Holocene thermokarst lake dynamics in northern Interior Alaska: the interplay of climate, fire, and subsurface hydrology

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Thermokarst processes in permafrost landscapes often lead to widespread lake formation and their spatial and temporal evolution reflects the combined effects of climate, ground conditions, vegetation, and fire. This investigation of thermokarst lake sediments of Holocene age from the southern loess uplands of the Yukon Flats includes bathymetry and sediment core analyses across a water depth transect. The sediment core results, dated by radiocarbon and 210Pb, indicate early basin development through inferred thermokarst processes followed by permanent onset of finely laminated lacustrine sedimentation at deepest water depths by ~8,000 cal yr BP. Thermokarst expansion to modern shoreline configurations continued until ~5000 cal yr BP and may have been influenced by increased fire. Between ~5000 and 2000 cal yr BP, the preservation of fine laminations at intermediate and deep-water depths indicates higher lake levels than present. At that time, the lake likely overflowed into an over-deepened gully system that is no longer occupied by perennial streams. By ~2000 cal yr BP, a shift to massive sedimentation at intermediate water depths indicates that lake levels lowered, which is interpreted to reflect a response to drier conditions based on correspondence with Yukon Flats regional fire and local paleoclimate reconstructions. Other contributing mechanisms include the possible influence of catastrophic lake drainages on down-gradient base-flow levels that may have enhanced subsurface water loss, although this mechanism is untested. Comparison with regional paleoclimate trends indicates that after thermokarst lakes formed, their size and depth has been affected by North Pacific atmospheric circulation in addition to the evolution of permafrost, ground ice, and subsurface hydrology. Results provide a framework for future investigations of paleoclimatic signals from similar lake systems of thermokarst origin, which characterizes large regions of Alaska and Siberia.

Seasonal Freeze-Thaw Dynamics Under and Around Streams in the McMurdo Dry Valleys, Antarctica

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Thaw of streambeds and ground adjacent to streams provides the opportunity for hyporheic exchange and related biogeochemical cycling in permafrost landscapes. However, there are few direct examples of thaw and freeze dynamics in these systems. Here we present data and findings from novel subsurface sensor arrays that measure temperature, salinity, and soil moisture under and adjacent to glacial meltwater streams in the McMurdo Dry Valleys, Antarctica. Streams flow for 8-12 weeks per year and hyporheic zones represent critical locations of nitrogen storage and rapid weathering in these ecosystems. For example, we find that the subsurface directly under streams, hyporheic zones are more consistently thawed during the flow season than lateral subsurface locations. We also note that lateral locations tend to have higher salinity, on average, than locations directly under streams. These findings help us to constrain the extent to which hyporheic processes can contribute to downstream evolution of water quality and biogeochemical fluxes to downstream parts of the ecosystem.

The Lake Agnes rock glacier as a climate resilient cold-water reservoir within the Colorado Front Range

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In Colorado, rock glaciers vastly outnumber traditional ice glaciers and cover a larger spatial extent, suggesting that they may contain a larger volume of ice than glaciers themselves. In certain basins, the reduced climate sensitivity of rock glaciers and their sustained cold-water input to mountain streams will likely provide a refuge for cold-water aquatic species in a warming climate. The Lake Agnes rock glacier is a transitional rock glacier located in the Never Summer Mountain Range of northern Colorado, and ranges from 3260 to 3520 m asl. This study incorporates geophysical, hydrochemical, and remote sensing data from summers 2019, 2020, and 2021 to quantify the hydrologic contribution to late-season streamflow, ice presence, and the displacement rate of the Lake Agnes rock glacier. Hydrochemical results (pH, temperature, ion concentrations, $\delta 18O$) of stream samples distinguish between rock glacier, non-rock glacier, and mixed source streams, with an increase in proportion of late season basin outflow from rock glacier-fed sources. Geophysical surveys in the upper portion of the rock glacier indicate ice presence and suggest an active layer depth of ~3 m. Photogrammetric analysis indicates that the upper, active part of the rock glacier is moving at a rate up to ~20 cm/year, though the lower lobe remains inactive. Comprehensive characterization of the Lake Agnes rock glacier is a first step in understanding the role of rock glaciers in alpine basins within northern Colorado, features which are an often-disregarded component of the alpine water budget.

Modeling Arctic Lakes with the LAKE2.0 Model

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Lakes in the Arctic are important reservoirs of heat with much lower albedo and larger absorption of solar radiation than surrounding tundra vegetation. Under climate warming scenarios, we expect Arctic lake heat balance to shift, thawing underlying permafrost. Previous studies of Arctic lakes have focused on ice cover and thickness, the ice decay process, catchment hydrology, lake water balance, and eddy covariance measurements, but little work has been done in the Arctic to model lake heat balance. We applied the LAKE model to simulate water temperatures in three Arctic lakes in Northern Alaska over several years. The LAKE model is a one-dimensional finite-difference model that explicitly solves vertical profiles of water state variables on a finite-difference grid, using a k-ε parameterization to calculate turbulent fluxes. We used a combination of meteorological data from local and remote weather stations, as well as data derived from remote sensing, to drive the model. We validated simulated water temperatures with data of observed lake temperatures at several depths. Our validation of the LAKE model completes a necessary step toward modeling changes in Arctic lake ice regimes, lake heat balance, and thermal interactions with permafrost.

Hydrogeology and permafrost dynamics of a degrading lithalsa near Umiujaq (Nunavik, Canada): insights from long-term monitoring

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Simulations of climate-driven permafrost degradation typically consider simple or idealized groundwater conditions due to the limited availability of hydrogeologic data in permafrost environments. However, in order to better understand the evolution of these highly non-linear systems, and to properly characterize the impact of groundwater flow on permafrost degradation, robust cryohydrogeological conceptual models are needed. This study uses long-term, high-temporal-resolution observations from an extensive network of monitoring equipment to characterize the thermal and hydrogeological regimes of a permafrost mound located in the discontinuous permafrost zone near Umiujaq (Nunavik, Canada). This instrumentation includes thermistor cables, groundwater monitoring wells, temperature and water content sensors in the active layer, heat flux plates, and a snow cover monitoring system.

Data indicate that ice-rich permafrost is restricted to a 15-m-thick unit of marine silt, which is overlain by a 4-m-thick layer of sand. The active layer encompasses the full extent of the surficial sand layer, as well as the top 2 m of the silt unit. Depending on climatic and surficial conditions, the furthest extent of the freezing front in a given year may not reach the permafrost table, resulting in the formation of a sporadic talik between the active layer and the permafrost table. Data further indicate that the surficial sand layer acts as an unconfined aquifer, and that infiltrating precipitation flows downward to the permafrost table before flowing radially towards the sides of the mound. A downward hydraulic gradient was observed across the low hydraulic conductivity silt unit. These observations were synthesized into a cryohydrogeological conceptual model to provide insight into the physical processes that govern local permafrost dynamics at the study site in order to guide future field campaigns and modelling projects.

Impact of lateral groundwater flow on hydrothermal conditions of the active layer in a high arctic hillslope setting

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The hydrothermal state of the active layer in permafrost landscapes is largely influenced by the presence of water. It greatly influences vertical conduction and advection of heat in areas with little topography. In a hillslope system, lateral water transport introduces additional effects on the hydrothermal state of the subsurface through water and moisture redistribution along the hillslope. In a semi-generic modeling study, we analyze the effect of groundwater flow in two hillslopes (steep and medium) in a high Arctic setting in comparison to a flat control case. We find that ground temperatures within the active layer uphill are generally warmer than downhill in both slopes (with a difference of up to 0.8°C in the steep, and 0.6°C in the medium slope). Further, the slopes are found to be warmer in the uphill section and colder in the base of the slopes compared to the flat control case. As a result, maximum thaw depth increases by about 5 cm from the flat (0.98 m) to the medium (1.03 m) and the steep slope (1.03 m). Uphill warming on the slopes is explained by overall lower heat capacity, additional energy gain through infiltration, and lower evaporation rates due to drier conditions caused by subsurface runoff. The major governing process causing the cooling on the downslope side is heat loss to the atmosphere through evaporation in summer and enhanced heat loss in winter due to wetter conditions and resulting increased thermal conductivity. On a catchment scale, these results suggest that temperature distributions in sloped terrain can vary considerably compared to flat terrain, which might impact the response of subsurface hydrothermal conditions to ongoing climate change.

Measurement and Modeling of Wildfire-Initiated Talik Development in Boreal Alaska

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As the Arctic warms and wildfire occurrence increases, talik formation in permafrost regions is projected to expand and affect the cycling of water and carbon. Yet, few unified field and modeling studies have examined this process in detail, particularly in areas with cold mean annual air temperatures. We address this gap by presenting multimethod, multiseasonal geophysical measurements of permafrost and in-situ liquid-water content that reveal substantial talik development in response to recent wildfire in continuous permafrost of boreal Alaska. Results from observation-based cryohydrogeologic model simulations suggest that predisturbance subsurface conditions are key factors influencing thaw response to fire disturbance and air temperature warming. Our high-resolution integrated study illustrates enhanced vulnerability of boreal continuous permafrost, with observed talik formation that exceeds coarse-scale model projections by ~100 years even under the most extreme future emissions scenario. Results raise important scaling questions for representing extreme permafrost thaw phenomena of growing widespread importance in large-scale predictive models.

Hydrologic implications of supra-permafrost taliks in disturbed landscapes of boreal Alaska, USA

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Recently, there has been focused attention on the development of supra-permafrost taliks (perennially unfrozen zones in permafrost) that follows active-layer thickening in the sequence of top down permafrost-thaw progression in high latitudes. Talik formation can substantially influence geomorphic, hydrologic, and biogeochemical processes in permafrost landscapes, thus motivating efforts to understand current talik distribution and provide constraints on future evolution under changing climate. Here we present examples of talik formation in contrasting field sites in upland and lowland boreal forest ecoregions in interior Alaska, USA. Sites are located near the broadly mapped transition between continuous and discontinuous permafrost. Multiple lines of geophysical data provide support for enhanced talik development in response to disturbance, including wildfire and ice jam river flooding, superimposed on atmospheric warming. Drawing from results of cryohydrogeologic model simulations, field measurements, and additional analytical assessments, we discuss hydrologic implications for talik development and permafrost thaw acceleration at our contrasted sites. We identify and explore landscape characteristics and initial thermal conditions that control the propensity for talik development. Field investigations show localized examples of rapid talik development that outpace current coarse scale talik projections under the most extreme greenhouse gas emission scenario by ~ 100 years. Though large-scale extrapolation of localized extremes is not advised, our research raises questions regarding the potential for aggregated localized thaw to evolve toward regional importance as widespread wildfire activity and flooding intensify in the future.

Are Concentration-Discharge Relations in Arctic Rivers Different from Temperate Rivers?

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Despite the impact of solute exports from the six largest Arctic rivers on the biogeochemistry of the Arctic Ocean and its surrounding ecosystems, the long term relationships between concentration and discharge from these river systems have been sparsely studied. Relationships between solute concentrations and river-discharge are important controls on intra-watershed transfers and exports of materials. In temperate watersheds, most geogenic (water-rock interaction controlled) solutes behave chemostatically (e.g. the log concentration versus log discharge patterns follow a near zero slope). Sufficiently long hydrological residence times are critical to this behavior, enabling kinetic source limitations to be overcome, as well as activation and mixing of different hydrological stores during wet up. Permafrost environments have not been well studied in a chemostatic context, but because permafrost limits deep groundwater flow paths and hydrological storage, chemodynamic (flushing or dilution) and non-systematic (high coefficient of variation ratio) behaviors may be dominant. We analyzed concentration-discharge data for 20 solutes from the six largest Arctic rivers using the Arctic Great Rivers Observatory (ArcticGRO) database and found that while chemostatic behavior is common, chemodynamic behavior frequently occurs for both geogenic and non-geogenic (e.g., nitrate and dissolved organic carbon) species. We also found many differences in the distribution of chemostatic, chemodynamic, and non-systematic behaviors between the different rivers, suggesting that physical and biogeochemical attributes of these basins controlling concentration-discharge vary substantially. This study provides an important baseline for comparison to other Arctic streams and rivers. In addition, by establishing the current trends of concentration-discharge relations we can monitor Arctic rivers for future changes that might occur through further permafrost degradation or other anthropogenic perturbations.

Long-term (2000-2017) response of lake-bottom temperatures and talik configuration to changes in climate at two adjacent tundra lakes, western Arctic coast, Canada

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Lakes are principal agents of disturbance to permafrost. Key variables which control these thermal disturbances are permafrost temperature, lake size, and lake-bottom temperature. Many Arctic lakes are shallow and well-mixed. Consequently, the lake-bottom temperature is closely associated with atmospheric conditions in summer. In winter, thermal regimes of the atmosphere and lake-bottom are distinct until the water column freezes to depth. Canada's western Arctic has experienced considerable climate change since 1970, dominantly in autumn and winter. Mean annual air temperatures at Inuvik, NWT, increased from -9.7 °C to -6.0 °C between 1960-69 and 2010-19. We present long-term measurements of lake-bottom temperatures at two adjacent tundra lakes near the western Arctic coast to determine responses in lake thermal regime to climate variation. Temperatures have been monitored on shallow near-shore terraces and in deep central pools between 2001-10 for one lake and 2000-17 for the other. In total, there are 25 lake-bottom-years for shallow water and 17 for the central pools. Air temperatures have been reconstructed from several years of monitoring and with reference to records at Tuktoyaktuk, NWT. Annual mean lake-bottom temperatures have varied (2000-17) between -5.7 and 2.8 °C in shallow water and between 1.1 and 4.5 °C in the deep central pools. Annual mean air temperatures have varied between -11.2 and -6.8 °C in the same period. The coefficient of determination (R2) between seasonal thawing degree-days at the lake bottom and in the air for three shallow sites ranged between 0.85 and 0.94. For two deep sites, comparable values are up to 0.79. For seasonal freezing conditions, R2 ranged up to 0.21 for shallow and had no correlation at deep sites. The data suggest that the greatest effects of climate change on lake taliks will likely occur through adjustments to permafrost in the littoral terraces of tundra lakes.

The uncertainty in InSAR-based active layer soil water storage estimates over the Arctic Foothills

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Recent studies show that groundwater flow through the topmost portion of permafrost soil, known as the active layer, has a significant contribution to the export of carbon in permafrost terrain. Because the Arctic covers continent-sized areas that are mostly inaccessible, remote-sensing has become a critical tool for observing continuous permafrost. Particularly, the density difference between liquid water and ice causes seasonal ground surface deformation that can be detected over large spatial scales using Interferometric Synthetic Aperture Radar (InSAR). Here, we analyzed L-band ALOS PALSAR scenes acquired between June and October from 2006 to 2010 (Path 255, Frame 1370-1380) near Toolik Lake and solved for the seasonal thaw subsidence and frost heave associated with the active layer freeze-thaw cycle. We confirmed that the maximum thaw subsidence is proportional to the total soil water content in the active layer using in-situ measurements of the hydraulic properties and stratigraphies at over 200 sites across the Arctic Foothills. We found that the average seasonal thaw subsidence increases along a geomorphic-ecohydrologic transect starting with heath vegetation on the drier ridge-tops, transitioning into tussock tundra on hillslopes, and draining into lowland riparian zones with wet sedge tundra. We also quantified the uncertainty in the InSAR measurements. We found that the misregistration between the Arctic DEM and a subset of SAR images leads to a DEM error in InSAR phase measurements. This is the dominant error source in the ALOS Toolik InSAR data, particularly in areas with large slope angles (> 7.5%). We developed a mitigation strategy, that reduces the uncertainty in the InSAR-based soil water estimates from > 20 cm to < 10 cm. Our study suggests that InSAR has greater observational capabilities than previously assumed for monitoring changes in hydrological and ecological characteristics above continuous permafrost and estimating large-scale soil moisture.

Simulating Arctic hydrology with WaSiM

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Climate change leads to rapid landscape change in the Arctic regions. Many aspects of those changes are related to hydrological processes. Arctic landscapes are dominated by ice where it is present in many forms from snow to glaciers and below ground with a variety of ground ice present in permafrost. All the ice depends and cool atmospheric conditions to remain frozen, but in many cases that is currently changing. Ice can be considered long term storage in the arctic hydrological system and the water is often decades to centuries old.

Ground ice degradation leads to changes in the topography resulting in modified surface runoff and watershed response to precipitation events. Surface water changes due to permafrost collapse both as the water accumulates in thermokarst pits or lake drainage due to thermal erosion events. Snow is of particular importance as the feedback to subsurface temperatures are strongly dependent on snow depth and density. With warming conditions also comes a change in vegetation and its effects on active layer temperatures and double feedbacks related to snow trapping as the shrub advance continuous in the Arctic.

Over the past years we have made progress in the development of the water Balance Simulation Model (WaSiM) toward an arctic hydrological simulation model. Some of the highlights are: soil temperature with freezing and thawing, snow temperature in the snow pack, efficient surface runoff, snow distribution variability, soil surface temperature effects of vegetation through n-factors. We are currently working on the development of a dynamic soil surface collapse module based on a known ground ice content and warming conditions. Surface vegetation conditions are dynamic and simulated by the Arctic Vegetation model (ArcVeg). We are implementing feedbacks from ground ice melt to soil surface collapse affecting surface runoff, local drying and wetting effects on the vegetation. Secondary affects are also considered through preferential snow accumulation in troughs and shrub establishment.

The model is centered on hydrology and it is therefore uniquely suitable for the simulation of processes on a watershed scale. It is highly efficient and can be used on a high resolution grid that includes the processes of ice wedge polygon collapse and preferential snow accumulation on a meter scale. In our developments we focus on the most important hydrological events in arctic watersheds.

The thermal response of permafrost to coastal flooding

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Permafrost warming is projected everywhere in the Arctic. Increases in air temperature directly drive permafrost warming, but flooding also indirectly contributes to permafrost warming by changing the surface reflectance of solar insolation. For example, more shortwave radiation is more likely to be absorbed when the ground is inundated. Historical data show that coastal regions of the North Slope of Alaska experience frequent flooding events due to spring snowmelt, summer storms, river ice-break-up, and Arctic Lake drainage. However, the impact of flooding on permafrost in the continuous permafrost environment has not been tested and remains poorly understood. To address this knowledge gap, we used a combination of available flooding data on the Ikpikpuk delta and a numerical model of permafrost conditions. We first constructed the four most common flood events based on water level data on the Ikpikpuk: high spring snowmelt flood, equally distributed flooding events over the whole summer, early-summer floods, and late-summer floods. The impact of these flooding events on permafrost was simulated on one-dimensional permafrost columns using the Advanced Terrestrial Simulator (ATSv1.0) fully coupled permafrost-hydrology numerical model. The results of our simulations show the extent of permafrost thaw and active layer deepening depend on the timing, duration, and frequency of flood events. Preliminary results suggest that shorter and more frequent summer flood events have a greater effect on permafrost thaw than longer snowmelt-driven floods.

Spatial distribution and temporal dynamics of the suprapermafrost subarial taliks in Eastern Siberia

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The research aims at the assessment of the spatial distribution and temporal dynamics of subaerial suprapermafrost aquifer taliks in Central Yakutia, Eastern Siberia, using geophysical methods, drilling, geothermal and hydrogeological monitoring. Subaerial suprapermafrost taliks are not anticipated in the continuous permafrost zone and extremely continental climate of Central Yakutia. We revealed relatively high proportion of the suprapermafrost subaerial taliks on a small catchment of the Shestakovka river near Yakutsk and in the western part of the region between the Lena and Viluy rivers. The thickness of the seasonally frozen layer above the taliks is 1.7-3 m, the thickness of the thawed layer is 3-20 m. The depth of zero annual amplitudes is 5-6 m, and the temperature at the depth of zero annual amplitudes is 0 °C. Taliks could include several thawed troughs oriented along the slope where water filtrates down the slope. In winter, taliks break up into separate closed water-saturated thawed areas and the talik water level can be higher than the surface due to the cryogenic pressure. In the warm period taliks groundwater and water of the active layer form a single aquifer is formed. The seasonal dynamics of the spatial distribution of taliks is more pronounced than the interannual ones. An approximate assessment of the suprapermafrost taliks fraction in the western part of Central Yakutia using GPR methods and key sites can be more than 6% only due to the subaerial taliks. This estimate does not include lake and channel taliks and is at least one and a half times higher than the previously published estimates. Suprapermafrost subaerial aquifers taliks can be used as a year-round source of water supply.

Hydrologic-land surface modelling of the Canadian sporadic-discontinuous permafrost: initialization and uncertainty quantification

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Permafrost is a critical feature in cold regions that significantly impacts hydrological processes, energy flux partitioning, plant communities, and carbon dynamics. Permafrost thaw has been observed in recent decades in the Northern Hemisphere and is expected to accelerate with continued global warming. Predicting the effects of climate warming on permafrost requires proper representation of the surface/subsurface thermal and hydrologic regimes. Land surface models (LSMs) are well suited for such predictions, as they couple heat and water interactions across soil-vegetation-atmosphere interfaces and can be applied at large scales. However, the long-term thermal and hydraulic memories of permafrost pose a major challenge for modelling. Historical records are too short to represent these dynamics under transient climate conditions; hence model initialization is problematic. Moreover, the significant interactions among the underlying processes in LSMs for model validation add further difficulty for model development. This study addresses the challenge of model initialization by characterizing the impact of initial climate conditions and initial soil frozen and liquid water states on the simulation length required for model warm-up. Further, we quantify how the uncertainty in model initialization propagates to simulated permafrost dynamics. We report model experiments conducted with the Modélisation Environmentale Communautaire – Surface and Hydrology (MESH) modelling framework and its embedded Canadian Land Surface Scheme (CLASS) to investigate permafrost simulations for sporadic and discontinuous permafrost regions. The study area is in the Liard River basin in Canada's Northwest Territories, where soil temperature/texture profiles are available at two sites. Results confirm that uncertainty in model initialization dominates the simulated permafrost attributes, especially the active layer thickness, which can change by 1-1.5m depending on the initial condition chosen. The least spin-up time to reach equilibrium was achieved with initial soil moisture near field capacity. We advise an extended spin-up of 200-1000 cycles to ensure proper model initialization under different climatic conditions and initial soil moisture contents.

Fine-Resolution Measurement of Soil Moisture from InSAR Phase Closure

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Acquiring high-resolution soil moisture data over large swaths of remote permafrost-covered areas is difficult due to the high cost of manual coverage and relatively coarse resolution of spaceborne passive radiometric observations. Here, we test how well fine-resolution interferometric synthetic aperture radar (InSAR) phase closure measurements match in situ soil moisture data. Phase closure refers to the net phase when linking three interferograms formed from three acquisitions so that the net phase in single-look interferograms is zero. The phase closure often becomes nonzero when regions of pixels are averaged spatially (in multilooked images) before the net phase is computed. Here, we show cases in which the discrepancy in phase closure corresponds to changes in soil moisture. Our data reduction approach includes an integration of the phase closure over time and subtraction of a random walk component to relate the differential phase values to soil moisture level. We find that for a large, simple test region of Oklahoma, the integrated phase closure using Sentinel-1 data tracks the soil moisture observed in the field. We also analyze results from a more complex region of permafrost in Alaska, with less straightforward results. In other cases, the match is less than good. If we can determine under what circumstances the InSAR measurements provide a good match to soil moisture, we have a potentially valuable utility to remotely estimate soil moisture at high resolution in remote permafrost areas.

Modelling Water Release from Degrading Permafrost in Arid Mountain Environments

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Numerical cryo-hydrogeology models can be useful tools for understanding thermal and hydrological feedbacks that influence water flow in periglacial environments. With climate change expected to modify permafrost distribution globally, there is growing interest in developing such models for planning purposes, particularly in arid mountainous environments where headwaters can be important water sources to downstream users. In the arid Central Andes, permafrost is ubiquitous and debated as a possible resource to moderate water scarcity under climate change and drought. At many locations in the region, permafrost is in disequilibrium with existing climate and therefore expected to degrade even if current air temperatures are maintained. The coupled finite element codes TEMP/W and SEEP/W were used to explore a range in hydrologic outcomes from degrading permafrost within a typical watershed for such an arid region, subject to a suite of characteristic permafrost distribution, ground ice content and hydrogeologic conditions. A 3 km-long 2D cross-sectional numerical model was developed using simplified topography (altitude up to ~6000 m), and ground temperatures representative of the region. The model uses constitutive relationships that consider conductive and advective heat transport, as well as unsaturated water flow, and includes surface boundary conditions derived from local monitoring data. Predictive simulations were performed to estimate changes in water quantities and flow-paths should current temperature conditions in the watershed persist. Preliminary results for a continuous permafrost case suggest an overall decrease in downstream discharge as ground-ice thawed. As permafrost degraded laterally and the active layer thickened, supra-permafrost water migrated downward through the unsaturated zone toward the regional ground water system. It is noted that these results are strongly subject to the assigned initial conditions and simplified topography. Future efforts will explore scenarios with more complex landform topography and permafrost distribution, under climate change influences.