Permafrost is defined as ground that remains frozen throughout the year; it covers about a quarter of the land surface in the Northern Hemisphere (Fig. 1) and has been long considered a terrestrial indicator of long-term changes in the climate system as the subsurface slowly responds to changes in atmospheric conditions. Studies have shown that the rate of air temperature warming is greater in high latitudes and altitudes than the global average, thereby enhancing the vulnerability of permafrost to thaw. Due to past and future changes in water fluxes and flowpaths associated with climate-induced permafrost thaw, permafrost hydrology is a rapidly developing field. A new article in *Vadose Zone Journal* reviews the impact of permafrost thaw on hydrologic processes with a focus on the discontinuous permafrost zone of the pan-Arctic basin. Recent advances are discussed along with limitations towards predicting hydrologic consequences of projected warming in permafrost environments.

Changes in the vertical and spatial distribution of permafrost alter the hydrology of the landscape. These changes include changes in soil moisture, groundwater recharge, streamflow seasonality, flowpaths, and the amount of water stored on and beneath the land surface. Permafrost generally begins in the shallow subsurface (<1 m to several meters) and extends to several meters to upwards of 1,000 m deep (Fig. 2). Above the permafrost is a zone known as the “active layer,” which is seasonally thawed—frozen in winter and unfrozen in summer. The frozen ground serves as a barrier for infiltration because the hydraulic conductivity of the soil can vary by several orders of magnitude between the frozen and unfrozen layers. One of the by-products of the positive trend in air temperature is an increase in the thickness of the active layer through which water can flow. Other important controls on the active layer thickness that may vary with time include snow thickness and summer soil moisture. Permafrost thaw from climate warming has also been linked to enhanced recharge and increased groundwater discharge to streamflow (Fig. 3). Warming trends may also influence the frequency and intensity of flooding events from ice jams that occur during ice breakup of major rivers in the spring. In addition, there are ecosystem changes linked to permafrost thaw resulting from shifts in the lake distribution and connectivity and to changes in soil moisture that can modify the composition and distribution of vegetation.

However, in spite of the importance of permafrost in influencing the hydrological cycle and ecosystems in northern latitudes, observations and baseline characterization in these remote regions have been limited. The spatial coverage of permafrost across the pan-Arctic drainage basin has been mapped at a low spatial resolution with discrete regions mapped at higher resolution. Hydrogeologic characterization and critical permafrost properties including spatial distribution, ice content, thickness, and temperature are insufficiently mapped for modeling approaches to project future change at scales that are useful for land managers and decision makers. However, geophysical ground-based and airborne methods that include electromagnetics, radar, seismic, and electrical resistivity help fill critical permafrost characterization gaps. In these methods, differences between the electrical properties and compressibility of ice and liquid water enable mapping of frozen zones. This
is an important and active area of research. Strategies that employ multiple geophysical methods and integrate with remote-sensing techniques are being developed to address the inherent trade-off between data resolution and coverage. Emerging airborne and satellite methods for broad permafrost mapping include observations by synthetic aperture radar (SAR) and interferometric synthetic aperture radar (InSAR). Improved techniques for large-scale deep characterization, particularly in discontinuous permafrost zones, are still needed.

Process-based hydrological models serve as useful tools to predict future hydrologic change in permafrost regions and inform climate change adaptation strategies. There are various methods available to model the hydrology of permafrost areas, and these range in complexity and intended application. Many surface hydrological models use simple analytical equations to predict seasonal freezing and thawing near the ground surface. Accurately predicting ground thaw is critical for permafrost hydrology models as the near-surface thawed zone is often the primary route through which precipitation travels to streams, rivers, and lakes. Other more sophisticated hydrology models use numerical methods to obtain solutions to more complex heat transfer equations. Recently, several permafrost hydrogeology models have been developed by coupling a groundwater flow equation to heat transfer equations with freezing and thawing. These “cryohydrogeology” models also account for the reduction in hydraulic conductivity with an increase in pore ice and have been applied to investigate changes to subsurface water flow systems as a result of permafrost thaw. Although the development of permafrost hydrology and hydrogeology models has intensified in recent years, there are a number of opportunities for advancements in this field, including linking model simulations with field data, developing better surface modules, and increasing the spatial scale of model applications.

As many of the world’s large river systems originate in high latitudes and altitudes, understanding changes in the hydrology of frozen regions under a warming climate is an important aspect to quantification of the freshwater resources of our planet.

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