017): Ecosystem engineers in rivers: An introduction to how and where organisms create positive biogeomorphic feedbacks. WIREs Water 5 (2), e1271. https://www.doi.org/10.1002/wat2.1271.

Pörtner, H.-O., Karl, D. M., Boyd, P. W., Cheung, W. W. L., Lluch-Cota, S. E., Nojiri, Y., Schmidt, D. N. and Zavialov, P. O. (2014): Ocean Systems. In: Field, C. B., Barros, V. R., Dokken, D. J., Mach, K. J., Mastrandrea, M. D., Bilir, T. E., Chatterjee, M., Ebi, K. L., Estrada, Y. O., Genova, R. C., Girma, B., Kissel, E. S., Levy, A. N., MacCracken, S., Mastrandrea, P. R. and White, L. L. (Hrsg.): Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press, 411–484.

Posthuma, L., Brack, W., van Gils, J., Focks, A., Müller, C., de Zwart, D. and Birk, S. (2019): Mixtures of chemicals are important drivers of impacts on ecological status in European surface waters. Environmental Sciences Europe 31 (71), 1–7. https://www.doi.org/10.1186/s12302-019-0247-4.

PPIC – Public Policy Institute of California (2018): California's Water. San Francisco, California: PPIC. https://www.ppic.org/wp-content/uploads/californias-water-november-2018.pdf.

PSF – Platform on Sustainable Finance (2024): A Compendium of Market Practices, How the EU's Taxonomy and sustainable finance framework are helping financial and non-financial actors transition to net zero. Brussels: EU. https://finance.ec.europa.eu/document/download/ff44591e-9d83-4027-a079-f3fe23bbaf41_en?filename=240129-sf-platform-report-market-practices-compendium-report_en.pdf.

Pulido-Velazquez, M., Marcos-Garcia, P., Girard, C., Sanchis-Ibor, C., Martinez-Capel, F., García-Prats, A., Ortega-Reig, M., García-Mollá, M. and Rinaudo, J. D. (2022): A Top-Down Meets Bottom-Up Approach for Climate Change Adaptation in Water Resource Systems. In: Kondrup, C., Mercogliano, P., Bosello, F., Mysiak, J., Scoccimarro, E., Rizzo, A., Ebrey, R., Ruiter, M. d., Jeuken, A. and Watkiss, P. (Hrsg.): Climate Adaptation Modelling. Cham: Springer International Publishing, 149–157. https://doi.org/10.1007/978-3-030-86211-4_18.

Qin, Y. and Gartner, T. (2016): Watersheds Lost Up to 22 % of Their Forests in 14 Years. Here's How it Affects Your Water Supply. Washington, D.C.: Global Forest Watch (GFW). https://www.globalforestwatch.org/blog/forest-insights/watersheds-lost-up-to-22-of-their-forests-in-14-years-heres-how-it-affects-your-water-supply/, published on 30.08.2016.

Quijano-Baron, J., Carlier, R., Rodriguez, J. F., Sandi, S. G., Saco, P. M., Wen, L. and Kuczera, G. (2022): And we thought the Millennium Drought was bad: Assessing climate variability and change impacts on an Australian dryland wetland using an ecohydrologic emulator. Water Research 218, 118487. https://www.doi.org/10.1016/j.watres.2022.118487.

Raabe, D. (2023): The Materials Science behind Sustainable Metals and Alloys. Chemical Reviews 123 (5), 2436–2608. https://www.doi.org/10.1021/acs.chemrev.2c00799.

Rahut, D. B. and Ali, A. (2017): Coping with climate change and its impact on productivity, income, and poverty: Evidence from the Himalayan region of Pakistan. International Journal of Disaster Risk Reduction 24, 515–525. https://www.doi.org/10.1016/j.ijdrr.2017.05.006.

Ramsar Convention on Wetlands (2018): Global Wetland Outlook: State of the World's Wetlands and their Service to People. Gland, Schweiz: Ramsar Convention Secreteriat.

Randell, H. and Gray, C. (2019): Climate change and educational attainment in the global tropics. Proceedings of the National Academy of Sciences 116 (18), 8840–8845. https://doi.org/10.1073/pnas.1817480116.

Ranjan, N., Singh, P. K. and Maurya, N. S. (2022): Pharmaceuticals in water as emerging pollutants for river health: A critical review under Indian conditions. Ecotoxicology and Environmental Safety 247, 114220. https://doi.org/10.1016/j.ecoenv.2022.114220.

Raskin, P. G., Peter; Kirshen, Paul; Pontius, Gil; Strzepek, Kenneth (1997): Comprehensive Assessment of the Freshwater Resources of the World. Water Futures: Asesment of long-range Patterns and Problems. Stockholm: Stockholm Environment Institute.

Rasul, G. and Molden, D. (2019): The Global Social and Economic Consequences of Mountain Cryospheric Change. Frontiers in Environmental Science 7, 1–18. https://doi.org/10.3389/fenvs.2019.00091.

Ray, P. A. and Brown, C. M. (2015): Confronting climate uncertainty in water resources planning and project design: The decision tree framework. Washington, D.C.: World Bank Publications.

Reckien, D., Magnan, A. K., Singh, C., Lukas-Sithole, M., Orlove, B., Schipper, E. L. F. and Coughlan de Perez, E. (2023): Navigating the continuum between adaptation and maladaptation. Nature Climate Change 13 (9), 907–918. https://doi.org/10.1038/s41558-023-01774-6.

Redonda, A., von Haldenwang, C. and Aliu, F. (2021): Tax expenditure reporting and domestic revenue mobilization in Africa. In: Mosquera Valderrama, I. J., Lesage, D. and Lips, W. (Hrsg.): Taxation, International Cooperation and the 2030 Sustainable Development Agenda. Band 19. Cham: Springer, 173–193. https://doi.org/10.1007/978-3-030-64857-2_9.

Rehman, K., Fatima, F., Waheed, I. and Akash, M. S. H. (2018): Prevalence of exposure of heavy metals and their impact on health consequences. Journal of Cellular Biochemistry 119 (1), 157–184. https://www.doi.org/10.1002/jcb.26234.

Reichhuber, A., Svoboda, M., King-Okumu, C., Mirzabaev, A., Vicente-Serrano, S. M., Srinivasan, R., Ehlert, K., Jia, X., Karnib, A., Lal, R., Mislimshoeva, B., Ravindranath, N. H., López Santos, A., Schipper, L., Stefanski, R., Vukovi-, A. and Zhang, H. (2022): Multiscale Approaches for the Assessment and Monitoring of Social and Ecological Resilience to Drought. A Report of the Science-Policy Interface. Bonn: United Nations Convention to Combat Desertification (UNCCD).

Reid, A. J., Carlson, A. K., Creed, I. F., Eliason, E. J., Gell, P. A., Johnson, P. T. J., Kidd, K. A., MacCormack, T. J., Olden, J. D., Ormerod, S. J., Smol, J. P., Taylor, W. W., Tockner, K., Vermaire, J. C., Dudgeon, D. and Cooke, S. J. (2019): Emerging threats and persistent conservation challenges for freshwater biodiversity. Biological Reviews of the Cambridge Philosophical Society 94 (3), 849–873. https://www.doi.org/10.1111/brv.12480.

Rice, J. and Westerhoff, P. (2015): Spatial and Temporal Variation in De Facto Wastewater Reuse in Drinking Water Systems across the U.S.A. Environmental Science & Technology 49 (2), 982–989. https://www.doi.org/10.1021/es5048057.

Richardson, C. J., Reiss, P., Hussain, N. A., Alwash, A. J. and Pool, D. J. (2005): The restoration potential of the Mesopotamian marshes of Iraq. Science 307 (5713), 1307–1311. https://www.doi.org/10.1126/science.1105750.

Richardson, J. R., Fitsanakis, V., Westerink, R. H. S. and Kanthasamy, A. G. (2019): Neurotoxicity of pesticides. Acta Neuropathologica 138 (3), 343–362. https://www.doi.org/10.1007/s00401-019-02033-9.

Rieckmann, M. (2020): Bildung für nachhaltige Entwicklung zum Thema „Verfügbarkeit and nachhaltige Nutzung von Wasser". In: Wulfmeyer, M. (Hrsg.): Bildung für nachhaltige Entwicklung im Sachunterricht: Grundlagen and Praxisbeispiele. Basiswissen Grundschule. Band 43. Baltmannsweiler: Schneider Hohengehren, 105–116.

Rimmert, M., Baudoin, L., Cotta, B., Kochskämper, E. and Newig, J. (2020): Participation in river basin planning under the water framework directive - Has it benefitted good water status? Water Alternatives 13 (3), 484–512. https://www.water-alternatives.org/index.php/alldoc/articles/volume-13/issue-3-1/589-a13-3-7.

Ringersma, J., Batjes, N. and Dent, D. (2003): Green Water: definitions and data for assessment. Report 2003/2. Wageningen: International Soil Reference and Information Centre (ISRIC).

Ripl, W. (2003): Water: the bloodstream of the biosphere. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 358 (1440), 1921–1934. https://www.doi.org/10.1098/rstb.2003.1378.

Ritchie, H. and Roser, M. (2017): Water Use and Stress. Oxford: Our World in Data, University of Oxford. https://ourworldindata.org/water-use-stress, published on 1.07.2018.

Ritchie, H., Rosado, P. and Roser, M. (2023): Data Page: Share of electricity generated by hydropower. Oxford: Our World in Data, University of Oxford. https://ourworldindata.org/grapher/share-electricity-hydro, accessed on 7.12.2023.

Ritchie, H., Spooner, F. and Roser, M. (2024): Clean Water. Clean and safe water is essential for good health. How did access change over time? Where do people lack access? Oxford: Our World in Data, University of Oxford. https://ourworldindata.org/clean-water, accessed on 4.07.2024.

Ritson, J. P., Bell, M., Brazier, R. E., Grand-Clement, E., Graham, N. J. D., Freeman, C., Smith, D., Templeton, M. R. and Clark, J. M. (2016): Managing peatland vegetation for drinking water treatment. Scientific Reports 6 (1), 36751. https://www.doi.org/10.1038/srep36751.

Ritzema, H., Limin, S., Kusin, K., Jauhiainen, J. and Wösten, H. (2014): Canal blocking strategies for hydrological restoration of degraded tropical peatlands in Central Kalimantan, Indonesia. Catena 114, 11–20. https://www.doi.org/10.1016/j.catena.2013.10.009.

Rivera-Dávila, O. L., Sánchez-Martínez, G. and Rico- Martínez, R. (2021): Ecotoxicity of pesticides and semiochemicals used for control and prevention of conifer bark beetle (Dendroctonus spp.) outbreaks. Chemosphere 263, 128375. https://doi.org/10.1016/j.chemosphere.2020.128375.

Robock, A. (2003): HYDROLOGY. Soil Moisture. In: Holton, J. R. (Hrsg.): Encyclopedia of Atmospheric Sciences. Oxford: Academic Press, 987–993. https://doi.org/10.1016/B0-12-227090-8/00169-X.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C. and Schellnhuber, H. J. (2009a): A safe operating space for humanity. nature 461 (7263), 472–475. https://doi.org/10.1038/461472a.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C. and Schellnhuber, H. J. (2009b): Planetary boundaries: exploring the safe operating space for humanity. Ecology and society 14 (2), 32. https://www.jstor.org/stable/26268316.

Rockström, J., Gupta, J., Qin, D., Lade, S. J., Abrams, J. F., Andersen, L. S., Armstrong McKay, D. I., Bai, X., Bala, G., Bunn, S. E., Ciobanu, D., DeClerck, F., Ebi, K., Gifford, L., Gordon, C., Hasan, S., Kanie, N., Lenton, T. M., Loriani, S., Liverman, D. M., Mohamed, A., Nakicenovic, N., Obura, D., Ospina, D., Prodani, K., Rammelt, C., Sakschewski, B., Scholtens, J., Stewart-Koster, B., Tharammal, T., van Vuuren, D., Verburg, P. H., Winkelmann, R., Zimm, C., Bennett, E. M., Bringezu, S., Broadgate, W., Green, P. A., Huang, L., Jacobson, L., Ndehedehe, C., Pedde, S., Rocha, J., Scheffer, M., Schulte-Uebbing, L., de Vries, W., Xiao, C., Xu, C., Xu, X., Zafra-Calvo, N. and Zhang, X. (2023a): Safe and just Earth system boundaries. Nature 619 (7968), 102–111. https://doi.org/10.1038/s41586-023-06083-8.

Rockström, J., Mazzucato, M., Andersen, L. S., Fahrländer, S. F. and Gerten, D. (2023b): Why we need a new economics of water as a common good. Nature 615, 794–797. https://doi.org/10.1038/d41586-023-00800-z.

Rockström, J., Kotze, L., Milutinovic, S., Biermann, F., Brovkin, V., Donges, J., Ebbesson, J., French, D., Gupta, J., Kim, R., Lenton, T., Lenzi, D., Nakicenovic, N., Neumann, B., Schuppert, F., Winkelmann, R., Bosselmann, K., Folke, C., Lucht, W., Schlosberg, D., Richardson, K. and Steffen, W. (2024): The planetary commons: A new paradigm for safeguarding Earth-regulating systems in the Anthropocene. Proceedings of the National Academy of Sciences (PNAS) 121 (5), e2301531121. https://www.doi.org/10.1073/pnas.2301531121.

Rogers, B. C., Dunn, G., Hammer, K., Novalia, W., de Haan, F. J., Brown, L., Brown, R. R., Lloyd, S., Urich, C., Wong, T. H. F. and Chesterfield, C. (2020): Water Sensitive Cities Index: A diagnostic tool to assess water sensitivity and guide management actions. Water Research 186, 116411. https://doi.org/10.1016/j.watres.2020.116411.

Rohling, E. J., Hibbert, F. D., Grant, K. M., Galaasen, E. V., Irvali, N., Kleiven, H. F., Marino, G., Ninnemann, U., Roberts, A. P., Rosenthal, Y., Schulz, H., Williams, F. H. and Yu, J. (2019): Asynchronous Antarctic and Greenland ice-volume contributions to the last interglacial sea-level highstand. Nat Commun 10 (1), 5040. https://www.doi.org/10.1038/s41467-019-12874-3.

Rollins-Smith, L. A. and Le Sage, E. H. (2023): Heat stress and amphibian immunity in a time of climate change. Philosophical Transactions of the Royal Society B: Biological Sciences 378 (1882), 20220132. https://doi.org/10.1098/rstb.2022.0132.

Romanello, M., Napoli, C. d., Green, C., Kennard, H., Lampard, P., Scamman, D., Walawender, M., Ali, Z., Ameli, N., Ayeb-Karlsson, S., Beggs, P. J., Belesova, K., Berrang Ford, L., Bowen, K., Cai, W., Callaghan, M., Campbell-Lendrum, D., Chambers, J., Cross, T. J., van Daalen, K. R., Dalin, C., Dasandi, N., Dasgupta, S., Davies, M., Dominguez-Salas, P., Dubrow, R., Ebi, K. L., Eckelman, M., Ekins, P., Freyberg, C., Gasparyan, O., Gordon-Strachan, G., Graham, H., Gunther, S. H., Hamilton, I., Hang, Y., Hänninen, R., Hartinger, S., He, K., Heidecke, J., Hess, J. J., Hsu, S.-C., Jamart, L., Jankin, S., Jay, O., Kelman, I., Kiesewetter, G., Kinney, P., Kniveton, D., Kouznetsov, R., Larosa, F., Lee, J. K. W., Lemke, B., Liu, Y., Liu, Z., Lott, M., Lotto Batista, M., Lowe, R., Odhiambo Sewe, M., Martinez-Urtaza, J., Maslin, M., McAllister, L., McMichael, C., Mi, Z., Milner, J., Minor, K., Minx, J. C., Mohajeri, N., Momen, N. C., Moradi-Lakeh, M., Morrissey, K., Munzert, S., Murray, K. A., Neville, T., Nilsson, M., Obradovich, N., O'Hare, M. B., Oliveira, C., Oreszczyn, T., Otto, M., Owfi, F., Pearman, O., Pega, F., Pershing, A., Rabbaniha, M., Rickman, J., Robinson, E. J. Z., Rocklöv, J., Salas, R. N., Semenza, J. C., Sherman, J. D., Shumake-Guillemot, J., Silbert, G., Sofiev, M., Springmann, M., Stowell, J. D., Tabatabaei, M., Taylor, J., Thompson, R., Tonne, C. (2023): The 2023 report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. The Lancet 402 (10419), 2346–2394. https://www.doi.org/10.1016/S0140-6736(23)01859-7.

Rosa, L., Chiarelli, D. D., Rulli, M. C., Dell'Angelo, J. and D'Odorico, P. (2020): Global agricultural economic water scarcity. Science Advances 6 (18), eaaz6031. https://www.doi.org/10.1126/sciadv.aaz6031.

Rosa, L., Sanchez, D. L., Realmonte, G., Baldocchi, D. and D'Odorico, P. (2021): The water footprint of carbon capture and storage technologies. Renewable & Sustainable Energy Reviews 140, 110773. https://www.doi.org/10.1016/j.rser.2021.110773.

Rosenstock, T. S., Dawson, I. K., Aynekulu, E., Chomba, S., Degrande, A., Fornace, K., Jamnadass, R., Kimaro, A., Kindt, R., Lamanna, C., Malesu, M., Mausch, K., McMullin, S., Murage, P., Namoi, N., Njenga, M., Nyoka, I., Paez Valencia, A. M., Sola, P., Shepherd, K. and Steward, P. (2019): A Planetary Health Perspective on Agroforestry in Sub-Saharan Africa. One Earth 1 (3), 330–344. https://doi.org/10.1016/j.oneear.2019.10.017.

Rosinger, A. Y. and Young, S. L. (2020): The toll of household water insecurity on health and human biology: Current understandings and future directions. Wiley Interdisciplinary Reviews: Water 7 (6), e1468. https://doi.org/10.1002/wat2.1468.

Ross, B. (2017): Water Finance and Management: The Potential of Crowdfunding for Water P3s. https://waterfm.com/crowdfunding-p3-water/, published on 15.02.2017.

Roussel, J.-M., Soissons, L., Duda, J. J. and McCaffery, R. (2024): Editorial: Large-scale dam removal and ecosystem restoration. Frontiers in Ecology and Evolution 12, 1471146. https://doi.org/10.3389/fevo.2024.1471146.

RRC – River Restoration Centre (2024): Startpage: About Us. Cranfield: RRC. https://www.therrc.co.uk/rrc, accessed on 28.06.2024.

Rusca, M., Savelli, E., Di Baldassarre, G., Biza, A. and Messori, G. (2023): Unprecedented droughts are expected to exacerbate urban inequalities in Southern Africa. Nature Climate Change 13 (1), 98–105. https://doi.org/10.1038/s41558-022-01546-8.

Rusk, J., Maharjan, A., Tiwari, P., Chen, T.-H. K., Shneiderman, S., Turin, M. and Seto, K. C. (2022): Multi-hazard susceptibility and exposure assessment of the Hindu Kush Himalaya. Science of The Total Environment 804, 150039. https://doi.org/10.1016/j.scitotenv.2021.150039.

Sahu, P. and Debsarma, C. (2023): Urban Water Scarcity: A Global Challenge and Impending Solutions. In: Thambidurai, P. and Dikshit, A. K. (Hrsg.): Impacts of Urbanization on Hydrological Systems in India. Cham: Springer Nature, 129–142. https://doi.org/10.1007/978-3-031-21618-3_7.

Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., Zink, M., Sheffield, J., Wood, E. F. and Marx, A. (2018): Anthropogenic warming exacerbates European soil moisture droughts. Nature Climate Change 8 (5), 421–426. https://www.doi.org/10.1038/s41558-018-0138-5.

Sameh, A. (2023): A systematic review of frequency and geographic distribution of water-borne parasites in the Middle East and North Africa. Eastern Mediterranean Health Journal 29 (2), 151–161. https://doi.org/10.26719/emhj.23.016.

Sands, P., Peel, J., Fabra, A. and Mackenzie, R. (2018): Principles of International Environmental Law. Cambridge, New York: Cambridge University Press.

San-Miguel-Ayanz, J., Durrant, T., Boca, R., Maianti, P., Libertá, G., Artés-Vivancos, T., Oom, D., Branco, A., de Rigo, D., Ferrari, D., Pfeiffer, H., Grecchi, R., Onida, M. and Löffler, P. (2022): Forest Fires in Europe, Middle East and North Africa 2021. Luxemburg: EU. https://www.doi.org/10.2760/34094.

Sanganyado, E. and Gwenzi, W. (2019): Antibiotic resistance in drinking water systems: Occurrence, removal, and human health risks. Science of The Total Environment 669, 785–797. https://doi.org/10.1016/j.scitotenv.2019.03.162.

Santoro, A. (2023): Traditional oases in Northern Africa as multifunctional agroforestry systems: a systematic literature review of the provided Ecosystem Services and of the main vulnerabilities. Agroforestry Systems 97, 81–96. https://doi.org/10.1007/s10457-022-00789-w.

Sarkar, S., Gil, J. D. B., Keeley, J. and Jansen, K. (2021): The use of pesticides in developing countries and their impact on health and the right to food. Brussels: European Union. https://www.doi.org/10.2861/953921.

Sartori, M. and Schiavo, S. (2015): Connected we stand: a network perspective on trade and global food security. Food Policy 57, 114–127. https://doi.org/10.1016/j.foodpol.2015.10.004.

Sartori, M., Schiavo, S., Fracasso, A. and Riccaboni, M. (2017): Modeling the future evolution of the virtual water trade network: A combination of network and gravity models. Advances in Water Resources 110, 538–548. https://doi.org/10.1016/j.advwatres.2017.05.005.

Savelli, E., Mazzoleni, M., Di Baldassarre, G., Cloke, H. and Rusca, M. (2023): Urban water crises driven by elites' unsustainable consumption. Nature Sustainability 6, 929–940. https://www.doi.org/10.1038/s41893-023-01100-0.

SAWPA – Santa Ana Watershed Projekt Authority (2024): One Water One Watershed (OWOW) Program. Riverside, California: SAWPA. https://sawpa.gov/owow/, accessed on 25.03.2024.

Scanlon, B. R., Fakhreddine, S., Rateb, A., de Graaf, I., Famiglietti, J., Gleeson, T., Grafton, R. Q., Jobbagy, E., Kebede, S., Kolusu, S. R., Konikow, L. F., Long, D., Mekonnen, M., Schmied, H. M., Mukherjee, A., MacDonald, A., Reedy, R. C., Shamsudduha, M., Simmons, C. T., Sun, A., Taylor, R. G., Villholth, K. G., Vörösmarty, C. J. and Zheng, C. (2023): Global water resources and the role of groundwater in a resilient water future. Nature Reviews Earth & Environment 4, 87–101. https://www.doi.org/10.1038/s43017-022-00378-6.

Schambeck, C. M., Magnus, B. S., Rozone de Souza, L. C., Moreira Leite, W. R., Derlon, N., Bittencourt Guimarães, L. and Ribeiro da Costa, R. H. (2020): Biopolymers recovery: dynamics and characterization of alginate-like exopolymers in an aerobic granular sludge system treating municipal wastewater without sludge inoculum. Journal of Environmental Management 263, 110394. https://www.doi.org/10.1016/j.jenvman.2020.110394.

Schellekens, G. and van Toor, J. (2019): Values at risk? Sustainability risks and goals in the Dutch financial sector. Amsterdam: De Nederlandsche Bank. https://www.dnb.nl/media/hm1msmzo/values-at-risk-sustainability-risks-and-goals-in-the-dutch.pdf.

Schembergue, A., da Cunha, D. A., de Matos Carlos, S., Pires, M. V. and Faria, R. M. (2017): Sistemas agroflorestais como estratégia de adaptação aos desafios das mudanças climáticas no Brasil. Revista de Economia e Sociologia Rural 55 (1), 9–30. http://dx.doi.org/10.1590/1234-56781806-94790550101.

Scherer, L., Boom, H. A., Barbarossa, V. and van Bodegom, P. M. (2023): Climate change threats to the global functional diversity of freshwater fish. Glob Chang Biol 29 (13), 3781–3793. https://www.doi.org/10.1111/gcb.16723.

Schipper, L. (2020): Maladaptation: When Adaptation to Climate Change Goes Very Wrong. One Earth 3, 409–414. https://www.doi.org/10.1016/j.oneear.2020.09.014.

Schlacke, S. (2021): Planende Verwaltung. In: Kahl, W. and Ludwigs, M. (Hrsg.): Handbuch des Verwaltungsrechts Band I Grundstrukturen des deutschen Verwaltungsrechts. Munich: C.F. Müller, 761–806.

Schlacke, S. (2023): Umweltrecht. Baden-Baden: Nomos.

Schleifer, L. and Otto, B. (2019): Water Can Exacerbate Inequality— or It Can Help Solve It. Washington, D.C.: World Resources Institute (WRI). https://www.wri.org/insights/water-can-exacerbate-inequality-or-it-can-help-solve-it, published on 22.03.2019.

Schmeier, S. (2013): Governing International Watercourses. River Basin Organizations and the sustainable governance of internationally shared rivers and lakes. London: Routledge.

Schmeisser, S., Miccoli, A., von Bergen, M., Berggren, E., Braeuning, A., Busch, W., Desaintes, C., Gourmelon, A., Grafström, R., Harrill, J., Hartung, T., Herzler, M., Kass, G. E. N., Kleinstreuer, N., Leist, M., Luijten, M., Marx-Stoelting, P., Poetz, O., van Ravenzwaay, B., Roggeband, R., Rogiers, V., Roth, A., Sanders, P., Thomas, R. S., Marie Vinggaard, A., Vinken, M., van de Water, B., Luch, A. and Tralau, T. (2023): New approach methodologies in human regulatory toxicology – Not if, but how and when! Environment International 178, 108082. https://doi.org/10.1016/j.envint.2023.108082.

Schmidt, M., Bastian, D. and Kresse, C. (2023): DERA Rohstoffinformationen Rohstoffrisikobewertung - Lithium. 54 Berlin: Deutsche Rohstoffagentur (DERA). https://www.deutsche-rohstoffagentur.de/DERA/DE/Aktuelles/rohstoff_lithium.html.

Schomberg, A. C., Bringezu, S. and Flörke, M. (2021): Extended life cycle assessment reveals the spatially-explicit water scarcity footprint of a lithium-ion battery storage. Communications Earth & Environment 2 (11), 1–10. https://www.doi.org/10.1038/s43247-020-00080-9.

Schreefel, L., Schulte, R. P. O., de Boer, I. J. M., Schrijver, A. P. and van Zanten, H. H. E. (2020): Regenerative agriculture – the soil is the base. Global Food Security 26, 100404. https://www.doi.org/10.1016/j.gfs.2020.100404.

Schulte, P. and Morrison, J. (2014): Driving harmonization of water-related terminology. CEO Water Mandate Discussion Paper. Oakland: Pacific Institute.

Schürings, C., Feld, C. K., Kail, J. and Hering, D. (2022): Effects of agricultural land use on river biota: a meta-analysis. Environmental Sciences Europe 34, 124. https://www.doi.org/10.1186/s12302-022-00706-z.

Schwachula, A. (2019): The BMBF's sustainability concept vs. global sustainable development. In: Schwachula, A. (Hrsg.): Sustainable Development in Science Policy-Making. Bielefeld: transcript Verlag, 262–267. https://doi.org/10.14361/9783839448823-043.

SCM – Somerset Catchment Market (2024): The Somerset Catchment Market is an environmental services market that aims to accelerate the delivery of Nature-based Projects such as the creation of new woodlands and wetlands across South Somerset. Bath and North East Somerset (England): SCM. https://www.somersetcatchmentmarket.uk/, accessed on 18.06.2024.

Scott, C. A., Zhang, F., Mukherji, A., Immerzeel, W., Mustafa, D. and Bharati, L. (2019): Water in the Hindu Kush Himalaya. In: Wester, P., Mishra, A., Mukherji, A. and Shrestha, A. B. (Hrsg.): The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People. Cham: Springer Nature, 257–299. https://doi.org/10.1007/978-3-319-92288-1_8.

SDSN – Sustainable Development Solutions Network (2023): Implementing the SDG Stimulus. Sustainable Development Report 2023. Paris, Dublin: SDSN, Dublin University Press. https://www.doi.org/10.25546/102924.

SDSN – Sustainable Development Solutions Network (2024a): International Spillovers. New York: SDSN. https://www.unsdsn.org/our-work/sdg-transformation-center/, accessed on 4.07.2024.

SDSN – Sustainable Development Solutions Network (2024b): Tracking Spillover Effects. Measure and promote actions to curb negative transboundary SDG impacts. New York: SDSN. https://sdgtransformationcenter.org/spillovers, accessed on 4.07.2024.

Seebacher, F., Narayan, E., Rummer, J. L., Tomlinson, S. and Cooke, S. J. (2023): How can physiology best contribute to wildlife conservation in a warming world? Conservation Physiology 11 (1), coad038. https://www.doi.org/10.1093/conphys/coad038.

Seenivasagan, R. and Babalola, O. O. (2021): Utilization of Microbial Consortia as Biofertilizers and Biopesticides for the Production of Feasible Agricultural Product. Biology 10 (11), 1111. https://doi.org/10.3390/biology10111111.

Segal, M. (2024): Singapore to Provide Funding for Companies to Meet New Climate Reporting Requirements. ESG Today. https://www.esgtoday.com/singapore-to-provide-funding-for-companies-to-meet-new-climate-reporting-requirements/, published on 6.03.2024.

Seijger, C., Ellen, G. J., Janssen, S., Verheijen, E. and Erkens, G. (2017): Sinking deltas: trapped in a dual lock-in of technology and institutions. Prometheus 35 (3), 193–213. https://www.doi.org/10.1080/08109028.2018.1504867.

Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-Serrano, S. M., Wehner, M. and Zhou, B. (2021): Weather and Climate Extreme Events in a Changing Climate. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B. (Hrsg.): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press, 1513–1766. https://www.doi.org/10.1017/9781009157896.013.

Sengupta, N. (1980): The indigenous irrigation organization in South Bihar. The Indian Economic & Social History Review 17 (2), 157–189. https://doi.org/10.1177/001946468001700201.

Seto, K. C., Davis, S. J., Mitchell, R. B., Stokes, E. C., Unruh, G. and Ürge-Vorsatz, D. (2016): Carbon Lock-In: Types, Causes, and Policy Implications. Annual Review of Environment and Resources 41, 425–452. https://www.doi.org/10.1146/annurev-environ-110615-085934.

Sharkov, A. (2022): Water abstraction charges in Bulgaria. Brussels: Institute for European Environmental Policy (IEEP).

Sharma, S., Yadav, R. K. and Singh, A. P. (2022): Presence of medicinal materials in drinking water: A review. Materials Today: Proceedings 61, 1067–1072. https://doi.org/10.1016/j.matpr.2021.10.336.

Sharma, S., Bhardwaj, A., Thakur, M. and Saini, A. (2023): Understanding microplastic pollution of marine ecosystem: a review. Environmental Science and Pollution Research, 1–44. https://www.doi.org/10.1007/s11356-023-28314-1.

Sheikholeslami, R. and Hall, J. W. (2023): Global patterns and key drivers of stream nitrogen concentration: A machine learning approach. Science of The Total Environment 868, 161623. https://doi.org/10.1016/j.scitotenv.2023.161623.

Shively, G. E. (2017): Infrastructure mitigates the sensitivity of child growth to local agriculture and rainfall in Nepal and Uganda. Proceedings of the National Academy of Sciences 114 (5), 903–908. https://doi.org/10.1073/pnas.1524482114.

Shlezinger, M., Amitai, Y., Akriv, A., Gabay, H., Shechter, M. and Leventer-Roberts, M. (2018): Association between exposure to desalinated sea water and ischemic heart disease, diabetes mellitus and colorectal cancer; A population-based study in Israel. Environmental Research 166, 620–627. https://www.doi.org/10.1016/j.envres.2018.06.053.

Sibanda, W., Hansen, M. M. and Mukwada, G. (2023): Grappling with Gendered Crises: Women's Access and Participation in Water, Sanitation and Hygiene Activities at Tongogara Refugee Camp, Zimbabwe. International Journal of Social Science Research and Review 6 (7), 212–228. https://doi.org/10.47814/ijssrr.v6i7.1462.

SIC-ICWC – Scientific-Information Center of the Interstate Commission for Water Coordination of Central Asia (2010): Online data of the Basin Water Organisation Amudarya. Taschkent, Usbekistan: SIC-ICWC. http://www.cawater-info.net, accessed on 19.08.2024.

Siebert, S., Burke, J., Faures, J. M., Frenken, K., Hoogeveen, J., Döll, P. and Portmann, F. T. (2010): Groundwater use for irrigation - a global inventory. Hydrology and Earth System Sciences 14 (10), 1863–1880. https://www.doi.org/10.5194/hess-14-1863-2010.

Simoens, M. C., Leipold, S. and Fuenfschilling, L. (2022): Locked in unsustainability: Understanding lock-ins and their interactions using the case of food packaging. Environmental Innovation and Societal Transitions 45, 14–29. https://www.doi.org/10.1016/j.eist.2022.08.005.

Simpson, N. P., Simpson, K. J., Ferreira, A. T., Constable, A., Glavovic, B., Eriksen, S. E. H., Ley, D., Solecki, W., Rodríguez, R. S. and Stringer, L. C. (2023): Climate-resilient development planning for cities: progress from Cape Town. npj Urban Sustainability 3, 10. https://www.doi.org/10.1038/s42949-023-00089-x.

Simwambi, A., Hibler, S., Pietruschka, B. and Hawkins, P. (2017): Approaches to Faecal Sludge Management in Peri-Urban Areas: A Case Study in the City of Lusaka. Seattle, USA: Bill & Melinda Gates Foundation (BMGF).

Simwambi, A., Kapembwa, M. A. and Kapanda, K. (2023): Effects of Poor Solid Waste Management on Faecal Sludge Emptying, Treatment and Disposal Services in Lusaka. European Journal of Applied Sciences 11 (4), 330–360. https://www.doi.org/10.14738/aivp.114.15405.

Singh, N. K., Gourevitch, J. D., Wemple, B. C., Watson, K. B., Rizzo, D. M., Polasky, S. and Ricketts, T. H. (2019): Optimizing wetland restoration to improve water quality at a regional scale. Environmental Research Letters 14 (6), https://www.doi.org/10.1088/1748-9326/ab1827.

Sinharoy, S. S., Pittluck, R. and Clasen, T. (2019): Review of drivers and barriers of water and sanitation policies for urban informal settlements in low-income and middle-income countries. Utilities policy 60, 100957. https://doi.org/10.1016/j.jup.2019.100957.

SIWI – Stockholm International Water Institute and UNICEF – United Nations Children's Fund (2023): Water Scarcity and Climate Change Enabling Environment Analysis for WASH: Middle East and North Africa. Stockholm, New York: SIWI, UNICEF.

Slater, D. (2019): Water Scarcity in Brazil: A Case Study. Quantico, USA: Marine Corps University Press (MCUP). https://www.doi.org/10.36304/ExpwMCUP.2019.02, published on 23.10.2019.

Smakhtin, V. (2018): Ecosystems in the Global Water Cycle. UN Chronicle - The Quest for Water. New York: United Nations (UN). https://www.un.org/en/chronicle/article/ecosystems-global-water-cycle, published on 1.03.2018.

Smith, D. M., Gordon, C., Kittikhoun, A., Molwantwa, J., Pacheco Mollinedo, P., Romdhane, A. B., Shrestha, R., Tindimugay, C. and McDonnell, R. (2023): Research and innovation missions to transform future water systems. Nature Water 1 (3), 219–222. https://www.doi.org/10.1038/s44221-023-00049-w.

Söderberg, C. (2016): Complex governance structures and incoherent policies: Implementing the EU water framework directive in Sweden. Journal of Environmental Management 183, 90–97. https://www.doi.org/10.1016/j.jenvman.2016.08.040.

Sokolow, S. H., Huttinger, E., Jouanard, N., Hsieh, M. H., Lafferty, K. D., Kuris, A. M., Riveau, G., Senghor, S., Thiam, C., N'Diaye, A., Faye, D. S. and De Leo, G. A. (2015): Reduced transmission of human schistosomiasis after restoration of a native river prawn that preys on the snail intermediate host. PNAS 112 (31), 9650–9655. https://www.doi.org/10.1073/pnas.1502651112.

Solent Catchment Market (2024): Solent Catchment Market. What is the Solent Catchment Market? https://www.solentnutrientmarket.org.uk/, accessed on 18.06.2024.

Solomon, D., Lehmann, J., Fraser, J. A., Leach, M., Amanor, K., Frausin, V., Kristiansen, S. M., Millimouno, D. and Fairhead, J. (2016): Indigenous African soil enrichment as a climate-smart sustainable agriculture alternative. Frontiers in Ecology and the Environment 14 (2), 71–76. https://www.doi.org/10.1002/fee.1226.

Soriano, É., Londe, L. d. R., Di Gregorio, L. T., Coutinho, M. P. and Santos, L. B. L. (2016): Water crisis in São Paulo evaluated under the disaster's point of view. Ambiente & Sociedade 19 (1), 21–42. https://www.doi.org/10.1590/1809-4422asoc150120r1v1912016.

Sowby, R. and Hotchkiss, R. (2022): Minimizing Unintended Consequences of Water Resources Decisions. Journal of Water Resources Planning and Management 148 (11), 1–3. https://www.doi.org/10.1061/(ASCE)WR.1943-5452.0001623.

Sowers, J. (2012): Institutional change in authoritarian regimes: Water and the state in Egypt. In: Steinberg, P. F. and VanDeveer, S. D. (Hrsg.): Comparative Environmental Politics Theory, Practice, and Prospects. Cambridge, US: MIT Press, 231–254. http://www.jstor.org/stable/j.ctt5vjs7f.

Sproule, B. (2002): Lithium in Bipolar Disorder. Clinical Pharmacokinetics 41 (9), 639–660. https://doi.org/10.2165/00003088-200241090-00002.

Srigiri, S. R. and Dombrowsky, I. (2021): Governance of the water-energy-food nexus for an integrated implementation of the 2030 Agenda: Conceptual and methodological framework for analysis. Discussion Paper 2/2021. Bonn: Deutsches Institut für Entwicklungspolitik (DIE). https://doi.org/10.23661/dp2.2021.

Srigiri, S. R. and Dombrowsky, I. (2022): Analysing the Water-Energy-Food Nexus from a polycentric governance perspective: Conceptual and methodological framework. Frontiers in Environmental Science 10, 725116. https://doi.org/10.3389/fenvs.2022.725116.

Srigiri, S. R., Scheumann, W. and Alamirew, T. (o.J.): Responsible governance of water tenure for achieving the 2030 Agenda: challenges in the Awash River Basin, Ethiopia. Rome: Food and Agriculture Organization (FAO).

Srivastava, S. (2020) (Hrsg.): Arsenic in drinking water and food. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-981-13-8587-2.

SRU – Sachverständigenrat für Umweltfragen (2023): Umwelt and Gesundheit konsequent zusammendenken. Sondergutachten. Berlin: SRU.

Stapleton, J., Bates, S., Lewis, M., Turner, S. R., Warne, D. and Florentine, S. (2023): A global review on arid zone restoration: approaches and challenges. Restoration Ecology, e14078. https://www.doi.org/10.1111/rec.14078.

Stephenson, K. and Shabman, L. (2017): Can water quality trading fix the agricultural nonpoint source problem? Annual Review of Resource Economics 9, 95–116. https://doi.org/10.1146/annurev-resource-100516-053639.

Stern, J. H. and Stern, A. (2011): Water harvesting through sand dams. North Fort Myers, Florida: ECHO. https://www.echocommunity.org/resources/7fdbb758-a1f7-4c4a-adc2-0a07a9f9981a.

Stock, N. L., Furdui, V. I., Muir, D. C. G. and Mabury, S. A. (2007): Perfluoroalkyl Contaminants in the Canadian Arctic: Evidence of Atmospheric Transport and Local Contamination. Environmental Science & Technology 41 (10), 3529–3536. https://www.doi.org/10.1021/es062709x.

Strank, O. (2019): Common Concern of Humankind im Völkerrecht. Heidelberg: Springer. https://doi.org/10.1007/978-3-662-60430-4.

Strobl, K., Moning, C. and Kollmann, J. (2019): Positive trends in plant, dragonfly, and butterfly diversity of rewetted montane peatlands. Restoration Ecology 28 (4), 796–806. https://www.doi.org/10.1111/rec.12957.

Stroud, H. M., Kirshen, P. H. and Timmons, D. (2022): Monetary evaluation of co-benefits of nature-based flood risk reduction infrastructure to promote climate justice. Mitigation and Adaptation Strategies for Global Change 28 (5), 1–21. https://www.doi.org/10.1007/s11027-022-10037-2.

Stuart-Hill, S., Lukat, E., Pringle, C. and Pahl-Wostl, C. (2020): Lösung komplexer Wasserprobleme durch Koordination jenseits des Staates – Erkenntnisse aus Südafrika. Analysen and Stellungnahmen 20/2020. Bonn: Deutsches Institut für Entwicklungspolitik (DIE). https://doi.org/10.23661/as20.2020.

Suckling, J., Hoolohan, C., Soutar, I. and Druckman, A. (2021): Unintended Consequences: Unknowable and Unavoidable, or Knowable and Unforgivable? Frontiers in Climate 3, 1–12. https://www.doi.org/10.3389/fclim.2021.737929.

Sugg, M., Runkle, J., Leeper, R., Bagli, H., Golden, A., Handwerger, L. H., Magee, T., Moreno, C., Reed-Kelly, R., Taylor, M. and Woolard, S. (2020): A scoping review of drought impacts on health and society in North America. Climatic Change 162, 1177–1195. https://www.doi.org/10.1007/s10584-020-02848-6.

swa – Stadtwerke Augsburg (2021): Augsburger Modell für sauberes Trinkwasser. Augsburg: SWA. https://www.sw-augsburg.de/magazin/detail/augsburger-modell-fuer-sauberes-trinkwasser/, published on 15.10.2021.

Syvrud, A., Pohlner, H., Punthakey, J. F., Grant, M. and Green, T. (2021): Advancing Urban Water Security in the Indus Basin, Pakistan - Priority Actions for Karachi and Lahore. Water 13 (23), 3399. https://doi.org/10.3390/w13233399.

Tabari, H. (2020): Climate change impact on flood and extreme precipitation increases with water availability. Scientific Reports 10, 13768. https://www.doi.org/10.1038/s41598-020-70816-2.

Takakura, J. y., Fujimori, S., Hanasaki, N., Hasegawa, T., Hirabayashi, Y., Honda, Y., Iizumi, T., Kumano, N., Park, C., Shen, Z., Takahashi, K., Tamura, M., Tanoue, M., Tsuchida, K., Yokoki, H., Zhou, Q., Oki, T. and Hijioka, Y. (2019): Dependence of economic impacts of climate change on anthropogenically directed pathways. Nature Climate Change 9 (10), 737–741. https://www.doi.org/10.1038/s41558-019-0578-6.

Talbot, R. and Chang, H. (2022): Microplastics in freshwater: A global review of factors affecting spatial and temporal variations. Environmental Pollution 292, 118393. https://www.doi.org/10.1016/j.envpol.2021.118393.

Tambe, S. (2022): Rights-Based Approach to Livelihoods. In: Tambe, S. (Hrsg.): Teaching and Learning Rural Livelihoods: A Guide for Educators, Students, and Practitioners. Cham: Springer, 83–94. https://doi.org/10.1007/978-3-030-90491-3_7.

Tamea, S., Laio, F. and Ridolfi, L. (2016): Global effects of local food-production crises: a virtual water perspective. Scientific reports 6 (1), 18803. https://doi.org/10.1038/srep18803.

Tang, F. H. M., Lenzen, M., McBratney, A. and Maggi, F. (2021): Risk of pesticide pollution at the global scale. Nature Geoscience 14 (4), 206–210. https://doi.org/10.1038/s41561-021-00712-5.

Tanveer, M., Hasanuzzaman, M. and Wang, L. (2019): Lithium in Environment and Potential Targets to Reduce Lithium Toxicity in Plants. Journal of Plant Growth Regulation 38 (4), 1574–1586. https://doi.org/10.1007/s00344-019-09957-210.1007/s00344-019-09957-2.

Tanzi, A. M. (2020): The inter-relationship between no harm, equitable and reasonable utilisation and cooperation under international water law. International Environmental Agreements-Politics Law and Economics 20 (4), 619–629. https://www.doi.org/10.1007/s10784-020-09502-7.

Taylor, C., Robinson, T. R., Dunning, S., Rachel Carr, J. and Westoby, M. (2023): Glacial lake outburst floods threaten millions globally. Nature Communications 14 (1), 487. https://www.doi.org/10.1038/s41467-023-36033-x.

Taylor, K. S., Longboat, S. and Grafton, R. Q. (2019): Whose Rules? A Water Justice Critique of the OECD's 12 Principles on Water Governance. Water 11 (4), 809. https://www.doi.org/10.3390/w11040809.

Taylor, P., Hornidge, A.-K., Leach, M., MacGregor, H., Mehdi, A. and Fung, M. L. (2022): Research, Evidence and Learning – the Need for Global Infrastructure. Think7 Policy Brief. Bonn: Deutsches Institut für Entwicklungspolitik (DIE).

te Wierik, S. A., Gupta, J., Cammeraat, E. L. H. and Artzy-Randrup, Y. A. (2020): The need for green and atmospheric water governance. WIREs Water 7 (2), e1406. https://www.doi.org/10.1002/wat2.1406.

te Wierik, S. A., Cammeraat, E. L. H., Gupta, J. and Artzy-Randrup, Y. A. (2021): Reviewing the Impact of Land Use and Land-Use Change on Moisture Recycling and Precipitation Patterns. Water Resources Research 57 (7), e2020WR029234. https://www.doi.org/10.1029/2020WR029234.

Teskey, R., Wertin, T., Bauweraerts, I., Ameye, M., McGuire, M. A. and Steppe, K. (2015): Responses of tree species to heat waves and extreme heat events. Plant Cell Environ 38 (9), 1699–1712. https://www.doi.org/10.1111/pce.12417.

TFCCA – Task Force for Climate Change Adaptation (2012): How to manage cloudburst and rainwater - Action plan for a climate-proof Denmark. Copenhagen: Danish Nature Agency.

The City of Copenhagen (2012): Cloudburst Management Plan 2012. Copenhagen: The City of Copenhagen.

The City of Copenhagen (2015): Climate Change Adaptation and Investment Statement. Copenhagen: The City of Copenhagen.

The City of Copenhagen (2016): Klimakvarter: Copenhagen's first climate resilient neighborhood. Copenhagen: The City of Copenhagen.

Thielbörger, P. (2014): The Right(s) to Water. The Multi-Level Governance of a Unique Human Right. Heidelberg: Springer. https://www.doi.org/10.1007/978-3-642-33908-0.

Thieme, M., Birnie-Gauvin, K., Opperman, J. J., Franklin, P. A., Richter, H., Baumgartner, L., Ning, N., Vu, A. V., Brink, K., Sakala, M., O'Brien, G. C., Petersen, R., Tongchai, P. and Cooke, S. J. (2023): Measures to safeguard and restore river connectivity. Environmental Reviews 0 (0), 1–21. https://doi.org/10.1139/er-2023-0019.

Thierfelder, C., Rusinamhodzi, L., Setimela, P., Walker, F. and Eash, N. S. (2015): Conservation agriculture and drought-tolerant germplasm: Reaping the benefits of climate-smart agriculture technologies in central Mozambique. Renewable Agriculture and Food Systems 31 (5), 414–428. https://www.doi.org/10.1017/s1742170515000332.

Thomashausen, S., Maennling, N. and Mebratu-Tsegaye, T. (2018): A comparative overview of legal frameworks governing water use and waste water discharge in the mining sector. Resources Policy 55, 143–151. https://doi.org/10.1016/j.resourpol.2017.11.012.

Thompson-Hall, M., Carr, E. R. and Pascual, U. (2016): Enhancing and expanding intersectional research for climate change adaptation in agrarian settings. Ambio 45 (3), 373–382. https://www.doi.org/10.1007/s13280-016-0827-0.

Tickner, D., Opperman, J. J., Abell, R., Acreman, M., Arthington, A. H., Bunn, S. E., Cooke, S. J., Dalton, J., Darwall, W., Edwards, G., Harrison, I., Hughes, K., Jones, T., Leclere, D., Lynch, A. J., Leonard, P., McClain, M. E., Muruven, D., Olden, J. D., Ormerod, S. J., Robinson, J., Tharme, R. E., Thieme, M., Tockner, K., Wright, M. and Young, L. (2020): Bending the Curve of Global Freshwater Biodiversity Loss: An Emergency Recovery Plan. Bioscience 70 (4), 330–342. https://www.doi.org/10.1093/biosci/biaa002.

Timmermann, A., Yun, K. S., Raia, P., Ruan, J., Mondanaro, A., Zeller, E., Zollikofer, C., Ponce de Leon, M., Lemmon, D., Willeit, M. and Ganopolski, A. (2022): Climate effects on archaic human habitats and species successions. Nature 604 (7906), 495–501. https://www.doi.org/10.1038/s41586-022-04600-9.

Tischbein, B., Manschadi, A. M., Conrad, C., Hornidge, A.-K., Bhaduri, A., Ul Hassan, M., Lamers, J. P. A., Awan, U. K. and Vlek, P. L. G. (2013): Adapting to water scarcity: constraints and opportunities for improving irrigation management in Khorezm, Uzbekistan. Water Supply 13 (2), 337–348. https://doi.org/10.2166/ws.2013.028.

TNC – The Nature Conservancy (2018): Water Funds. Field Guide 2018. Arlington, USA: TNC.

Tomar, P., Thakur, N., Jhamta, S., Chowdhury, S., Kapoor, M., Singh, S., Shreaz, S., Rustagi, S., Rai, P. K., Rai, A. K. and Yadav, A. N. (2024): Bacterial biopesticides: Biodiversity, role in pest management and beneficial impact on agricultural and environmental sustainability. Heliyon 10 (11), e31550. https://doi.org/10.1016/j.heliyon.2024.e31550.

Tomscha, S. A., Bentley, S., E., P., Jackson, B., de Roiste, M., Hartley, S., Norton, K. and Deslippe, J. R. (2021): Multiple methods confirm wetland restoration improves ecosystem services. Ecosystems and People 17 (1), 25–40. https://doi.org/10.1080/26395916.2020.1863266.

Toshovski, S., Kaiser, M., Fuchs, S., Sacher, F., Thoma, A. and Kümmel, V. (2020): Prioritäre Stoffe in kommunalen Kläranlagen: Ein deutschlandweit harmonisiertes Vorgehen. Dessau-Roßlau: Umweltbundesamt (UBA).

Toxopeus, H. and Polzin, F. (2021): Reviewing financing barriers and strategies for urban nature-based solutions. Journal of Environmental Management 289, 112371. https://doi.org/10.1016/j.jenvman.2021.112371.

Tozer, L. (2023): Water pollution ‚timebomb' threatens global health. Berlin: Nature. https://doi.org/10.1038/d41586-023-02337-7, published on 18.07.2023.

TPI – Tibet Policy Institute (2016): Lichu River Poisoned. Dharamsala, Indien: https://tibetpolicy.net/lichu-river-poisoned/, published on 4.06.2016.

Trémolet, S., Favero, A., Karres, N., Toledo, M., Kampa, E., Lago, M., Anzaldua, G., Vidaurre, R., Tarpey, J., Makropoulos, C., Lykou, A., Hanania, S., Rebollo, V. and Anton, B. (2019): Investing in Nature for European Water Security. London: The Nature Conservancy, Ecologic Institute and ICLEI.

Truppa, C., Yaacoub, S., Valente, M., Celentano, G., Ragazzoni, L. and Saulnier, D. (2024): Health systems resilience in fragile and conflict-affected settings: a systematic scoping review. Conflict and Health 18 (1), 2. https://www.doi.org/10.1186/s13031-023-00560-7.

Tschora, H. and Cherubini, F. (2020): Co-benefits and trade-offs of agroforestry for climate change mitigation and other sustainability goals in West Africa. Global Ecology and Conservation 22, e00919. https://doi.org/10.1016/j.gecco.2020.e00919.

Tsilimekis, K. (2023): Antibiotika schützen, Resistenzen bekämpfen. Antibiotikaeinsatz in der industriellen Tierhaltung systematisch reduzieren. Bonn: Germanwatch.

TU Berlin – Technische Universität Berlin Chair of Sustainable Engineering (2020): The Water Footprint of Organizations - Local Measures in Global Supply Chains, Final Report WELLE project. Berlin: TU Berlin. https://bmbf-grow.de/de/welle.

Tubridy, F. (2020): Green climate change adaptation and the politics of designing ecological infrastructures. Geoforum 113, 133–145. https://doi.org/10.1016/j.geoforum.2020.04.020.

Tups, G. (2022): Goldkugel oder Krisenverstärker? Neue Abhängigkeiten von synthetischen Düngemitteln and ihre Folgen für den afrikanischen Kontinent. Berlin: INKOTA-netzwerk e.V.

Turkelboom, F., Demeyer, R., Vranken, L., De Becker, P., Raymaekers, F. and De Smet, L. (2021): How does a nature-based solution for flood control compare to a technical solution? Case study evidence from Belgium. Ambio 50 (8), 1431–1445. https://doi.org/10.1007/s13280-021-01548-4.

Twomlow, S., Hove, L., Mupangwa, W., Masikati, P. and Mashingaidze, N. (2008): Precision conservation agriculture for vulnerable farmers in low-potential zones. Proceedings of the Workshop on Increasing the Productivity and Sustainability of Rainfed Cropping Systems of Poor, Smallholder Farmers, Tamale, Ghana, 22-25 September 2008. Colombo, Sri Lanka: The CGIAR Challenge Program on Water and Food.

UBA – Umweltbundesamt (2017): Sind Biozideinträge in die Umwelt von besorgniserregendem Ausmaß? Empfehlungen des Umweltbundesamtes für eine Vorgehensweise zur Untersuchung der Umweltbelastung durch Biozide. UBA-Texte 15/2017. Dessau-Roßlau: UBA. https://www.umweltbundesamt.de/publikationen/sind-biozideintraege-in-die-umwelt-von.

UBA – Umweltbundesamt and BMU – Bundesministerium für Umwelt (2017): Wasserwirtschaft in Deutschland. Grundlagen, Belastungen, Maßnahmen. Dessau-Roßlau: UBA, BMU. https://www.umweltbundesamt.de/publikationen/wasserwirtschaft-in-deutschland-grundlagen.

UBA – Umweltbundesamt (2018a): Klimaschutz and Abwasserbehandlung. Sinnvolle Beiträge zur Energiewende. Dessau-Roßlau: UBA.

UBA – Umweltbundesamt (2018b): Dynamik der Klarwasseranteile in Oberflächengewässern and mögliche Herausforderung für die Trinkwassergewinnung in Deutschland. UBA-Texte 59/2018. Dessau-Roßlau: UBA.

UBA – Umweltbundesamt (2021a): 20 Jahre Wasserrahmenrichtlinie: Empfehlungen des Umweltbundesamtes. Dessau-Rosslau,: UBA. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2021_pp_20jahre_wrrl_bf.pdf.

UBA – Umweltbundesamt (2021b): Klimawirkungs- and Risikoanalyse 2021 für Deutschland, Teilbericht 1: Grundlagen. Dessau-Roßlau: UBA.

UBA – Umweltbundesamt (2022a): Konzeptionelle Weiterentwicklung des Wasserfußabdrucks. Zur Abbildung möglicher qualitativer and quantitativer Wasserbelastungen entlang eines Produktlebenszyklus. Texte 44/2022. Dessau-Roßlau: UBA. https://www.umweltbundesamt.de/publikationen/konzeptionelle-weiterentwicklung-des.

UBA – Umweltbundesamt (2022b): Wasserressourcen and ihre Nutzung. Dessau-Roßlau: UBA. https://www.umweltbundesamt.de/daten/wasser/wasserressourcen-ihre-nutzung#die-wassernutzer, published on 14.11.2022.

UBA – Umweltbundesamt (2022c): Indikator: Nutzung der Wasserressourcen. https://www.umweltbundesamt.de/print/17814, published on 14.11.2022.

UBA – Umweltbundesamt (2023a): Moving forward: The European Commission's Proposal for a Recast Urban Wastewater Treatment Directive. Scientific Opinion Paper. Dessau-Roßlau: UBA. https://www.umweltbundesamt.de/publikationen/moving-forward-the-european-commissions-proposal.

UBA – Umweltbundesamt (2023b): EU-Verordnung zu Wasserwiederverwendung. Dessau-Roßlau: UBA. https://www.umweltbundesamt.de/themen/wasser/wasser-bewirtschaften/wasserwiederverwendung/eu-verordnung-zu-wasserwiederverwendung#undefined, published on 20.07.2023.

UBA – Umweltbundesamt (2023c): Abwasserwärme Ad-hoc Papier. Dessau-Roßlau: UBA. https://www.umweltbundesamt.de/publikationen/abwasserwaerme.

UBA – Umweltbundesamt (2023d): Monitoringbericht 2023 zur Deutschen Anpassungsstrategie an den Klimawandel. Bericht der Interministeriellen Arbeitsgruppe Anpassungsstrategie der Bundesregierung. Dessau-Roßlau: UBA. https://www.umweltbundesamt.de/publikationen/monitoringbericht-2023.

UIS – UNESCO Institute for Statistics (2024): Research and Development Expenditure (% of GDP). Montreal, Quebec: UIS. http://data.uis.unesco.org, accessed on 25.07.2024.

UN – United Nations (1994): United Nations Convention to Combat Desertification in those Countries Experiencing Serious Drought and/or Desertification, particularly in Africa –UNCCD. New York: UN.

UN – United Nations (2002): General comment no. 15 (2002) of the Committee on Economic, Social and Cultural Rights, The right to water (arts. 11 and 12 of the International Covenant on Economic, Social and Cultural Rights). New York: UN. https://digitallibrary.un.org/record/486454?v=pdf.

UN – United Nations (2008): UN Human Rrights Council Resolution 7/22 Human rights and access to safe drinking water and sanitation. New York: UN.

UN – United Nations (2010): Resolution adopted by the Human Rights Council 15/9 Human rights and access to safe drinking water and sanitation. New York: UN.

UN – United Nations (2011): UN Human Rights Council Resolution 16/2 The human right to safe drinking water and sanitation. New York: UN.

UN – United Nations (2018): Sustainable Development Goal 6. Synthesis Report 2018 on Water and Sanitation. New York: UN. https://www.unwater.org/publications/sdg-6-synthesis-report-2018-water-and-sanitation.

UN – United Nations (2019): World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). New York: UN.

UN – United Nations (2022): The Sustainable Development Goals Report 2022. New York: UN. https://unstats.un.org/sdgs/report/2022/goal-06/.

UN – United Nations (2023a): The Sustainable Development Goals Report. Special edition: Towards a Rescue Plan for People and Planet. New York: UN. https://unstats.un.org/sdgs/report/2023/.

UN – United Nations (2023b): Letter from the President of the General Assembly – Water for Sustainable Development Conference Summary. New York: UN. https://www.un.org/pga/77/2023/05/08/letter-from-the-president-of-the-general-assembly-water-for-sustainable-development-conference-summary/.

UN – United Nations (2023c): Global Sustainable Development Report 2023: Times of crisis, times of change: Science for accelerating transformations to sustainable development. New York: UN.

UN – United Nations (2024): United Nations System-wide Strategy for Water and Sanitation. New York: UN.

UN Water – United Nations Water (2021): Summary Progress Update 2021 – SDG 6 – water and sanitation for all. Version: July 2021. Geneva: UN Water. https://www.unwater.org/publications/summary-progress-update-2021-sdg-6-water-and-sanitation-all.

UN Water – United Nations Water (2023): WMO's Early Warnings for All - Action Plan for Africa. Geneva: UN Water. https://www.unwater.org/news/wmo%E2%80%99s-early-warnings-all-action-plan-africa, published on 16.10.2023.

UN Water – United Nations Water (2024): Sustainable Development Goal 6 on water and sanitation (SDG 6): Global Status. Geneva: UN Water. https://www.sdg6data.org/en, accessed on 7.06.2024.

UN-Habitat – United Nations Human Settlements Programme (2022): World Cities Report 2022: Envisaging the Future of Cities. Nairobi: UN-Habitat. https://unhabitat.org/world-cities-report-2022-envisaging-the-future-of-cities.

UNCCD – United Nations Convention to Combat Desertification (2023): Global Drought Snapshot 2023: The Need For Proactive Action. Bonn, New York: UNCCD.

UNCTAD – United Nations Conference on Trade and Development (2024): UN list of least developed countries. Geneva: UNCTAD. https://unctad.org/topic/least-developed-countries/list, accessed on 6.02.2024.

UNDP – United Nations Development Programme (2022): Human Development Report 2021/2022: Uncertain times, unsettled lives. Shaping our future in a transforming world. New York: UNDP.

UNDP – United Nations Development Programme and OPHI – Oxford Poverty & Human Development Initiative (2022): Global Multidimensional Poverty Index 2022: Unpacking deprivation bundles to reduce multidimensional poverty. New York, Oxford: UNDP, OPHI.

UNDRR – United Nations Office for Disaster Risk Reduction (2024a): Regional Office for Europe and Central Asia. Geneva: UNDRR. https://www.undrr.org/about-undrr/where-we-work/regional-office-europe-central-asia, accessed on 4.03.2024.

UNDRR – United Nations Office for Disaster Risk Reduction (2024b): Regional platforms. Geneva: UNDRR. https://www.undrr.org/implementing-sendai-framework/regional-platforms, accessed on 4.03.2024.

UNECE – United Nations Economic Commission for Europe (1999): Protocol on Water and Health to the 1992 Convention on the Protection and Use of Transboundary Watercourses and International Lakes. MP.WAT/2000/1. EUR/ICP/EHCO 020205/8Fin. Den Haag: UNECE. https://unece.org/DAM/env/documents/2000/wat/mp.wat.2000.1.e.pdf.

UNECE – United Nations Economic Commission for Europe (2024): Accelerating transboundary water cooperation through increased accession to and strengthened implementation of the Water Convention. Geneva: UNECE. https://sdgs.un.org/partnerships/accelerating-transboundary-water-cooperation-through-increased-accession-and, accessed on 27.03.2024.

UNEP – United Nations Environment Programme (1991): Report of the meeting of the legal expert group to examine the concept of common concern of mankind in relation to environmental issues. Nairobi: UNEP.

UNEP – United Nations Environment Programme (2021a): Progress on Integrated Water Resources Management. Tracking SDG 6 series: global indicator 6.5.1 updates and acceleration needs. Nairobi: UNEP.

UNEP – United Nations Environment Programme (2021b): Progress on Freshwater Ecosystems: Tracking SDG 6 Series – Global Indicator 6.6.1 Updates and Acceleration Needs. Nairobi: UNEP. https://wedocs.unep.org/20.500.11822/36691.

UNEP – United Nations Environment Programme, WEF – World Economic Forum, ELD – Economics of Land Degradation Initiative and Vivid Economics (2021): State Of Finance For Nature: Tripling investments in nature-based solutions by 2030. Nairobi: UNEP.

UNEP – United Nations Environment Programme (2022): Integrated water resources management - climate change adaptation case studies. Nairobi: UNEP. https://www.unep.org/resources/case-study/integrated-water-resources-management-climate-change-adaptation-case-studies, accessed on 28.05.2024.

UNEP – United Nations Environment Programme (2023): Bracing for Superbugs: Strengthening environmental action in the One Health response to antimicrobial resistance. Nairobi: UNEP.

UNESCO – United Nations Educational Scientific and Cultural Organisation, UN Water – United Nations Water and WWAP – World Water Assessment Programme (2024): The United Nations World Water Development Report 2024: Water for Prosperity and Peace. Paris: UNESCO.

UNESCO – United Nations Educational Scientific and Cultural Organization (1971): Übereinkommen über Feuchtgebiete, insbesondere als Lebensraum für Wasser- and Watvögel, von internationaler Bedeutung. Ramsar, Paris: UNESCO.

UNESCO – United Nations Educational Scientific and Cultural Organization, UN Water – United Nations Water and WWAP – World Water Assessment Programme (2017): The United Nations World Water Development Report 2017. Wastewater: The Untapped Resource. Paris: UNESCO.

UNESCO – United Nations Educational Scientific and Cultural Organization, UN Water – United Nations Water and WWAP – World Water Assessment Programme (2020): The United Nations World Water Development Report 2020: Water and Climate Change. Paris: UNESCO.

UNESCO – United Nations Educational Scientific and Cultural Organization (2021): UNESCO Science Report - The Race against Time for Smarter Development. Paris: UNESCO.

UNESCO – United Nations Educational Scientific and Cultural Organization, UN Water – United Nations Water and WWAP – World Water Assessment Programme (2021): The United Nations World Water Development Report 2021: Valuing Water. Paris: UNESCO. https://www.unwater.org/publications/un-world-water-development-report-2021.

UNESCO – United Nations Educational Scientific and Cultural Organization, UN Water – United Nations Water and WWAP – World Water Assessment Programme (2023): The United Nations World Water Development Report 2023: Partnerships and Cooperation for Water. Paris: UNESCO.

UNESCO IHP – UNESCO Intergovernmental Hydrological Programme (2022): IHP-IX Strategic Plan: Science for a Water Secure World in a Changing Environment. Ninth Phase 2022-2029. Paris: UNESCO.

UNFCCC – United Nations Framework Convention of Climate Change (2023a): Matters relating to adaptation. Glasgow–Sharm el-Sheikh work programme on the global goal on adaptation referred to in decision 7/CMA.3. UN Doc: FCCC/PA/CMA/2023/L.18. New York: United Nations (UN).

UNFCCC – United Nations Framework Convention of Climate Change (2023b): Record Number of National Adaptation Plans Submitted in 2023, But More Are Needed. New York: United Nations (UN). https://unfccc.int/news/record-number-of-national-adaptation-plans-submitted-in-2023-but-more-are-needed, published on 13.12.2023.

UNFCCC – United Nations Framework Convention on Climate Change (2023c): National adaptation plans 2023. Progress in the formulation and implementation of NAPs. Bonn: United Nations (UN). https://unfccc.int/documents/635394.

UNFCCC – United Nations Framework Convention of Climate Change (2024a): New Collective Quantified Goal on Climate Finance. New York: United Nations (UN). https://unfccc.int/NCQG, accessed on 30.05.2024.

UNFCCC – United Nations Framework Convention of Climate Change (2024b): Loss and Damage. Online Guide. New York: United Nations (UN). https://unfccc.int/sites/default/files/resource/loss_and_damage_online_guide.pdf.

Unfried, K., Kis-Katos, K. and Poser, T. (2022): Water scarcity and social conflict. Journal of Environmental Economics and Management 113, 102633. https://doi.org/10.1016/j.jeem.2022.102633.

UNGA – United Nations General Assembly (2010): Resolution 64/292 „The human right to water and sanitation". New York: United Nations (UN).

UNGA – United Nations General Assembly (2013): Resolution 68/157: The human right to safe drinking water and sanitation. New York: United Nations (UN).

UNGA – United Nations General Assembly (2015a): Aktionsagenda von Addis Abeba der dritten Internationalen Konferenz über Entwicklungsfinanzierung (Aktionsagenda von Addis Abeba). Resolution der Generalversammlung A/RES/69/313, verabschiedet am 27. Juli 2015. New York: United Nations (UN).

UNGA – United Nations General Assembly (2015b): Resolution 70/169 The Human Right to safe drinking water and sanitation. New York: United Nations (UN).

UNGA – United Nations General Assembly (2022): Resolution 76/300. The human right to a clean, healthy and sustainable environment. New York: United Nations (UN).

UNGA – United Nations General Assembly (2023): Follow-up to the United Nations Conference on the Midterm Comprehensive Review of the Implementation of the Objectives of the International Decade for Action, "Water for Sustainable Development", 2018–2028. A/RES/77/334. New York: United Nations (UN).

UNICEF – United Nations Children's Fund (2018): Zimbabwe – Water, Sanitation and Hygiene (WASH) 2018 Budget Brief. New York: UNICEF.

UNICEF – United Nations Children's Fund and WHO – World Health Organization (2023): Progress on household drinking-water, sanitation and hygiene 2000-2022: Special focus on gender. New York: UNICEF, WHO. https://www.unwater.org/publications/who/unicef-joint-monitoring-program-update-report-2023.

UNICEF – United Nations Children's Fund (2021): Urban Water Scarcity Guidance Note. Preventing Day Zero. New York: UNICEF.

Unruh, G. C. (2000): Understanding carbon lock-in. Energy Policy 28 (12), 817–830. https://www.doi.org/10.1016/S0301-4215(00)00070-7.

UNWC – United Nations Water Conference (2023): Interactive dialogue 1: water for health: access to water, sanitation and hygiene, including the human rights to safe drinking water and sanitation (Sustainable Development Goal targets 6.1, 6.2 and 6.3 and Goals 1, 3, 4, 5 and 17). New York: United Nations (UN).

Upadhyay, V. (2006): A Rights Based Approach to Water User Associations in India. New Delhi: International Environmental Law Research Centre (IELRC). https://www.ielrc.org/activities/workshop_0612/content/d0620.pdf.

UWCI – Urban Water Catalyst Initiative (2024): The Urban Water Catalyst Initiative. Bonn: UWCI. https://www.urbanwaterci.org/home, accessed on 1.06.2024.

Vallino, E., Ridolfi, L. and Laio, F. (2021): Trade of economically and physically scarce virtual water in the global food network. Scientific Reports 11 (1), 22806. https://doi.org/10.1038/s41598-021-01514-w.

van Oppenraaij, J., Torkelson, R., van Ginhoven, D., Blokland, M., Mbage, N. a. a., Sweerts, J. P. and Njoroge, E. (2022): Chapter 15 - Tapping local capital markets for water and sanitation: the case of the Kenya Pooled Water Fund. In: Leflaive, X., Dominique, K. and Alaerts, G. J. (Hrsg.): Financing Investment in Water Security. Amsterdam: Elsevier, 309–345. https://doi.org/10.1016/B978-0-12-822847-0.00011-9.

van Veen, H. and Sasidharan, R. (2021): Shape shifting by amphibious plants in dynamic hydrological niches. New Phytologist 229 (1), 79–84. https://doi.org/10.1111/nph.16347.

van Vliet, M. T. H., Wiberg, D., Leduc, S. and Riahi, K. (2016): Power-generation system vulnerability and adaptation to changes in climate and water resources. Nature Climate Change 6 (4), 375–380. https://www.doi.org/10.1038/nclimate2903.

van Vliet, M. T. H., Thorslund, J., Strokal, M., Hofstra, N., Flörke, M., Ehalt Macedo, H., Nkwasa, A., Tang, T., Kaushal, S. S., Kumar, R., van Griensven, A., Bouwman, L. and Mosley, L. M. (2023): Global river water quality under climate change and hydroclimatic extremes. Nature Reviews Earth & Environment, 1–16. https://doi.org/10.1038/s43017-023-00472-3.

van Westen, R. M., Kliphuis, M. and Dijkstra, H. A. (2024): Physics-based early warning signal shows that AMOC is on tipping course. Science Advances 10 (6), eadk1189. https://www.doi.org/10.1126/sciadv.adk1189.

Vansteelant, W. M. G. (2023): A godwit perspective on rapid wetland loss in Doñana and the Guadalquivir delta. Wader Study 130 (2), 95–98. https://www.doi.org/10.18194/ws.00315.

Vari, A., Podschun, S. A., Eros, T., Hein, T., Pataki, B., Ioja, I. C., Adamescu, C. M., Gerhardt, A., Gruber, T., Dedic, A., Ciric, M., Gavrilovic, B. and Baldi, A. (2022): Freshwater systems and ecosystem services: Challenges and chances for cross-fertilization of disciplines. Ambio 51 (1), 135–151. https://www.doi.org/10.1007/s13280-021-01556-4.

VCI – Verband der Chemischen Industrie (2017): Beiträge der Chemie zur Wasserversorgung der Zukunft aus Sicht der Forschungs- and Technologiepolitik. Frankfurt am Main: VCI.

Veldwisch, G. J. A. (2008): Cotton, rice & water: the transformation of agrarian relations, irrigation technology and water distribution in Khorezm, Uzbekistan. Dissertation. Bonn: Rheinische Friedrich-Wilhelms-Universität Bonn. https://hdl.handle.net/20.500.11811/3285.

Vera, M. L., Torres, W. R., Galli, C. I., Chagnes, A. and Flexer, V. (2023): Environmental impact of direct lithium extraction from brines. Nature Reviews Earth & Environment 4, 149–165. https://www.doi.org/10.1038/s43017-022-00387-5.

Viviroli, D., Dürr, H. H., Messerli, B., Meybeck, M. and Weingartner, R. (2007): Mountains of the world, water towers for humanity: Typology, mapping, and global significance. Water Resources Research 43 (7), 1–11. https://www.doi.org/10.1029/2006wr005653.

Vogl, A. L., Bryant, B. P., Hunink, J. E., Wolny, S., Apse, C. and Droogers, P. (2017): Valuing investments in sustainable land management in the Upper Tana River basin, Kenya. Journal of Environmental Management 195 (1), 78–91. https://doi.org/10.1016/j.jenvman.2016.10.013.

von Bogdandy, A. and Goldmann, M. (2009): Die Ausübung internationaler öffentlicher Gewalt durch Politikbewertung. Die PISA-Studie der OECD als Muster einer neuen völkerrechtlichen Handlungsform. Zeitschrift für ausländisches öffentliches Recht and Völkerrecht (ZaöRV) 69, 51–102.

von der Leyen, U. (2024): Europe's Choice: Political Guidelines for the Next European Commission 2024–2029. Straßburg: EU.

von Haldenwang, C. (2017): The political cost of local revenue mobilization: decentralization of the property tax in indonesia. Public Finance and Management 17 (2), 124–151. https://doi.org/10.1177/152397211701700202.

von Haldenwang, C., Millán-Narotzky, L., Mosquera Valderrama, I. and Redonda, A. (2024): The Role of Tax Expenditures in Enabling Illicit Financial Flows. International Development Policy. Revue internationale de politique de développement, 17. https://doi.org/10.4000/11q99.

Wada, Y., van Beek, L. P. H., van Kempen, C. M., Reckman, J. W. T. M., Vasak, S. and Bierkens, M. F. P. (2010): Global depletion of groundwater resources. Geophysical Research Letters 37 (20), 1–5. https://www.doi.org/10.1029/2010gl044571.

Wada, Y., van Beek, L. P. H. and Bierkens, M. F. P. (2012): Nonsustainable groundwater sustaining irrigation: A global assessment. Water Resources Research 48 (6), 1–18. https://www.doi.org/10.1029/2011wr010562.

Wada, Y. and Bierkens, M. F. (2014): Sustainability of global water use: past reconstruction and future projections. Environmental Research Letters 9 (10), 104003. https://www.doi.org/10.1088/1748-9326/9/10/104003.

Wada, Y., Flörke, M., Hanasaki, N., Eisner, S., Fischer, G., Tramberend, S., Satoh, Y., Van Vliet, M. T. H., Yillia, P., Ringler, C., Burek, P. and Wiberg, D. (2016): Modeling global water use for the 21st century: the Water Futures and Solutions (WFaS) initiative and its approaches. Geoscientific Model Development 9 (1), 175–222. https://www.doi.org/10.5194/gmd-9-175-2016.

Wagenknecht, K., Woods, T., Nold, C., Rüfenacht, S., Voight-Heucke, S., Caplan, A., Hecker, S. and Vohland, K. (2021): A question of dialogue? Reflections on how citizen science can enhance communication between science and society. Journal of Science Communication 20 (3), A13. https://doi.org/10.22323/2.20030213.

Wagner-Wenz, R., van Zuilichem, A.-J., Göllner-Völker, L., Berberich, K., Weidenkaff, A. and Schebek, L. (2023): Recycling routes of lithium-ion batteries: A critical review of the development status, the process performance, and life-cycle environmental impacts. MRS Energy & Sustainability 10, 1–34. https://www.doi.org/10.1557/s43581-022-00053-9.

Waleng, N. J. and Nomngongo, P. N. (2022): Occurrence of pharmaceuticals in the environmental waters: African and Asian perspectives. Environmental Chemistry and Ecotoxicology 4, 50–66. https://doi.org/10.1016/j.enceco.2021.11.002.

Walker, W. E., Loucks, D. P. and Carr, G. (2015): Social Responses to Water Management Decisions. Environmental Processes 2 (3), 485–509. https://www.doi.org/10.1007/s40710-015-0083-5.

Wang, H. and Ma, M. (2016): Impacts of Climate Change and Anthropogenic Activities on the Ecological Restoration of Wetlands in the Arid Regions of China. Energies 9 (3), https://www.doi.org/10.3390/en9030166.

Wang, M., Bodirsky, B. L., Rijneveld, R., Beier, F., Bak, M. P., Batool, M., Droppers, B., Popp, A., van Vliet, M. T. H. and Strokal, M. (2024): A triple increase in global river basins with water scarcity due to future pollution. Nat Commun 15 (1), 880. https://www.doi.org/10.1038/s41467-024-44947-3.

Wang, R., Ding, J., Ge, X., Wang, J., Qin, S., Tan, J., Han, L. and Zhang, Z. (2023): Impacts of climate change on the wetlands in the arid region of Northwestern China over the past 2 decades. Ecological Indicators 149, https://www.doi.org/10.1016/j.ecolind.2023.110168.

Wang, X., Daigger, G., de Vries, W., Kroeze, C., Yang, M., Ren, N.-Q., Liu, J. and Butler, D. (2019): Impact hotspots of reduced nutrient discharge shift across the globe with population and dietary changes. Nature communications 10 (1), 2627. https://doi.org/10.1038/s41467-019-10445-0.

Wang-Erlandsson, L., Fetzer, I., Keys, P. W., van der Ent, R. J., Savenije, H. H. G. and Gordon, L. J. (2018): Remote land use impacts on river flows through atmospheric teleconnections. Hydrology and Earth System Sciences 22 (8), 4311–4328. https://www.doi.org/10.5194/hess-22-4311-2018.

Wang-Erlandsson, L., Tobian, A., Van Der Ent, R. J., Fetzer, I., Te Wierik, S., Porkka, M., Staal, A., Jaramillo, F., Dahlmann, H., Singh, C., Greve, P., Gerten, D., Keys, P. W., Gleeson, T., Cornell, S. E., Steffen, W., Bai, X. and Rockström, J. (2022): A planetary boundary for green water. Nature Reviews Earth & Environment 3 (6), 380–392. https://www.doi.org/10.1038/s43017-022-00287-8.

Wasser-Wissen (2024): Biochemischer Sauerstoffbedarf (BSB). Langwedel: Wasser-Wissen. http://www.wasser-wissen.de/abwasserlexikon/b/bsb.htm, accessed on 20.11.2024.

Wasti, A., Ray, P., Wi, S., Folch, C., Ubierna, M. and Karki, P. (2022): Climate change and the hydropower sector: A global review. WIREs Climate Change 13 (2), e757. https://www.doi.org/10.1002/wcc.757.

Watari, T., Nansai, K., Nakajima, K. and Giurco, D. (2021): Sustainable energy transitions require enhanced resource governance. Journal of Cleaner Production 312 (127698), https://www.doi.org/10.1016/j.jclepro.2021.127698.

Water for Climate Pavilion (2024): Achieving the Global Goal on Adaptation. Dubai: Water for Climate Pavilion. https://waterforclimate.net/themes/global-goal-on-adaptation/, accessed on 30.05.2024.

WaterAid (2024): Clean Nigeria Campaign. Nigeria ranks first among countries practicing open defecation globally. Here's what we are supporting the Government to implement to address the crisis. Jabi, Nigeria: WaterAid. https://www.wateraid.org/ng/get-involved/clean-nigeria-campaign, accessed on 10.04.2024.

Watts, J. (2017): The Amazon effect: how deforestation is starving São Paulo of water. London: The Guardian. https://www.theguardian.com/cities/2017/nov/28/sao-paulo-water-amazon-deforestation, published on 28.11.2017.

WBGU – German Advisory Council on Global Change (2011): World in Transition: A Social Contract for Sustainability. Flagship Report. Berlin: WBGU.

WBGU – German Advisory Council on Global Change (2016): Humanity on the move: Unlocking the transformative power of cities. Flagship Report. Berlin: WBGU.

WBGU – German Advisory Council on Global Change (2019): Towards our Common Digital Future. Flagship Report. Berlin: WBGU.

WBGU – German Advisory Council on Global Change (2020): Rethinking Land in the Anthropocene. Flagship Report. Berlin: WBGU.

WBGU – German Advisory Council on Global Change (2021): Beyond Climate Neutrality. Policy Paper 12. Berlin: WBGU.

WBGU – German Advisory Council on Global Change (2023): Healthy living on a healthy planet. Flagship Report. Berlin: WBGU.

WBGU – German Advisory Council on Global Change (2024): Biodiversity: Act Now for Nature and Humanity. Policy Paper 13. Berlin: WBGU.

WD – Wissenschaftliche Dienste des Deutschen Bundestages (2022): Kommunale Finanzhoheit in Deutschland. Sachstand WD 4 - 3000 - 046/22. Berlin: WD 4 Fachbereich - Haushalt and Finanzen.

WD – Wissenschaftliche Dienste des Deutschen Bundestages (2023): Material- and Ressourceneinsatz für den Bau von Kraftwerken. Ausarbeitung WD 5 - 3000 - 138/22. Berlin: WD5 Fachbereich - Wirtschaft and Verkehr, Ernährung and Landwirtschaft.

WEF – World Economic Forum (2024): Quantifying the Impact of Climate Change on Human Health. Insight report. Geneva: WEF.

Weidlich, E. W. A., Flórido, F. G., Sorrini, T. B., Brancalion, P. H. S. and Peralta, G. (2020): Controlling invasive plant species in ecological restoration: A global review. Journal of Applied Ecology 57 (9), 1806–1817. https://www.doi.org/10.1111/1365-2664.13656.

Weiss, E. B. (2012): The Coming Water Crisis: A Common Concern of Humankind. Transnational Environmental Law 1 (1), 153–168. https://www.doi.org/10.1017/S2047102511000100.

Weko, S. and Lahn, G. (2024): Tackling trade-related water risks: How importing countries can address water stress from global commodity production. London: The Royal Institute of International Affairs, Chatham House.

Wen, Y., Schoups, G. and Van De Giesen, N. (2017): Organic pollution of rivers: Combined threats of urbanization, livestock farming and global climate change. Scientific reports 7 (1), 43289. https://doi.org/10.1038/srep43289.

Werner, G., Abu Sin, M., Bahrs, C., Brogden, S., Feßler, A. T., Hagel, S., Kaspar, H., Köck, R., Kreienbrock, L., Krüger-Haker, H., Maechler, F., Noll, I., Pletz, M. W., Tenhagen, B.-A., Schwarz, S., Walther, B. and Mielke, M. (2023): Therapierelevante Antibiotikaresistenzen im One-Health-Kontext. Bundesgesundheitsblatt - Gesundheitsforschung - Gesundheitsschutz 66 (6), 628–643. https://www.doi.org/10.1007/s00103-023-03713-4.

Wester, P. and Warner, J. (2002): River basin management reconsidered. In: Turton, A. and Henwood, R. (Hrsg.): Hydropolitics in the developing world: A Southern African perspective. Pretoria: African Water Issues Research Unit (AWIRU), 61–71.

Westphal-Settele, K., Konradi, S., Balzer, F., Schönfeld, J. and Schmithausen, R. (2018): Die Umwelt als Reservoir für Antibiotikaresistenzen. Bundesgesundheitsblatt - Gesundheitsforschung - Gesundheitsschutz 61 (5), 533–542. https://www.doi.org/10.1007/s00103-018-2729-8.

Wezel, A., Zipfer, M., Aubry, C., Barataud, F. and Heißenhuber, A. (2016): Result-oriented approaches to the management of drinking water catchments in agricultural landscapes. Journal of Environmental Planning and Management 59 (2), 183–202. https://www.doi.org/10.1080/09640568.2014.1000453.

WGG – Wassergenossenschaft Gramastetten (2024): Willkommen: Wassergenossenschaft Gramastetten. Gramastetten: WGG. https://www.wassergenossenschaft.or.at, accessed on 5.03.2024.

Wheeler, S. A., Zuo, A., Xu, Y., Haensch, J. and Seidl, C. (2020): Water market literature review and empirical analysis. Canberra: Australian Competition and Consumer Commission (ACCC).

Whitmee, S., Green, R., Belesova, K., Hassan, S., Cuevas, S., Murage, P., Picetti, R., Clercq-Roques, R., Murray, K., Falconer, J., Anton, B., Reynolds, T., Sharma Waddington, H., Hughes, R. C., Spadaro, J., Aguilar Jaber, A., Saheb, Y., Campbell-Lendrum, D., Cortés-Puch, M., Ebi, K., Huxley, R., Mazzucato, M., Oni, T., de Paula, N., Peng, G., Revi, A., Rockström, J., Srivastava, L., Whitmarsh, L., Zougmoré, R., Phumaphi, J., Clark, H. and Haines, A. (2024): Pathways to a healthy net-zero future: report of the Lancet Pathfinder Commission. Lancet 403 (10421), 67–110. https://www.doi.org/10.1016/s0140-6736(23)02466-2.

WHO – World Health Organization and UNICEF – United Nations Children's Fund (2020): State of the world's sanitation: an urgent call to transform sanitation for better health, environments, economies and societies. New York: WHO, UNICEF.

WHO – World Health Organization (2022a): Guidelines for drinking-water quality. Geneva: WHO. https://www.who.int/publications/i/item/9789240045064.

WHO – World Health Organization (2022b): Fact sheet: Antibiotic Resistance. Geneva: WHO. https://www.who.int/news-room/fact-sheets/detail/antibiotic-resistance, published on 31.07.2020.

WHO – World Health Organization (2023): Burden of disease attributable to unsafe drinking-water, sanitation and hygiene, 2019 update. Geneva: WHO. https://www.who.int/publications/i/item/9789240075610.

WHO – World Health Organization and UNICEF – United Nations Children's Fund (2024): Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP) – bearbeitet durch Our World in Data. Oxford: Our World in Data.

Wilkes, M. A., Carrivick, J. L., Castella, E., Ilg, C., Cauvy-Fraunie, S., Fell, S. C., Fureder, L., Huss, M., James, W., Lencioni, V., Robinson, C. and Brown, L. E. (2023): Glacier retreat reorganizes river habitats leaving refugia for Alpine invertebrate biodiversity poorly protected. Nature Ecology & Evolution 7 (6), 841–851. https://doi.org/10.1038/s41559-023-02061-5.

WISE – Water Information System for Europe (2021): Chemical status - map (with or without uPBTs) by RBD. https://water.europa.eu/freshwater/resources/metadata/dashboards/chemical-status/chemical-status-map-with-or-without-upbts-by-rbd?activeTab=e406a006-cc3c-4948-a680-998dfbd3ad05, published on 14.07.2021.

WMO – World Meteorological Organization (2023): State of Global Water Resources 2022. Geneva: WMO. https://library.wmo.int/idurl/4/68473.

Wohl, E., Lane, S. N. and Wilcox, A. C. (2015): The science and practice of river restoration. Water Resources Research 51 (8), 5974–5997. https://doi.org/10.1002/2014WR016874.

Wolf, J., Johnston, R. B., Ambelu, A., Arnold, B. F., Bain, R., Brauer, M., Brown, J., Caruso, B. A., Clasen, T., Colford, J. M., Jr., Mills, J. E., Evans, B., Freeman, M. C., Gordon, B., Kang, G., Lanata, C. F., Medlicott, K. O., Pruss-Ustun, A., Troeger, C., Boisson, S. and Cumming, O. (2023): Burden of disease attributable to unsafe drinking water, sanitation, and hygiene in domestic settings: a global analysis for selected adverse health outcomes. Lancet 401 (10393), 2060–2071. https://doi.org/10.1016/s0140-6736(23)00458-0.

Wolf, S., Esser, V., Schüttrumpf, H. and Lehmkuhl, F. (2021): Influence of 200 years of water resource management on a typical central European river. Does industrialization straighten a river? Environmental Sciences Europe 33, 15. https://doi.org/10.1186/s12302-021-00460-8.

Wołowiec, M., Komorowska-Kaufman, M., Pruss, A., Rzepa, G. and Bajda, T. (2019): Removal of Heavy Metals and Metalloids from Water Using Drinking Water Treatment Residuals as Adsorbents: A Review. Minerals 9 (8), 487. https://www.doi.org/10.3390/min9080487.

Wong, T. H. F., Rogers, B. C. and Brown, R. R. (2020): Transforming Cities through Water-Sensitive Principles and Practices. One Earth 3 (4), 436–447. https://doi.org/10.1016/j.oneear.2020.09.012.

Woolway, R. I., Sharma, S., Weyhenmeyer, G. A., Debolskiy, A., Golub, M., Mercado-Bettin, D., Perroud, M., Stepanenko, V., Tan, Z., Grant, L., Ladwig, R., Mesman, J., Moore, T. N., Shatwell, T., Vanderkelen, I., Austin, J. A., DeGasperi, C. L., Dokulil, M., La Fuente, S., Mackay, E. B., Schladow, S. G., Watanabe, S., Marce, R., Pierson, D. C., Thiery, W. and Jennings, E. (2021): Phenological shifts in lake stratification under climate change. Nature Communications 12 (1), 2318. https://www.doi.org/10.1038/s41467-021-22657-4.

World Bank (2016a): High and dry: Climate change, water, and the economy. Washington, D.C.: World Bank.

World Bank (2016b): Modernizing Uzbekistan's Water Sector – with Citizen Engagement. Washington, D.C.: World Bank. https://www.worldbank.org/en/news/feature/2016/02/11/modernizing-uzbekistans-water-sector-with-citizen-engagement, published on 11.02.2016.

World Bank (2016c): Water Revolving Fund in the Philippines. Case studies in blended finance for water and sanitation. Washington, D.C.: World Bank Water Global Practice.

World Bank (2018): Beyond Scarcity: Water Security in the Middle East and North Africa. MENA Development Report Series. Washington, D.C.: World Bank. http://hdl.handle.net/10986/27659.

World Bank (2022): Market-Based Models and Public-Private Partnership Options for Non-Sewered Sanitation in Selected Cities and Towns in Kenya. Washington, D.C.: World Bank.

World Bank (2023a): Global Economic Prospects, Juni 2023. Washington, D.C.: World Bank. https://doi.org/10.1596/978-1-4648-1951-3.

World Bank (2023b): Water Overview. Washington, D.C.: World Bank. https://www.worldbank.org/en/topic/water/overview, accessed on 12.12.2023.

World Bank (2023c): What the Future Has in Store: A New Paradigm for Water Storage—Overview for Policy Makers. Washington, DC: World Bank.

World Bank (2023d): World Bank Country and Lending Groups. Washington, DC: World Bank. https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups, accessed on 10.03.2023.

WTO – World Trade Organization (2023): WTO's contribution to attaining UN Sustainable Development Goals: 2023 update to the High-Level Political Forum. Geneva: WTO. https://www.wto.org/english/res_e/publications_e/un_hlpf23_e.htm.

WTO – World Trade Organization (2024): Preparations for upcoming 2024 Global Review of Aid for Trade intensify. Geneva: WTO. https://www.wto.org/english/news_e/news24_e/aid_30apr24_e.htm, accessed on 4.06.2024.

Wunder, S., Kaphengst, T., Frelih-Larsen, A., McFarland, K. and Albrecht, S. (2018): Land Degradation Neutrality. Handlungsempfehlungen zur Implementierung des SDG-Ziels 15.3 and Entwicklung eines bodenbezogenen Indikator. Dessau-Roßlau: Umweltbundesamtes (UBA).

WWC – World Water Council and OECD – Organisation for Economic Co-operation and Development (2015): Water: Fit to Finance? Catalysing national growth through investment in water security. Report of the High Level Panel on Financing Infrastructure for a Water-Secure World. Marseille: WWC.

WWF – World Wide Fund for Nature (2020): Water Stewardship: Gemeinsame Probleme – gemeinsame Lösungen. Gland: WWF. https://www.wwf.de/themen-projekte/fluesse-seen/wasser-politik-maerkte/water-stewardship/, accessed on 4.06.2024.

Xie, Y., Liu, X., Wei, H., Chen, X., Gong, N., Ahmad, S., Lee, T., Ismail, S. and Ni, S.-Q. (2022): Insight into impact of sewage discharge on microbial dynamics and pathogenicity in river ecosystem. Scientific Reports 12 (1), 6894. https://doi.org/10.1038/s41598-022-09579-x.

Xu, H., Liu, L. and Ding, P. (2021a): Building Climate Resilient City through Multiple Scale Cooperative Planning: Experiences from Copenhagen. IOP Conference Series: Materials Science and Engineering 1203 (3), 032063. https://www.doi.org/10.1088/1757-899X/1203/3/032063.

Xu, H., Yang, R. and Song, J. (2021b): Agricultural Water Use Efficiency and Rebound Effect: A Study for China. International Journal of Environmental Research and Public Health 18 (13), 7151. https://www.doi.org/10.3390/ijerph18137151.

Xu, J., Morris, P. J., Liu, J. and Holden, J. (2018): Hotspots of peatland-derived potable water use identified by global analysis. Nature Sustainability 1 (5), 246–253. https://www.doi.org/10.1038/s41893-018-0064-6.

Xu, J., Badola, R., Chettri, N., Chaudhary, R. P., Zomer, R., Pokhrel, B., Hussain, S. A., Pradhan, S. and Pradhan, R. (2019): Sustaining Biodiversity and Ecosystem Services in the Hindu Kush Himalaya. In: Wester, P., Mishra, A., Mukherji, A. and Shrestha, A. B. (Hrsg.): The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People. Cham: Springer Nature, 127–165. https://doi.org/10.1007/978-3-319-92288-1_5.

Yao, T., Bolch, T., Chen, D., Gao, J., Immerzeel, W., Piao, S., Su, F., Thompson, L., Wada, Y., Wang, L., Wang, T., Wu, G., Xu, B., Yang, W., Zhang, G. and Zhao, P. (2022): The imbalance of the Asian water tower. Nature Reviews Earth & Environment 3 (10), 618–632. https://doi.org/10.1038/s43017-022-00299-4.

Yazdan, M. M. S., Kumar, R. and Leung, S. W. (2022): The Environmental and Health Impacts of Steroids and Hormones in Wastewater Effluent, as Well as Existing Removal Technologies: A Review. Ecologies 3 (2), 206–224. https://www.doi.org/10.3390/ecologies3020016.

Yin, J., Gao, Y., Chen, R., Yu, D., Wilby, R., Wright, N., Ge, Y., Bricker, J., Gong, H. and Guan, M. (2023): Flash floods: why are more of them devastating the world's driest regions? Nature 615 (7951), 212–215. https://doi.org/10.1038/d41586-023-00626-9.

Yuan, X., Wang, Y., Ji, P., Wu, P., Sheffield, J. and Otkin, J. A. (2023): A global transition to flash droughts under climate change. Science 380 (6641), 187–191. https://www.doi.org/10.1126/science.abn6301.

Zadjelovic, V., Wright, R. J., Borsetto, C., Quartey, J., Cairns, T. N., Langille, M. G. I., Wellington, E. M. H. and Christie-Oleza, J. A. (2023): Microbial hitchhikers harbouring antimicrobial-resistance genes in the riverine plastisphere. Microbiome 11, 225. https://www.doi.org/10.1186/s40168-023-01662-3.

Zak, D. and McInnes, R. J. (2022): A call for refining the peatland restoration strategy in Europe. Journal of Applied Ecology 59 (11), 2698–2704. https://www.doi.org/10.1111/1365-2664.14261.

Zampieri, M., Ceglar, A., Dentener, F. and Toreti, A. (2017): Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales. Environmental Research Letters 12 (6), 064008. https://www.doi.org/10.1088/1748-9326/aa723b.

Zeit Online (2023): US-Bundesstaaten wollen Wasser sparen, um den Colorado River zu retten. Hamburg: Zeit Online. https://www.zeit.de/politik/ausland/2023-05/usa-klimakrise-colorado-river-wasser-sparen, published on 23.05.2023.

Zeitoun, M., Goulden, M. and Tickner, D. (2013): Current and future challenges facing transboundary river basin management. Wiley Interdisciplinary Reviews: Climate Change 4 (5), 331–349. https://doi.org/10.1002/wcc.228.

Zengerling, C. (2020): Stärkung von Klimaschutz and Entwicklung durch internationales Handelsrecht. Expertise für das WBGU-Hauptgutachten „Landwende im Anthropozän: Von der Konkurrenz zur Integration". Berlin: WBGU.

Zhang, F., Zeng, C., Zhang, Q. and Yao, T. (2022): Securing water quality of the Asian Water Tower. Nature Reviews Earth & Environment 3 (10), 611–612. https://www.doi.org/10.1038/s43017-022-00347-z.

Zhang, G., Carrivick, J. L., Emmer, A., Shugar, D. H., Veh, G., Wang, X., Labedz, C., Mergili, M., Mölg, N., Huss, M., Allen, S., Sugiyama, S. and Lützow, N. (2024): Characteristics and changes of glacial lakes and outburst floods. Nature Reviews Earth & Environment, 1–16. https://www.doi.org/10.1038/s43017-024-00554-w.

Zhang, H., Xu, Y. and Kanyerere, T. (2020): A review of the managed aquifer recharge: Historical development, current situation and perspectives. Physics and Chemistry of the Earth, Parts A/B/C 118–119, 102887. https://doi.org/10.1016/j.pce.2020.102887.

Zhang, T., Wang, W., An, B. and Wei, L. (2023): Enhanced glacial lake activity threatens numerous communities and infrastructure in the Third Pole. Nature Communications 14 (1), 8250. https://www.doi.org/10.1038/s41467-023-44123-z.

Zhang, Y., Zhang, L., Huang, Z., Li, Y., Li, J., Wu, N., He, J., Zhang, Z., Liu, Y. and Niu, Z. (2019): Pollution of polycyclic aromatic hydrocarbons (PAHs) in drinking water of China: Composition, distribution and influencing factors. Ecotoxicology and Environmental Safety 177, 108–116. https://doi.org/10.1016/j.ecoenv.2019.03.119.

References

Zhang, Y. K. and Schilling, K. E. (2006): Effects of land cover on water table, soil moisture, evapotranspiration, and groundwater recharge: A Field observation and analysis. Journal of Hydrology 319 (1–4), 328–338. https://www.doi.org/10.1016/j.jhydrol.2005.06.044.

Zhao, Y., Wang, G., Zhao, M., Wang, M., Hu, N., Jiang, M. and Qin, L. (2021): The potentials of wetland restoration after farming differ between community types due to their differences in seed limit and salt tolerances in the Songnen Plain, China. Ecological Indicators 131, https://www.doi.org/10.1016/j.ecolind.2021.108145.

Zhou, T. and Endreny, T. (2020): The Straightening of a River Meander Leads to Extensive Losses in Flow Complexity and Ecosystem Services. Water 12 (6), 1680. https://doi.org/10.3390/w12061680.

Glossary

2030 Agenda
The declaration 'Transforming our World: the 2030 Agenda for Sustainable Development' (Agenda 2030) adopted by the international community at the United Nations in 2015with its 17 development goals represents a political orientation framework for global sustainability. The goals of the Agenda are to be achieved by 2030. Ideas are already being floated under the heading 'post-2030 Agenda' on future development goals to be agreed for the subsequent period.

Aquifer
An aquifer is a body of rock that contains cavities and is therefore suitable for conducting groundwater. A distinction can be made between pore aquifers (unconsolidated or consolidated rock with predominantly permeable porosity), fissure aquifers (consolidated rock with predominantly permeable fissures) and karst aquifers (consolidated rock with predominantly permeable karst cavities; DIN, 1994).

Biochemical oxygen demand
is the amount of oxygen dissolved in water that is required for the biological degradation of dissolved organic compounds in wastewater (Wasser-Wissen, no date).

Biodiversity
"means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic → *ecosystems* and the ecological complexes of which they are part"; it encompasses the diversity of genes, the diversity of species and the diversity of ecosystems (CBD, 1992: Art. 2).

Blue water
includes all water resources in surface waters (streams, rivers, lakes, reservoirs) and → *groundwater.*

Climate-resilient water management
is an approach to the forward-looking, systemic and adaptable management of local, regional and global water cycles that considers both, blue and green water, and can react flexibly, particularly to climate change.

Cryosphere
refers to all forms of ice and snow in the Earth's climate system: sea ice, ice shelves, land ice, glaciers, icecaps, permafrost ice, seasonally frozen ground, and snow (DWD, 2024).

Deliberative participation processes
Deliberative participation processes (also known as dialogue-oriented participation) are procedures for a discursive process through which an issue is dealt with collectively in order to inform a political decision. Participants can be invited either specifically or by random selection. The latter aims to achieve a composition of participants that reflects a mini-public with a cross-section of society (in terms of age, gender and education). In practice, deliberative participation processes should be designed in such a way that they really lead to gains in information and reflection.

Desertification
is land degradation in arid, semi-arid and dry, sub-humid areas resulting from various factors such as climate variability or human activities (UNCCD, 1994: Art. 1).

Drought
occurs when rainfall is significantly below normal and causes a serious hydrological imbalance that affects production systems for land resources (Reichhuber et al., 2022).

Ecosystem
"means a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit" (CBD, 1992: Art. 2).

Ecosystem restoration
is a measure aimed at enabling the substantive recovery or restoration of a degraded or destroyed → *ecosystem*. Restoration does not mean returning to an original or ideal state. Rather, the aim is to manage ecosystems sensibly and to keep them within sustainable limits, as well as to contribute to climate-change mitigation, climate adaptation, biodiversity conservation and gain and → *climate-resilient water management*. Examples include the rewetting of peatlands and the restoration of natural river courses and floodplain landscapes.

Ecosystem services
denotes the benefits that humans derive from → *ecosystems*. 18 ecosystem services have been identified, divided into regulatory, material and non-material services. A further development of this term is the concept of nature's contributions to people (NCP), which encompasses "all the contributions, both positive and negative, of living nature (...) to people's quality of life", also taking into account the cultural context and the role of Indigenous and local knowledge (Díaz et al., 2018).

Evaporation
refers to water turning into vapour from open surfaces and soils.

Evapotranspiration
is the sum of direct evaporation from the soil and water surfaces (evaporation) and the release of water vapour from the plant and animal world (transpiration).

Exacerbated water-related challenges
The WBGU uses the term exacerbated water-related challenges to describe the consequences of climate change for the water cycle, → *water availability* and → *water quality,* as well as the growing human pressure on water resources, which will continue to increase as a result of unequal distribution and unsustainable lifestyles. In addition, there are geopolitical upheavals that make sustainable water management more difficult. Depending on the regional context, these exacerbations can escalate into → *water emergencies.*

Faecal coliform bacteria
are a physiological group of different bacteria from the *Enterobacteriaceae* family. Only the genus *Escherichia* is unequivocally of faecal origin; all other genera can also occur in the environment. Faecal coliform bacteria (FC) are indicator germs for faecal contamination in water.

Flash droughts
are caused by a heat wave with unusually high air temperatures or as a reaction to an unusually extreme dry period due to a lack of precipitation.

Framework agreement
a treaty under international law under which as large a group of states as possible agrees to cooperate on a particular issue; it is most prevalent in international environmental law (Bodansky et al., 2017; Sands et al., 2018: 106). First, general definitions, goals and principles are established in framework conventions; then commitments, such as scientific research, information exchange and cooperation, are agreed, followed by a rough structure for legal and institutional frameworks for future cooperation (Bodansky et al., 2017: 57). Conferences of the Parties provide a forum for the subsequent development of a common legal and policy framework.

Governance
encompasses 'structures, processes and actions through which private and public actors interact to pursue societal goals. This includes formal and informal institutions and the associated norms, rules, laws and procedures for deciding, managing, implementing and monitoring policies and measures at any geographic or political scale, from global to local' (IPCC, 2022b: 1803). In the context of sustainability, 'global governance' means the institutions, actors, control processes and policy instruments that shape international cooperation and obstacles standing in the way of the transformation towards sustainability (Pattberg and Widerberg, 2015).

Green water
refers to the soil moisture available to plants; when it rains over land areas, some of the water is absorbed in the soil and is available to plants. The rest evaporates or turns into → *blue water.*

Groundwater
is underground water that fills cavities in the lithosphere (outermost layer of the Earth's crust) and whose ability to move is determined solely by gravity (DIN, 1994).

High-income countries
→ *Low- and middle-income countries*

Incremental adaptation measures
→ *Transformative adaptation measures*

Limits of controllability
refers to reaching a threshold beyond which humans and nature are either deprived of their life-support systems or else the risks involved are intolerably high. For example, in a city or region affected by a massive water shortage, a water emergency may arise due to decreasing adaptability and the narrowing room for manoeuvre, and the limits of controllability may be exceeded. The aim must be to maintain a safe distance from these limits.

Lock-in effect
describes persistence in a certain situation due to a decision in favour of a certain technology. A change in the situation is uneconomical or organizationally unfeasible due to high (upfront) investments or other structural limitations. For example, certain technologies may become locked in (→ *Path dependency*) if the subsequent switch to alternative technologies would cause high costs or if entire production chains and societal structures would have to be adapted.

Low-, middle- and high-income countries
The World Bank classifies countries into four income groups, with annual updates based on the previous year's data (hereafter data for fiscal year 2023–2024; World Bank, 2023d): low-income countries (gross national income per capita of US$1,135 or less), lower middle-income countries (US$1,136–4,465); upper middle-income countries (US$4,466–13,845), and high-income countries (US$13,846 or higher).

MENA region
The MENA region (Middle East and North Africa) comprises Algeria, Bahrain, Djibouti, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tunisia, Yemen, the United Arab Emirates, the West Bank and Gaza (World Bank, 2018).

Multidimensional poverty
is a measure of poverty based on the Multidimensional Poverty Index of the United Nations Development Programme (UNDP). This concept of poverty takes into account several indicators from the areas of education, health and standard of living. The focus is on elementary deficiencies, such as a lack of access to long-term education or to clean drinking water (Lepenies and Sieler, 2010).

Novel ecosystems
are "ecosystems that differ in composition and/or function from present and past systems" (Hobbs et al., 2009). Their emergence is associated with global environmental changes, particularly climate change, land-use changes and the spread of invasive species. One example is the emergence of post-glacial ecosystems as a result of melting glaciers (Bosson et al., 2023).

Path dependency
is a situation in which an ongoing development is determined by historical developments or decisions and thus follows a path whose structure becomes increasingly rigid over time (→ *lock-in effect)*. For example, the fact that one technology and not another becomes dominant on the market is not necessarily due to its superiority, but may be the result of historical coincidences and a self-reinforcing process. The costs of 'traditional' technology are low compared to the upfront investment in a new technology, since learning effects have been used in the application, and compatible technologies and standards can be used.

Peak water
refers to the turning point between increasing and decreasing meltwater runoff due to disappearing glaciers (Hock et al., 2019).

Population equivalent
is a comparative figure commonly used in water management to measure the pollution loads contained in wastewater. One population equivalent (PE) is the product of the number of inhabitants connected to the wastewater system and the daily amount of organic carbon compounds released into the wastewater by one inhabitant.

Regional water emergencies with a planetary dimension
The WBGU refers to crises that arise from the interaction of → *exacerbated water-related challenges* as "regional water emergencies". Examples include the imminent collapse of a city's water supply or serious crop failures due to drought. The scale of a regional water emergency can be so severe that the → *limits of controllability* are reached. Water emergencies can be observed as recurring, typical patterns worldwide; they therefore often have a planetary dimension. Several regional water emergencies can lead to a planetary emergency (e.g. food crisis, political crisis).

Representative Concentration Pathways – RCPs
are scenarios that were published in the IPCC's 5th Assessment Report of 2014. The Representative Concentration Pathways (RCPs) contain examples of time series of climate-active gases, aerosols and land covers up to 2100, which lead to varying intensities of climate change. The four RCPs – RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 – are named after their radiative forcing values in 2100. Radiative forcing refers to the change in the radiation balance (i.e. downward minus upward radiation energy per area) at the tropopause (boundary layer between the troposphere and the stratosphere) and is a measure of how much the Earth is heating up. RCPs are supplemented by → *Shared Socioeconomic Pathways*.

Resilience
is defined differently in different disciplines and describes a property of biological, ecological, social or technical systems (including individual organisms, groups of organisms and organizations). As a rule, resilience is understood as a measure of the system's resistance to external influences, i.e. the ability to return to its initial state after disruptions (or at least close to it, without permanent qualitative changes to the system or its state or functions).

Shared Socio-economic Pathways – SSPs
supplement the → *Representative Concentration Pathways* (RCPs). The various manifestations of emissions and climate change described by the RCPs can be explored against the background of different socio-economic development paths. The five SSPs range from a scenario with a high level of sustainability (SSP1) to a scenario with a high level of technological innovation and continued heavy use of fossil fuels (SSP5). This integrative SSP-RCP framework is used in much of the literature on climate impacts and climate policy.

Soil moisture
is the water content of the upper soil layer in the active layer of the soil, as a rule in the upper 1–2 metres. It is usually the main source of water for agriculture and natural vegetation (Robock, 2003).

Spillover effects
at the international level are "the positive or negative external effects that arise from the actions of one country on another" (SDSN, 2024a). In the context of the 2030 Agenda, international spillover effects can weaken the efforts of other countries, e.g. if one country's measures impose economic or other costs, such as environmental degradation, on another country (SDSN, 2024b).

Sponge city
is a concept of urban planning that aims to retain and use as much rainwater and surface water as possible in order to improve urban water storage instead of merely channelling and draining it away. Part of the concept is the creation of urban blue and green spaces. The aim of the sponge city concept is to make cities more resilient to weather extremes (heat, heavy rainfall, droughts) and to promote a healthy urban climate.

Stationarity
describes the circumstance that statistical properties of natural systems remain constant within a time frame.

Subsidiarity principle
means performing a task at the lowest suitable level.

Tipping point
is a threshold value beyond which a system reorganises itself, often abruptly or irreversibly. Examples include losses of function by ecosystems in the case of flooding or vegetation falling below a tolerance threshold for soil moisture (Fu et al., 2024); or economic or societal downturns, e.g. in the case of critical water shortages in cities.

Total dissolved solids
The sum of all solids dissolved in water (TDS) is used as a measure of water pollution by salts.

Transformative adaptation measures
describe necessary fundamental system changes when conventional approaches or incremental measures are no longer sufficient for adaptation to the consequences of climate change. The IPCC defines transformative adaptation as adaptation in which fundamental characteristics of a socio-ecological system are changed. Incremental adaptation measures, on the other hand, are measures that do not require a fundamental change to the system.

Virtual water
refers to the amount of water – measured over the entire production chain – that is absorbed, polluted or consumed during the manufacture of a product (e.g. because it evaporates; → *water consumption)*. The concept of virtual water is used, among other things, to describe the water consumption associated with international trade. For example, a country's virtual water exports refer to the amount of water consumed and polluted domestically for the production of exported goods. Such virtual water flows are also taken into account when calculating a country's → *water footprint*.

Water availability
An area's water availability is the usable quantity of freshwater available from the natural water cycle for a certain period of time (UBA, 2022).

Water consumption
Water consumption (also known as consumptive use of water) refers to water that is withdrawn from freshwater sources and not returned to that source after use. Water is consumed due to evaporation or being incorporated into a product (Schulte and Morrison, 2014). The remainder that flows back into the groundwater or surface waters is referred to as return flow and is available for water use elsewhere. However, the water quality is often impaired in this context (Bierkens and Wada, 2019).

Water demand
is a planning figure for the volume of water expected to be required for the supply of water in a certain period of time for the development of a water supply system, e.g. drinking water, process water, domestic water, cooling water, water for firefighting and irrigation, as well as the water requirement for public facilities.

Water footprint
measures the amount of water associated with the production or consumption of goods and services. It can be determined at various levels, e.g. for a single manufacturing process, a product, a company, or for the consumption of an individual or a country. A country's water footprint can be calculated, for example, from domestic water consumption, plus the water consumption for the production abroad of imports, minus the → *virtual water* content of exports. The water footprint can provide information on how much water is consumed in a particular river catchment area or from an aquifer. The water footprint is often based solely on the amount of water consumed (volumetric).

Water-related ecosystems
are ecosystems whose functions depend on the availability of sufficient water of adequate quality, but which are also of particular relevance for the maintenance and stabilisation of the local, regional or global water cycle and water balance through balanced water storage and release. In addition to inland waters and wetlands such as peatlands, this also includes terrestrial ecosystems such as forests and grasslands.

Water scarcity
or water shortage are terms commonly used to describe the challenge of limited water availability for humans and nature. The lack of blue water describes the state in which the demand for surface and groundwater exceeds its availability (Savenije, 2000). Based on the principle of sustainable use, it is defined as the "ratio between the societal demand for blue water and the available amount of renewable blue water". A lack of green water is said to occur when soil moisture is insufficient for plant production, and irrigation is required (Rosa et al., 2020).

Water shortage
→ *Water scarcity*

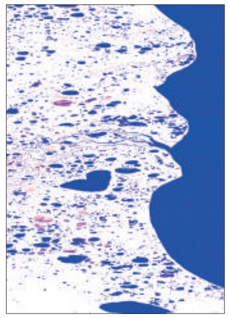
Water stress
The development of water stress due to scarcity depends on the ratio between the total freshwater withdrawal for all uses and the total renewable freshwater resources after taking into account the ecological water requirement. In the context of the 2030 Agenda, the FAO speaks of water stress when more than 25 % of freshwater resources in an area have been abstracted (FAO and UN Water, 2021: 9).

Water supply
refers to water that is accessible to humans.

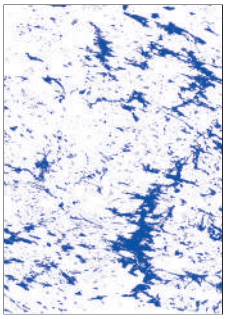
Water withdrawal
is the amount of → *blue water* withdrawn to cover the total → *water demand*. If there is a sufficient → water availability, water withdrawal corresponds to the gross water demand. If this is not the case, water withdrawal corresponds to the → *water availability* (Bierkens and Wada, 2019).

Explanatory notes on the introductory graphics to the chapters

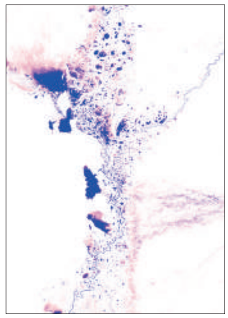
The graphics used to introduce chapters 1–9 show extracts from high-resolution maps of waterbody structures in different regions of the world (source: Pekel et al., 2016). Further surface waterbodies can be explored on the Global Surface Water Explorer website: https://global-surface-water.appspot.com



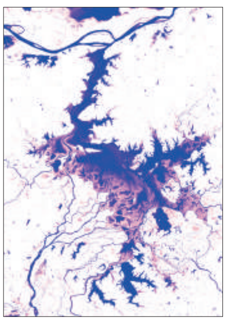
Yaptik-Sale is located on the Siberian Yamal peninsula in Russia, which belongs to the Yamal-Nenets autonomous region. The thawing of the permafrost as a result of climate change, overgrazing and the extraction of large natural-gas reserves are changing the tundra, with serious consequences for the indigenous population (graphic in Chapter 5).



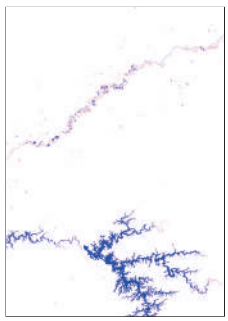
Lake Päijänne is part of the Finnish Lakeland, Europe's largest lake district. The region is a habitat for many animal and plant species, an important recreational area and a key source of drinking water, i.a. for the capital Helsinki (graphic in Chapter 1).



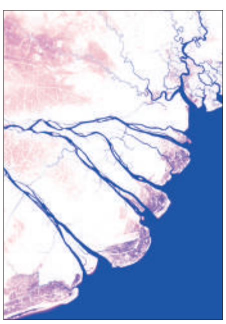
The Pantanal Biosphere Reserve is the largest inland wetland in the world. It is located mainly in Brazil, but also partly in Paraguay and Bolivia. The species-rich wetland biotope is one of the most important natural water reservoirs in South America (graphic in Chapter 6).



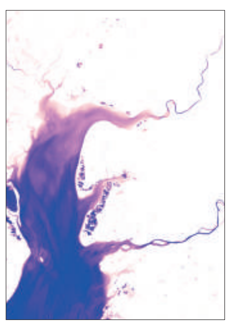
Poyang Lake is the largest freshwater lake in China. It is an important sand mining area, but is shrinking as a result of droughts (graphic in Chapter 2).



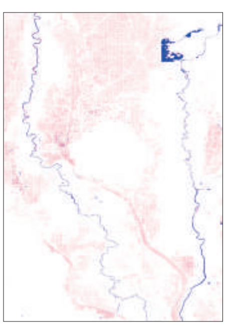
The Rio Paraíba do Sul flows through densely populated and industrialized areas of Brazil. It suffers from contamination and pollutant loads. Some sections are fragmented by dams, while other stretches of bank contain artificial lakes as a result of sand extraction (graphic in Chapter 7).



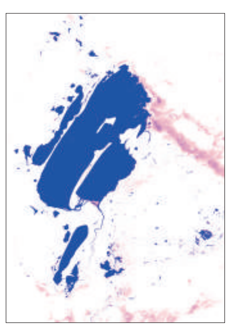
Many people in the Mekong Delta live from agriculture; the Delta is known as the 'rice bowl' of Vietnam. However, fluctuating water levels, overexploitation and the destruction of ecosystems threaten the life-support systems for both humans and nature (graphic in Chapter 3).



The Gulf of Khambhat is located on the Indian coast in the Arabian Sea. Challenges are posed by natural phenomena such as tidal changes, as well as strong population growth in the coastal regions, changes in land use and the erosion of the coastline (graphic in Chapter 8).



The Sacramento River and the Feather River flow in the northern part of California's Central Valley, which is known for its agricultural production. Climate change and groundwater overexploitation are jeopardizing the drinking water supply in the region (graphic in Chapter 4).



Lake Bangweulu and the neighbouring wetlands in Zambia are a Ramsar site and a habitat for a wide variety of flora and fauna, especially waterfowl. The population living within the protected area can use the resources sustainably (graphic in Chapter 9).

The German Advisory Council on Global Change

(Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen – WBGU)

The WBGU is an independent, scientific advisory body to the German Federal Government set up in 1992 in the run-up to the Rio Earth Summit. The Council has nine members appointed for a term of four years by the German Federal Cabinet. He is jointly funded by the Federal Ministry of Education and Research and the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. He is supported by an interministerial committee comprising representatives of all ministries and the German Federal Chancellery. The Council's principal task is to provide scientifically-based policy advice on global change issues. The Council:

- analyses global environment and development problems and reports on these,
- reviews and evaluates national and international research in the field of global change,
- provides early warning of new issue areas,
- identifies gaps in research and initiates new research,
- monitors and assesses national and international policies for the achievement of sustainable development,
- elaborates recommendations for action, and
- raises public awareness and heightens the media profile of global change issues.

The WBGU publishes flagship reports every two years, making its own choice of focal themes. In addition, the German government can commission the Council to prepare special reports and policy papers.

More at: www.wbgu.de/en/

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ISBN978-3-946830-10-8