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Runoff generation and storage dynamics of a polygonal tundra catchment, Lena River Delta, northern Siberia (Russia)

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Present understanding of the hydrology of catchments underlain by permafrost is still insufficient to correctly predict ecological impacts brought about by climate change. Ice-wedge polygonal tundra is a typical landscape type of the continuous permafrost zone and is characterised by a pronounced micro- but a flat meso-topography. It consists of polygon sub-catchments with low-lying centres and surrounding elevated rims that feature a range of connectedness to other polygons and the inter-rim surface drainage network of troughs above degraded ice-wedges. This pattern distinguishes the hydrology of polygonal tundra from other permafrost-affected landscapes. Therefore, this study aims to define the hydrological functions of characteristic landscape units of polygonal tundra (i.e. polygon rims, centres, and troughs). We examine runoff generation and water storage dynamics in a small polygonal tundra catchment in northern Siberia (0.6 km^2) by analysing spatially distributed water balances together with catchment runoff dynamics between May and August 2011.

Despite the evapotranspiration rate (137.9 mm) exceeding precipitation (108.6 mm), and the low topographic gradient, lateral outflow (60.9 mm – 167.4 mm) considerably influenced the water storage of the main landscape units within the catchment. Low polygon centres with intact rims stored snow melt water longer than either polygons with degraded rims or the troughs. The micro-topography of the rims and the associated soil thaw dynamics determined the magnitude and the timing of outflow through the blocking function of frozen soils. These dynamics controlled the redistribution of storage water within the catchment during the summer.

Hydraulic conductivity in the rims declines by three orders of magnitude within the first 15 cm of the soil. The high conductivities in the shallow soil layers cause a rapid shallow subsurface drainage of rainwater towards the depressed centres and troughs. Once the rims are deeply thawed, the re-release of storage water from the centres through deeper and less conductive layers helps maintain a high water table in the surface drainage network of troughs throughout the summer.

In turn, catchment runoff was mainly controlled (R^2 = 0.99, RMSE = 0.34 L s^{-1}, N = 2165) by the water level (i.e. hydraulic gradient) in this drainage network, and baseflow was maintained throughout the study period. The interconnected network contracts and expands in relation to the water level. Together with sharp declines of hydraulic conductivity within the upper soil layers, this catchment characteristic favours the observed exponential increase of catchment runoff with ascending water levels in the network. This relationship promotes enhanced runoff as a response to large, infrequent inputs of rain or snow melt water whereas vertical water fluxes dominate during periods of frequent but homogeneously distributed rain events of smaller magnitude.

This study shows that a nested approach is suitable to identify characteristic hydrological processes at different scales and to assess how the hydrological functions of the main landscape units interact on the catchment scale. The results emphasise the need to account for micro-topography of polygonal tundra and temporal distributions of precipitation and evapotranspiration when investigating the storage and runoff dynamics, and the interactions with carbon or energy fluxes.