North Sea Wrecks - An interdisciplinary approach towards understanding the risks posed by wrecks containing munitions in the North Sea

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Abstract— **Shipwrecks and dumped munitions continue to be a major hazard in the North Sea. Research within the EU Interreg project North Sea Wrecks (NSW), in cooperation with the German Aerospace Agency, Institute for the Protection of Maritime Infrastructures (DLR), is generating new insights into the status of wrecks, the potential leakage of pollutants from munitions and the effects of these pollutants on exposed marine organisms in the North Sea. Historical documents are compared to models and visual inspections of the wreck, and samples of water, sediment and organisms are analysed. Combining the results of these different fields of research gives a better understanding of the environmental risks associated with these wrecks. This process is shown below using the case study of the German light cruiser SMS MAINZ, which sank in 1914.**

Keywords—shipwrecks, underwater munitions, marine pollution, historical documents, underwater inspection, chemical analysis, biological effects of explosives, data fusion, maritime risk assessment

I. INTRODUCTION

Millions of tons of munitions were deliberately introduced into European seas during and after the two world wars: Mine belts were laid to protect coasts and harbours from other war parties, and naval battles were fought leading to unexploded munitions from warships, planes and artillery on the seafloor. Munitions were also ditched by bombers returning to airports, and warships were scuttled to avoid enemy capture. Today, the amount of munitions derived from wartime activities is hard to estimate, but they are found in nearly all marine areas. Most munitions, however, entered the seas after the wars when the Allies decided to disarm Germany by dumping the remaining munitions and chemical warfare material in both the North and Baltic Seas [1].

From both world wars, 1.3 million metric tons of conventional munitions are estimated to lie in the North Sea along the German coast [2]. In addition, the North Sea Basin is littered with thousands of ship and aircraft wrecks. Most ships sank during the sea battles of World War I (WWI) and World War II (WWII), several of them equipped or loaded with hazardous goods since they were war ships or military transporters. Others were scuttled during dumping activities after the war.

II. CONCEPUTAL FRAMEWORK: MARINE SLOW DISASTERS

For a long time, the ocean was regarded as a vast repository that could absorb endless quantities of waste, including radioactive substances or heavy metals – out of sight, out of mind. Incineration of munitions on land has caused palpable environmental harm, so disposal at sea was considered a safe long-term solution [3]. However, munitions, no matter how old, may explode, and if they do not explode, toxic chemicals are released as the metal shells corrode. Today, many munitions are severely corroded and risk leaking contaminants.

In contrast to the obvious dangers of munition such as its explosion risk, which is life-threatening for fishermen or offshore workers, the initially invisible and slower impacts of munitions on the marine ecosystem of the North Sea have received little attention. The special temporality of these particular cases of environmental pollution – still causing problems more than 100 years after WWI and more than 75 years after WWII – allows us to speak of the particularity of "slow disasters" [4], [5].

The term "slow disasters" was developed in Science and Technology Studies and describes disasters that unfold slowly over years or decades. Munitions in the sea could be an example of a marine slow disaster because there is a risk of them affecting future generations of various species including humans either directly or via the food web [6]. In the marine environment, the mobility, sedimentation, and accumulation of anthropogenic substances, such as toxic chemicals, is difficult to track and detect; impacts of these pollutants on the environment and species, including humans, that may only occur in the future demonstrate the speculative and indeterminate nature of this field of research [7], [8]. Even if a toxic substance such as TNT is detected in certain locations, the effects remain unpredictable because, for example, studies of accumulation in marine food chains are not yet available.

The end of a war may mean the end of direct combat, but it says nothing about the long-term impact on the environment and people, the "toxic legacies of war" as we have called them for the exhibition of the project "North Sea Wrecks (NSW)". The long-term repercussions of catastrophic wars and industrial accidents of the 20th century are examples of slow disasters that both affected the past and will affect the future [9], [10]. Wars thus leave behind complex "post-conflict landscapes" [11] that still bear fast and slow disasters as shown by shipwrecks in the North Sea discussed in this article. The risks they pose range from explosive potentials to the long-term and often unpredictable environmental pollution and intoxication of living species that is in the focus of our research.

III. Methodical Approach

A. Selection of survey locations

Fifteen wrecks within the NSW study region were selected as case studies on which to trial survey and toxicology research using standardised sampling and analysis methods. Ten wrecks were surveyed using a reduced survey method focused on scanning methods. Five wrecks from Denmark (1), Germany (2) and Belgium (3), however, were fully assessed using all methods presented in this study. The case study wrecks are former naval ships, civilian ships converted for military purposes, decommissioned civilian ships and demilitarised naval ships. The latter were used for munitions dumping in the years following the end of WWII [12]. The wrecks selected for the project date from WWI and WWII and cover a wide range of ship types (light cruisers, submarines, barrier breakers, outpost boats, destroyers and Liberty ships).

The focus was on identified wrecks to allow a compilation of the ship's history and an estimation of the munitions still on board at the time of sinking. In addition, the distance of the wreck to shore and accessibility for divers were criteria for selecting the wrecks for pilot studies. Partners from nine institutions of five countries (Norway, Denmark, Germany, Netherlands and Belgium) selected suitable wrecks within their territorial waters and/or Exclusive Economic Zone (EEZ) for pilot studies. The wreck of the SMS MAINZ, located approximately 23 nm north of the island of Borkum at a depth of approx. 30 m (Fig. 1), was selected for the German pilot study.

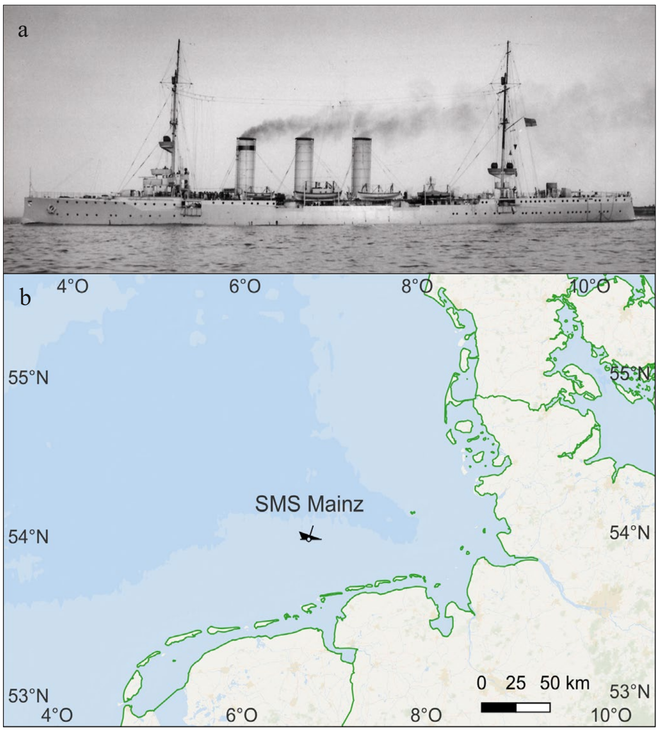

Fig.1. **a** SMS MAINZ, July 1912, portside abeam © Photo archive German Maritime Museum; **b** position of the wreck in the German North Sea.

B. Historical research

A detailed ship biography was compiled for the SMS MAINZ through archival research in the Bundesarchiv-Militärarchiv in Freiburg i. B. (BArch-MA) and other literature. She was a light cruiser of the Kolberg-class and was assigned to the IV. Torpedo Boat Flotilla in August 1914 and part of the protection of the German Bight in the first weeks of WWI [13]. She had a displacement of 4.889 tonnes, an overall length of 130.55 m, a breadth of 14.0 m and a maximum side-height of 8.1 m [14]. She had a maximum speed of approx. 26 knots and was able to carry max. 970 t of coal to fire 15 water-tube boilers. The crew of the SMS MAINZ consisted of 383 people including 18 officers.

The ship's main armament consisted of twelve single mounting L/45 calibre (cal.) 10.5 cm quick-firing guns, six guns on port and six guns on starboard side. In addition, two cal. 8 mm machine guns could be mounted on deck. Furthermore, the ship had two fixed torpedo tubes cal. 45 cm [15]. The munitions stored in the ship can be estimated only roughly and is assumed as approx. 2,000 grenade shells cal. 10.5 cm and 5 torpedoes (type C/06). She was also capable of carrying and laying mines, although these weapons were most likely not part of the standard armament and probably not on board at the time of sinking.

The SMS MAINZ was sunk along with the German light cruisers SMS ARIADNE and SMS COELN and Torpedo Boat V187 during the Battle of Heligoland on August 28th1914. This battle was the first direct confrontation

between the British Royal Navy and the German Imperial Navy during WWI [16].
According to battle reports the SMS MAINZ stood in a single fight, southwest from the main fighting area, with British light cruisers and destroyers from 12:30 p.m. until ca. 1:35 p.m. and received many heavy artillery as well as at least one torpedo hit at midship portside. At 2:10 p.m. the ship turned portside and sank.
The Battle of Heligoland and the individual fights between ships during that day are described in detail in the first volume of the series "Der Krieg zur See. 1914-1918", which was published by the German Naval Archive in 1920 [17]. Further sources on this battle, such as the war diaries, battle and eyewitness reports, construction plans and reports about shipyard repairs etc. are available at the BArch-MA mentioned above.
The extensive archive material and literature on the fate of the SMS MAINZ allows some rough estimations regarding the preserved amount of munitions on the wreck. From the course of the battle, a consumption of approx. 1,280 to 1,700 rounds -assuming an average of 6 to 8 rounds per minute per gun- of explosive grenades as well as 3 torpedoes can be deduced. However, this assumption is only valid if the ship participated in the battle with the maximum number of usable guns. Based on these assumptions the amount of explosives in the ammunition that may have been preserved at the time of the ship's sinking, is estimated to be approx. 1.5 to 3.4 tonnes [18].
However, a ship biography based on archival sources and secondary literature can only be traced up to the sinking of the ship. Once the ship has become a wreck, its second biography begins. However, a detailed wreck biography is often more difficult to compile than a ship biography, due to often lacking data. The first comprehensive dataset of the wreck of the SMS MAINZ dates back to the year 1993 and is presented in a report prepared by the German Federal Maritime and Hydrographic Agency (BSH) [19]. However, these wreck reports are often incomplete, since not all clearance or salvage operations are listed, and illegal looting can take place on wrecks. Such activities may influence the amount of munitions still preserved on the wreck. Due to these uncertainties, an estimate of the amount of preserved munitions must always be accompanied by the phrase "at the time of ship's sinking".

C. *Physical inspection*

An autonomous underwater vehicle (AUV) and remotely operated vehicle (ROV) were used to map, scan and visually inspect the wreck of the SMS MAINZ and the surrounding area to visualise the current state of the wreck and confirm the historical-archaeological assessment.
The AUV flies previously planned missions largely autonomously to obtain sonar data in 2D with a side scan sonar (Fig. 2a) and in 3D with a multibeam echosounder (Fig. 2b).
Reports from previous investigations of the wreck site by BSH were examined to determine position and orientation of the wreck as exactly as possible. Information on minimum altitude, obstacles protruding from the wreck and overall state were considered when planning AUV missions. Additionally, historic documents on the type of armament and the sinking process of the ship are taken into account for determining the area of interest.
First, an overview AUV mission at a safe depth was planned and executed to validate the reports and gain real time situational awareness. The data were processed and analysed on the spot to plan a more detailed, while still safe and economical, mission to obtain optimum multibeam data resolution. The wreck was scanned in a pattern of perpendicular lines. Line spacing was set according to the desired resolution, the opening angle of the multibeam sonar and a safe distance from the wreck. For optimum data quality, flying at a constant depth is usually preferred following the sea floor at a fixed altitude.
The data from the AUV’s sensors were processed immediately after resurfacing and used as a detailed map for navigation and targeted inspection with an ROV.
The ROV was steered via cable. It was carrying a forward-looking imaging sonar (FLS, Fig. 2c) and a low light camera (Fig. 2d). The live feed from the FLS was compared to the sonar data from the previous AUV missions for navigation. With its better manoeuvrability compared to the AUV, the ROV allowed close inspection of the wreck via a live video feed and can be used to confirm the presence of munitions on and around the wreck.

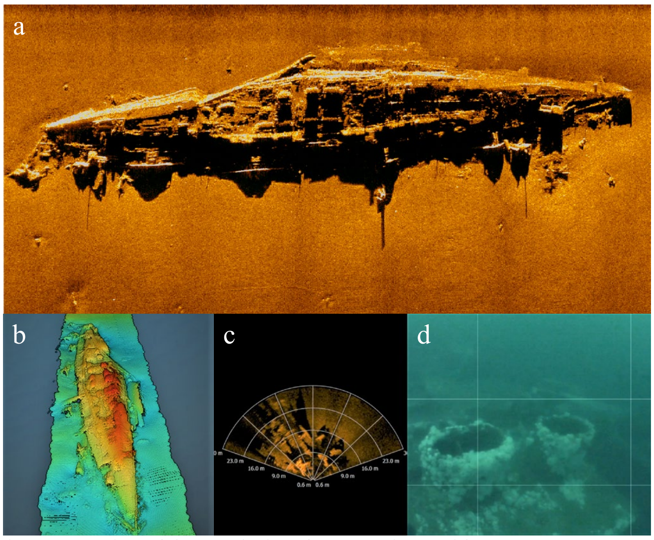

Fig.2. Inspection of the wreck site of SMS Mainz. **a** side scan sonar; **b** multibeam sonar; **c** front looking multibeam; **d** low light camera.

D. *Sampling campaign*

As explained above the estimation of remaining munitions on the wrecks based on historical data and/or visible inspections are not easy to conduct and remain often inaccurate. Water, sediment and biota living on or around a wreck can be analysed for the presence of explosives as an indirect measure of the existence of munitions. If munitions are still present on the wreck and they are corroded, so that leakage takes place, traces of munition compounds will most probably be measurable in the surrounding waters or sediments of the wreck. In contrast, if no traces of explosives are found, munition remains on the wreck are either low or still encapsulated by intact shells. All these results are incorporated into the subsequent risk analysis.
To trace explosives, water samples were collected in lee of the current, which in this study was at the northern portside

of the wreck, at stern, midships and bow. Water samples were taken at seafloor level, as well as at 5 and 10 m above seafloor using a water sampling rosette equipped with hydrographic sensors (CTD). Two times one litre of sampled water per depth was extracted over solid phase extraction (SPE) columns immediately after collection.

Subsequently sediment samples were taken on both sides of the wreck at bow, midship and stern using a standard Van-Veen grabber. Two sediment samples were taken from each grab sample: one from the sediment surface and one from ca. 5 cm below. Further, organisms living on and in the sediment were collected for chemical analysis. Samples and water extracts for chemical analysis were stored at -20 °C until they were processed in the laboratory.

Furthermore, non-migrating flatfish (dab, *Limanda limandes*) were fished as close as possible to the wreck sites. Fish of a minimum size of 25 cm were visually inspected regarding the liver colour and dissected for samples of liver and kidney for biomarker assessments. Further, gill, blood, fillet and bile samples for chemical analysis were taken directly thereafter. Finally, otoliths for age determination were sampled and stored separately.

Blue mussels (*Mytilus edulis*) derived from the island of Sylt, an area free of dumped munitions, were transferred and exposed for several weeks in steel cages mounted on remotely operated tripods placed close to the wrecks at bow, midship and stern using the ship's crane. Steel cages with passive sampling devices, were also mounted on the tripods able to collect chemicals, including dissolved explosives, from the water column. The passive sampling devices accumulated even the lowest concentrations, potentially not detectable in pure water samples. During the pilot study at the SMS MAINZ, no current meters were added to the passive sampling devices.

After retrieval, mussels were dissected and samples of the digestive gland, mantle and gills were taken for further chemical and biomarker analysis. Mussel and fish tissue samples for biological analysis were snap frozen in liquid nitrogen and stored in a dewer containing nitrogen vapor until further processing. Tumors found in fish liver tissue were separated and fixated in a formalin solution for further microscopic analysis.

E. Chemical analysis

Sediment and water samples, membranes of passive sampling devices, as well as tissues of organisms living on or around the wrecks, were screened for traces of dissolved explosives and their metabolites.

Water and sediment samples were treated according to the method published in Bünning et al. 2021 [20]. Mussels and fish fillets were lyophilised and processed according to the solid phase extraction mussel method from Bünning et al. 2021 [20]. For bile, an adapted workup according to Ek et al. 2006 was used [21], in which 100 mg of bile was incubated with 3600 u glucuronidase in buffer (pH = 4.8) for 18 h at 37 °C, then extracted over 1 mL SPE columns and eluted with 250 µL acetonitrile.

All samples were analysed for the energetic compounds 1,3-dinitrobenzene (1,3-DNB), 2,4-dinitrotoluene (2,4-DNT), and 2,4,6-trinitrotoluene (TNT), as well as the TNT-metabolites 4-amino-2,6-dinitrotoluene (4-ADNT) and 2-amino-4,6-dinitrotoluene (2-ADNT) by GC-MS/MS in SRM mode. A Thermo Scientific TSQ8000 EVO triple quadrupole mass spectrometer coupled to a TRACE1310 gas chromatograph was used. Sample injection was done on a split/splitless injector for water and sediment samples, and by large volume injection on a PTV injector for biota samples, each on quartz wool liner. The separation was performed on Thermo Scientific TG-5MS amine columns (15 m x 0.25 mm x 0.25 µm). GC oven temperature programs, SRM transitions, and detection and quantification limits are described in Bünning et al. 2021 [20]. Quantification was performed using external calibration curves of the energetic compounds.

F. Biological effects of exposed organisms

In the marine environment organisms are exposed to a range of substances, many of which can cause metabolic disorders, an increase in disease prevalence, and may affect even the population by changes in e.g., growth, reproduction, and survival. It is agreed that the effects of hazardous substances are assessed by both, chemical and biological measurements in an integrated manner [22]. Like this, the bioavailability of hazardous substances and their impact on marine organisms or processes can be correlated.

Wrecks and their remaining munitions are subject to corrosion over the decades. In case munition remains are not silted up, but are in contact with the surrounding water, it is most likely that shells are not fully intact anymore and that leakage of toxic munition compounds takes place. Therefore, these wrecks may become a significant point source for dissolved explosives. From field investigations and lab experiments it is known that exposed organisms take up explosives from the surrounding water [23], [24]. At the SMS MAINZ the concentrations of explosives and their metabolites were measured in water, passive sampler, sediment and in the tissues of fish and mussels. Samples of mussels and fish were analysed for biological effects on different organismal levels using a multi-biomarker approach. Measured effects were correlated with the detected level of explosives in the respective tissue. Furthermore, chemical and biological data from the wreck sites were compared to samples taken at the reference area to eliminate local effects unrelated to the wrecks.

G. Data fusion and risk assessment

All data were fed into a database that supports a model-based risk assessment. By combining the current state of the wreck with the conditions it is exposed to in terms of sea conditions and frequency of human disturbance at the site, the probability of discharge of pollutants was approximated using the VRAKA probabilistic risk assessment model [25]. Combined with the amount of total pollutants present at the wreck site a risk evaluation was made. This risk was put in relation to the chemical and biological characterization of the wreck's surroundings to develop an understanding of the extent of current pollution and attempt a forecast of how the situation could develop in the future.

Based on the outcomes of this risk assessment, wrecks were ranked according to the threat they pose to the environment, to critical infrastructures such as offshore installations, harbours, pipelines and cables but also to regions used for tourism. After ranking the wrecks, a tailored monitoring approach for the individual wreck can be developed and

possibilities of remediation discussed if the risks assigned to the wreck are high or even unacceptable.
Further, with an increasing number of wrecks assessed in a respective region, the probability increases that wrecks can be grouped to categories according to type and/or other criteria potentially reducing the assessment effort for additional wrecks from the same category.

IV. IV Preliminary results

By deploying an AUV at the wreck site, existing reports of the BSH were confirmed showing an intact wreck, preserved up to the Armoured Deck and half buried in the sediments, at approx. 25 to 30 m depth with remaining superstructures of several meters in height. Overall, the wreck seemed to be in a stable position with no immediate risk of moving or breaking apart. Many details such as bow, stern, guns and gun towers, machinery fragments, etc. could be clearly identified in the sonar images. The following visual inspection by ROV revealed very good comparison possibilities between sonar images and construction plans. However, munition remains could not be determined, so the total amount of munition left on the wreck could only be addressed via archival research or chemical analysis.
The analysis of water, sediment, passive sampling device and biota samples confirmed the presence of dissolved explosives in the vicinity of the wreck, thus indicating that the wreck is a source of dissolved explosives. Calculating the remaining amount of munition on-board of the wreck is, however, not possible using these results. Water and sediment concentrations are dependent on the hydrographical regime of the wreck site and sediment quality, but no flow measurements were conducted so values measured in the passive sampling devices cannot be correlated to any volumes of water.
In the present study mussel and fish species were investigated regarding their response to exposure with explosives in the water and sediments. The investigations are still ongoing but macroscopic analysis of fish organs revealed higher numbers of liver diseases in fish caught directly at the wreck of SMS MAINZ compared to species caught in a reference area at Borkum Riffgrund that is free of munition remains
Beyond that, another result of the NSW project is a travelling exhibition as a creative and accessible form of science communication. It is intended to raise public awareness of the still rather unknown environmental problem of underwater munitions. The exhibition, called "Toxic Legacies of War", has seen at several locations since August 2021. It is conceived as a pop-up exhibition that can be shown both outdoors in public spaces and indoors, such as in museums or other institutions.
At the centre of the exhibition are several stations in the design of ammunition boxes containing selected objects as well as media stations. The media stations are equipped with Leap Motion technology, which allows the monitor to be controlled by gestures via hand tracking, i.e. without touching it. The media stations work didactically with "scrollytelling". This makes it possible to tell a story made up of various elements such as text, images, audio or videos by scrolling through these elements on the screen. In this way, visitors are introduced to the historical context, the environmental problem and the research carried out within the NSW project. The exhibition has toured all partner countries aiming to increase society's awareness of the problem and encourage a dialogue between stakeholders. The presentation of the content and the design has received much interest by visitors, among whom were many who previously knew little or nothing about the problem. The website of the German Maritime Museum features an online version of the exhibition, additional information and in-depth texts about the work in the project and the investigated wrecks [26].

V. Discussion

Any consideration of the risks posed by wrecks in the North Sea must account for the limitations of the underlying dataset(s) which impact both the collective assessment of the inventory as well as that of individual wrecks. These are derived from the wreck databases compiled by various national bodies, and which are used in the production of hydrographic charts. As such, they are invariably excellent for their primary purpose which is to ensure navigational safety. Individual wrecks, and particularly those in shallower waters, are accurately positioned with a good level of detail on their condition, dimensions, and orientation with many frequently updated via recurrent surveys. However, a proportion of wrecks are either marked as ‘unknown’ or have been misidentified and this problem becomes more pronounced where deeper, more remote, and less frequently re-surveyed wrecks are concerned. The exact scale of this issue is difficult to quantify but the implications for the many thousands of North Sea war wrecks is obvious as accurate identification is fundamental to the subsequent risk assessment process.
While details of the armament allocated to individual ships can often be determined from archival research it is often difficult to ascertain the quantity of remaining munition. Consequently, even when the identity of a wreck has been confirmed, significant effort may still be required to confirm where munition is likely to be present and in what amounts before sampling and risk assessment can take place.
In Germany, the BSH is responsible for surveying wrecks and conducts the monitoring of wrecks on different time scales according to their estimated risk towards shipping traffic. Other risks, such as environmental hazards posed by the wreck’s remaining fuel, armament and/or other dangerous cargo are not recorded systematically. Within the frame of the North Sea Wrecks project, the partners developed a concept for measuring and assessing war wrecks, according to their potential as a source of explosives. Following the described unified approach, the SMS Mainz was investigated during two consecutive sampling seasons.
The historical research revealed that several tons of munitions should have been on board at the time of sinking, but the visual inspection could not confirm munition items in or around the wreck. Chemical analysis of environmental samples gave strong evidence for munitions remaining on the SMS MAINZ; however, quantities cannot be estimated based on these measurements. In contrast, statements about the status of the munitions are possible, since dissolved explosives were detected in passive sampling devices, water samples and fish tissues, proving that munitions are corroded and leaking.
The extent to which substances such as TNT significantly impact marine species and ecosystems is of great scientific

interest. Despite increasing research, our knowledge about long-term effects of energetic compounds on the environment is still limited and more research is needed. With the exception of disasters and accidents where e.g. tankers release huge amounts of pollutants in a short period of time, the effects of industrial and military loads of wrecks in the ocean are difficult to determine because they usually manifest slowly and often in unpredictable ways.

In the present study, explosives were detected in the tissues of both mussel and fish species investigated. Further, mussels and fish were analysed for their response to exposure to explosives in the water and sediments. The investigations are still ongoing but microscopic analysis of fish organs revealed more liver diseases in the vicinity of the wreck than in areas with no munitions. If this is true, and rather low concentrations of dissolved explosives measured at the wreck site caused these diseases symptoms, then the still virulent idea of diffusion of pollutants in the ocean and a dilution approach as the solution to pollution must be rejected.

The absorption capacity of the oceans is finite and results of the NSW project and former research projects show that organisms such as mussels and fish take up dissolved explosive chemicals and might therefore be a source of contamination for human seafood consumers [27]–[31]. Detailed studies regarding a potential transfer of energetic compounds into the food chain are urgently needed to ensure marine food safety.

Overall, the information about the SMS MAINZ is comprehensive and a strong basis for the individual risk evaluation of the wreck. In a next step data will be fed into the project database and used for the calculation of the overall risk for the SMS MAINZ. Results will then be compared to other wrecks investigated within the project or with wrecks investigated in the future using a comparable approach as suggested in this current study. Parts of the risk assessment and the results of the measurements at the wreck site are also displayed in the public travelling and online exhibition "Toxic Legacies of War".

VI. Operational Implications

The North Sea was an active battleground in both WWI and WWII, with ship losses of the various participants widely dispersed without respect to current national boundaries. Consequently, active management of the risks posed by the inventory must take account of the differing positions of the countries bordering the North Sea on such fundamental issues as wreck ownership, willingness to share existing survey data, attitudes to war losses and the interplay between environmental/safety concerns and heritage management. In the case of heritage management several, though by no means all, of the countries bordering the North Sea are signatories to the 2001 UNESCO Convention on the Protection of the Underwater Cultural Heritage (Convention on the Protection of the Underwater Cultural Heritage - UNESCO Digital Library). How the obligation this places on signatories to protect "Underwater cultural heritage" that has been submerged for at least 100 years (so encompassing wrecks from WWI) aligns with managing the risks associated with the same inventory has yet to be fully worked through. Further work is certainly required as future remedial action to address the problems detailed in this paper might involve the removal of ammunition from wrecks with intrusive, and potentially destructive, work; for example, by cutting out sections of a wreck to allow access to internal magazines.

Indeed, this challenge highlights the shifting attitudes to wrecks and the interplay between different stakeholders. The heritage value of wrecks has long been recognised, encompassing their archaeological significance and in many cases their importance as the last resting place of the sailors lost in their sinking leading to them being afforded protection by a variety of means.

Concerns over the environmental and safety risks posed by these same wrecks is a more recent phenomenon with initial work in this area focused on addressing the problems posed by the oil remaining on many legacy wrecks [32]. Similarly, while the potential explosive risk posed by the munitions remaining in such wrecks has long been acknowledged, the impact of toxic substances leaking from munitions contained within wrecks and entering the food chain is a new area of research.

Thus, the work of the NSW project is contributing to the increasingly dynamic nature of wreck management and is further highlighting the need to work collaboratively with stakeholders across a range of disciplines to ensure that safety and environmental issues are addressed in a manner sympathetic to the heritage and emotive value of individual wrecks. It is likely that a pragmatic approach to dealing with environmental problems on protected wrecks can be found that minimises disturbance to them, and key to this will be an open and honest dialogue between all interest groups to identify workable solutions.

VII. Acknoledgements

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References

[1] G. Carton and A. Jagusiewicz, "Historic disposal of munitions in U.S. and European coastal waters, how historic information can be used in characterizing and managing risk," *Mar. Technol. Soc. J.*, vol. 43, no. 4, pp. 16–32, Oct. 2009, doi: 10.4031/MTSJ.43.4.1.

[2] C. Böttcher, T. Knobloch, N.-P. Rühl, J. Sternheim, U. Wichert, and J. Wöhler, "Munitionsbelastung der deutschen Meeresgewässer - Bestandsaufnahme und Empfehlungen," p. 174, Nov. 2011.

[3] A. Neimanis, "'The chemists' war' in Sydney's seas: Water, time, and everyday militarisms," *Environ. Plan. E Nat. Space*, vol. 4, no. 2, pp. 337–353, Jun. 2021, doi: 10.1177/2514848620904276.

[4] S. G. Knowles, "Learning from disaster? The history of technology and the future of disaster research," *Technol. Cult.*, vol. 55, no. 4, pp. 773–784, 2014.

[5] M. Liboiron, M. Tironi, and N. Calvillo, “Toxic politics: Acting in a permanently polluted world,” *Soc. Stud. Sci.*, vol. 48, no. 3, pp. 331–349, Jun. 2018, doi: 10.1177/0306312718783087.
[6] H. Davis, “Toxic progeny: The plastisphere and other queer futures,” *Philos. J. Cont. Fem.*, vol. 5, no. 2, pp. 231–250, 2015.
[7] S. Bergmann, “Speculative ecologies: Salmon farming and marine microplastics as slow disasters,” in *Ecologies of Gender: Contemporary Nature Relations and the Nonhuman Turn*, S. Lettow and S. Nessel, Eds. London, 2022, pp. 206–226.
[8] A. Schrader, “Responding to *Pfiesteria piscicida* (the fish killer): Phantomatic ontologies, indeterminacy, and responsibility in toxic microbiology,” *Soc. Stud. Sci.*, vol. 40, no. 2, pp. 275–306, Apr. 2010, doi: 10.1177/0306312709344902.
[9] J. Masco, “The Age of Fallout,” *Hist. Present*, vol. 5, no. 2, pp. 137–168, Oct. 2015, doi: 10.5406/historypresent.5.2.0137.
[10] R. Nixon, *Slow Violence and the Environmentalism of the Poor*. Harvard University Press, 2011. doi: 10.4159/harvard.9780674061194.
[11] V. Pholsena and O. Tappe, “Interactions with a violent past: Reading post-conflict landscapes in cambodia, laos, and vietnam,” *J. Soc. Issues Southeast Asia*, vol. 29, no. 2, p. 483, 2014, doi: 10.1355/sj29-2i.
[12] J. A. Tørnes, Ø. A. Voie, E. Mariussen, and P. Lågstad, “Kjemisk ammunisjon senket utenfor norskekysten etter andre verdenskrig – hva er senket og hvilke effekter har dette på marine organismer?,” 2015/00925.
[13] H. H. Hildebrand, A. Röhr, and H.-O. Steinmetz, *Die deutschen Kriegsschiffe. Biographien, ein Spiegel der Marinegeschichte von 1815 bis zur Gegenwart.*, vol. 4. Herford: Mundus, 1981.
[14] Reichsmarineamt, “Kleine Kreuzer. Heft 14: Emden, Mainz, Kolberg,” in *Deutsche Kriegsflotte Band IV*, Berlin, 1910.
[15] G. Koop and K.-P. Schmolke, Eds., *Kleine Kreuzer 1903 - 1918 (Bremen- bis CÖLN-Klasse)*. Bonn: Bernard und Graefe, 2004.
[16] F. Huber and J. M. Witt, “Der Feind überschüttet uns mit einem Hagel von Stahl und Eisen. Das Seegefecht bei Helgoland am 28. August 1914,” in *Zeitreisen unter Wasser. Spektakuläre Entdeckungen zwischen Ostsee und Bodensee. Funde von Archäologen und Forschungstauchern*, F. Huber, Ed. Darmstadt: wbg Theiss, 2021, pp. 164–175.
[17] Marinearchiv, “Band 1. Von Kriegsbeginn bis Anfang September 1914,” in *Der Krieg zur See. 1914-1918*, Berlin, 1920.
[18] N. Friedman, *Naval Weapons of World War One.* Havertown: Seaforth Publishing, 2011.
[19] Bundesamt für Seeschifffahrt und Hydrographie, “BSH-Bericht 1993,” unpublished.
[20] T. H. Bünning, J. S. Strehse, A. C. Hollmann, T. Bötticher, and E. Maser, “A toolbox for the determination of nitroaromatic explosives in marine water, sediment, and biota samples on femtogram levels by GC-MS/MS,” *Toxics*, vol. 9, no. 3, Art. no. 3, Mar. 2021, doi: 10.3390/toxics9030060.
[21] H. Ek, G. Dave, E. Nilsson, J. Sturve, and G. Birgersson, “Fate and effects of 2,4,6-Trinitrotoluene (TNT) from dumped ammunition in a field study with fish and invertebrates,” *Arch. Environ. Contam. Toxicol.*, vol. 51, no. 2, pp. 244–252, Aug. 2006, doi: 10.1007/s00244-005-0117-5.
[22] Davies, I. M.; And Vethaak D. (Eds.), “Integrated marine environmental monitoring of chemicals and their effects,” 2012, doi: 10.17895/ICES.PUB.5403.
[23] J. S. Strehse, D. Appel, C. Geist, H.-J. Martin, and E. Maser, “Biomonitoring of 2,4,6-trinitrotoluene and degradation products in the marine environment with transplanted blue mussels (M. edulis),” *Toxicology*, vol. 390, pp. 117–123, Sep. 2017, doi: 10.1016/j.tox.2017.09.004.
[24] R. Schuster *et al.*, “Exposure to dissolved TNT causes multilevel biological effects in Baltic mussels (Mytilus spp.),” *Mar. Environ. Res.*, vol. 167, p. 105264, May 2021, doi: 10.1016/j.marenvres.2021.105264.
[25] H. Landquist *et al.*, “A fault tree model to assess probability of contaminant discharge from shipwrecks,” *Mar. Pollut. Bull.*, vol. 88, no. 1–2, pp. 239–248, Nov. 2014, doi: 10.1016/j.marpolbul.2014.08.037.
[26] “Toxic Legacies of War - North Sea Wrecks,” Accessed Jul. 07, 2022. https://www.dsm.museum/en/exhibition/exhibitions/toxic-legacies-of-war-north-sea-wrecks
[27] J. Bełdowski *et al.*, “Chemical munitions search & ssessment—An evaluation of the dumped munitions problem in the Baltic Sea,” *Deep Sea Res. Part II Top. Stud. Oceanogr.*, vol. 128, pp. 85–95, Jun. 2016, doi: 10.1016/j.dsr2.2015.01.017.
[28] D. Appel, J. S. Strehse, H.-J. Martin, and E. Maser, “Bioaccumulation of 2,4,6-trinitrotoluene (TNT) and its metabolites leaking from corroded munition in transplanted blue mussels (M. edulis),” *Mar. Pollut. Bull.*, vol. 135, pp. 1072–1078, Oct. 2018, doi: 10.1016/j.marpolbul.2018.08.028.
[29] D. Koske, K. Straumer, N. I. Goldenstein, R. Hanel, T. Lang, and U. Kammann, “First evidence of explosives and their degradation products in dab (Limanda limanda L.) from a munition dumpsite in the Baltic Sea,” *Mar. Pollut. Bull.*, vol. 155, p. 111131, Jun. 2020, doi: 10.1016/j.marpolbul.2020.111131.
[30] E. Maser and J. S. Strehse, “‘Don’t Blast’: blast-in-place (BiP) operations of dumped World War munitions in the oceans significantly increase hazards to the environment and the human seafood consumer,” *Arch. Toxicol.*, vol. 94, no. 6, pp. 1941–1953, Jun. 2020, doi: 10.1007/s00204-020-02743-0.
[31] E. Maser and J. S. Strehse, “Can seafood from marine sites of dumped World War relicts be eaten?,” *Arch. Toxicol.*, vol. 95, no. 7, pp. 2255–2261, Jul. 2021, doi: 10.1007/s00204-021-03045-9.
[32] Landquist, H., Hassellöv, I. M., Rosén, L., Lindgren, J. F., and Dahllöf, I. (2013). Evaluating the needs of risk assessment methods of potentially polluting shipwrecks. J. Environ. Manage. 119, 85–92. doi: 10.1016/j.jenvman.2012.12.036