Preface: Hydrogeology of cold regions

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Introduction

Almost half a century ago, Williams (1970) compiled an annotated bibliography of published materials (up to 1960) on permafrost groundwater in the former Soviet Union, United States and Canada, and Scandinavia. That comprehensive survey encompassed literature on permafrost and related temperature and hydrological phenomena, and scientific and applied aspects of groundwater in permafrost terrain. In the intervening years, there have been major advances in permafrost hydrogeology, accompanied by shifts in research emphasis driven by scientific, environmental and societal demands. The present theme issue of *Hydrogeology Journal* presents a collection of articles that reflect the current status of progress in research on the hydrogeology of cold regions.

Several of the papers in this theme issue describe current conditions of resources and processes in different specific regions of the world. Overall, the studies address conditions across different parts of Alaska (USA), Canada, Siberia, China, Fennoscandia and other parts of Europe, and Antarctica. Although snow and seasonally or permanently frozen ground recurs as a common consideration, each paper presents a unique perspective on widely varying conditions. Greater understanding of polar and sub-polar processes may be gleaned from a comparison among these results.

With the focus of this thematic issue being on the hydrogeology of cold regions, all the papers in the issue discuss important elements of subsurface hydrology, and there is particular emphasis on ground ice and permafrost interactions with groundwater. However, the studies also deal with externalities that impact the subsurface such as surface energy budget, snow hydrology or glaciers, and groundwater below ice sheets, and some contributions address subsurface controls on the surface conditions via interaction with surface water or ecology.

With regard to investigation approaches, the studies deal with interpretation of field or remotely sensed data, theory of ice-impacted hydrologic processes, field techniques, and modeling of groundwater systems in cold regions. Some of the modeling papers combine in pointing at safety assessment of nuclear waste repositories under climate-cooling scenarios as an important motivation for development and application of numerical simulation approaches for the hydrogeology of cold regions. Some articles are about management of groundwater resources, and there is also some discussion on societal aspects of cold-regions hydrology, for example, impacts of climate warming in these regions.

In summary, the range of investigations presented in this thematic issue constitutes a valuable compilation of the state of knowledge of cold region hydrogeology. This contribution is timely, with groundwater resources in cold regions facing immediate or impending changes as a consequence of the ongoing climate change, the intensification of the hydrologic cycle, and in response to increased demands from communities and industry.

Regional studies

Cheng and Jin review the occurrence, circulation and nature of groundwater in permafrost regions of China.

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They present a methodical summary of processes in various parts of China as a function of the predominance of continuous or discontinuous permafrost. Most of the permafrost in China is located in mountainous areas and on the Qinghai-Tibet Plateau, which also corresponds with important sources of freshwater for Asia. The permafrost greatly limits moisture exchanges between surface and subsurface, and thus plays an important role in water cycling and water availability through controls on recharge, flow pathways and discharge. China has experienced some of the greatest degradation of permafrost in the last 30 years, with areal extent decreasing by nearly 20 % and markedly affecting hydrogeology, and with consequent effects on surface hydrology, ecology and social systems.

Callegary et al. report on groundwater conditions in Alaska as related to its climate, physiography and glaciation history. They discuss the groundwater and surface-water interactions in six different hydrologic sub-regions of Alaska, ranging from boreal rain forests to Arctic deserts. They further discuss issues of groundwater contamination, particularly in association with mining and petroleum development, along with climate-change effects on permafrost and, consequently, the hydrogeology of Alaska.

For the continuous permafrost regions of northeastern Alaska, **Kane et al.** note the frequent occurrence of springs and formation of icing. They suggest that the groundwater comes from a source at the south side of Brooks Range, on the other side of the Continental Divide. There, limestone beds facilitate groundwater recharge and groundwater flow can be transmitted through deep sub-permafrost paths. Groundwater can further be discharged through taliks along fault lines that pierce the permafrost, and at the northern edge of the permafrost along the Beaufort Sea coast.

For more shallow groundwater in northern latitudes subject to seasonal frost, **Ireson et al.** provide a general survey of literature on soil freeze–thaw and related moisture migration processes, with particular examples from the prairies and boreal forests of western Canada. Infiltration and recharge of seasonally frozen soils are described. Their synthesis of northern hydrogeology focuses primarily on seasonally frozen soil and examines seasonal differences in water-balance processes. They note that snow accumulation and soil freeze–thaw cycles control the timing and magnitude of infiltration, groundwater recharge, and baseflow in northern regions, and propose a conceptualization for modeling the principal processes that influence the seasonally frozen–thawed vadose and shallow groundwater zones. They further discuss various problems associated with quantitative models of these processes, and assert that much can be gained by combining field experiments with modeling, and by integrating models of the near surface with models of deeper groundwater.

Process studies

Papers on process studies focus mainly on supra-permafrost groundwater (i.e. water in the zone subject to seasonal freeze–thaw) and involve field investigations or make use of measured data. The scale of enquiry ranges from small drainage basins to water tracks or ponds. **Carey et al.** use hydrometric records together with stable isotope and dissolved ions data to investigate groundwater contributions during snowmelt in a small alpine, discontinuous permafrost basin in Yukon, Canada. Runoff from snowmelt freshet is derived largely from old water that existed prior to the melt event. The unsaturated organic layer that overlies mineral soils provides the capacity for storing old water over-winter and the high soil porosity permits infiltration of meltwater to displace the existent water in the soil. There is much inter-annual variability in the magnitude of the freshet, and meltwater can contribute from 10 to over 25 % of streamflow.

Utting et al. study the recharge and flow of groundwater in carbonate terrain of northwestern Canada. Recharge is enhanced where air temperature inversion causes permafrost to be thinner at the higher elevations than at the lower elevations. P_{CO2} and $\delta^{13}C$ values point to a recharge of groundwater through organic-rich soils that overlie fractured bedrock. Noble gas results show that recharge occurs close to 0 °C, suggesting the absence of heat advection to the subsurface. As dated by ^{3}He-ingrowth from tritium, groundwater has a circulation time on the order of two to three decades, indicating that karst groundwater systems have substantial flow paths and storage capacity.

Koch et al. studied a permafrost basin, with an organic layer overlying silt, near Fairbanks, in interior Alaska. They find that runoff shifts from shallow throughflow in spring and early summer to deeper preferential flow as the active layer thaws. Throughflow is topographically controlled, while preferential flow follows steep slopes, near-stream zones and newly exposed silt along thawing margins. Tracer dilution gauging suggests occurrence of preferential flow through pipes formed at the boundary between thawed silt and impermeable ice-rich frozen soil below. Uranium isotopes provide indication that these preferential flow paths are renewed seasonally and they erode the ice-rich sediments below, thus releasing ancient carbon to the ecosystem.

Semenova et al. present a model analysis of data for the Kolyma basin situated in a mountainous continuous permafrost setting in Siberia. They use a physically based hydrological model that accounts for heat and water transfer in soils, and apply it to three small watersheds with distinctive terrains. The model satisfactorily simulates thaw depth, infiltration, surface and subsurface flows. It is found that a mainly bare watershed with coarse, talus materials has deeper seasonal thaw and larger subsurface flow than a basin covered with larch and underlain by peaty ice-rich soil. A third basin with tundra vegetation exhibits thaw and runoff conditions intermediate between these two. This paper provides useful information on subsurface properties and water flow in Siberia, as well as citations to many important, but relatively unknown Russian research publications. Although extensive, the contributions of Russian research on permafrost hydrology

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are not well known in English language literature. This watershed was the first permafrost research watershed established, dating back to at least 1948, and in the 1960–1980s, the Soviet hydrological scientists had already studied the mechanisms of runoff generation and associated variations with land cover and topography. This paper makes those early studies and that information more accessible.

For watersheds in northern Sweden, **Sjöberg et al.** combine results from a numerical model with measured streamflow data to connect shifts in two discharge characteristics with permafrost thaw. Baseflow has increased significantly in nine basins and seven basins display changes in recession characteristics consistent with degradation of permafrost. The increase in minimum flow in the winter is associated with a modification of flow connectivity in the aquifer system as permafrost thaws, and the change in recession flow during the summer responds to warming of the active layer. These observed flow tendencies are in general agreement with the outcomes of a warming scenario simulated with a non-isothermal, multi-phase flow model.

Helbig et al. investigate the hydrologic role of micro-topography, applying water-balance studies on low-centered tundra polygons in the Lena River delta in Siberia. During and immediately following the snowmelt period, the polygons and their adjoining troughs experience flooding and large lateral outflow conditions. In the second part of summer, a shift in lateral flow dynamics leads to reduced net outflow and even inflow conditions after rain events. Hydrologic connectivity of the tundra polygons network is a manifestation of the fill-and-spill mechanism in which lateral drainage is connected only when pond levels are filled above the outflow thresholds. The shallow depth of seasonal thaw maintains soil water as a limited but important component of the water balance, playing an important role in maintaining these wetlands.

In another tundra polygon terrain, near Barrow in Alaska, **Hubbard et al.** obtain and combine point measurements, LiDAR (light detection and ranging) and geophysical datasets (surface ground penetrating radar, electromagnetic and electrical resistance tomography data). They perform cluster analysis on these data to delineate zones, each with unique geomorphic, thermal, hydrological and geochemical properties. Such characterization of the temporal and spatial variability of land surface and subsurface properties contributes to quantifying the ecosystem-climate feedbacks in permafrost terrain.

For the extreme arid permafrost environment of the Dry Valley in Antarctica, **Gooseff et al.** report that meltwater from glaciers and from snow patches is the only source of runoff. Groundwater occurs in front of melting snow patches, beneath water tracks, along wetted margins of streams and lakes, and in hyporheic zones along the streams. The shallow supra-permafrost groundwater zones enhance the movement of solutes in the wet soils. The hydrologic function and the biogeochemistry of the wet zones control biological communities.

For the discontinuous permafrost area of Yukon Flats, Alaska, **Jepsen et al.** note that many lakes experience lowering of their water level, but the changes are not uniform across the region. This implies local control on the water balance of individual lakes. They studied specifically one lake that has displayed substantial volume loss since the early 1980s. Suggested explanations include an increased loss to lateral groundwater flow through gravel across the drainage divide, vertical groundwater flow through a sub-lacustrine talik, and substantial reduction in snow accumulation accompanied by increased infiltration of meltwater into the unfrozen sediment. Their analysis examines possible ranges in variability of properties and processes, which may explain why some lakes display marked changes and neighboring lakes show little apparent change.

Quinton and Baltzer describe the hydrologic behavior of a small permafrost peat plateau in a wetland environment of northwestern Canada and provide evidence of recent permafrost degradation, noting shrinkage in plateau size and increase in its active layer thickness. Field data indicate that both active layer moisture and temperature rose as ground thaw began progressively earlier during the decade. Both the water-balance computation and model study show that active-layer runoff in the spring is related to the snow–water equivalent, and the magnitude of summer runoff corresponds with the depth of summer rainfall. Modeled sensitivity runs that incorporate changes associated with permafrost degradation show that decreased hydraulic gradient and increased thaw depth have slight effect, but plateau shrinkage gives rise to the greatest reduction of runoff from the permafrost plateau. In total, the runoff is 47 % of what it would have been without the changes in hydraulic gradient, active layer thickness and plateau surface area that occurred between 2002 and 2010.

Model studies

Models are used increasingly to study groundwater in permafrost regions, particularly the sub-permafrost and intra-permafrost groundwater systems, which are rarely amenable to direct field investigation. Models are also employed to explore the evolution of permafrost and its attendant effects on groundwater, under both climate warming and climate cooling scenarios.

Painter et al. discuss challenges that confront modeling prediction of the hydrologic response to degrading permafrost. In their essay, they comment that models need to consider approaches for coupling various surface and subsurface processes, and incorporate the deformation of topography, including micro-topography, and drainage network as the landscape evolves. These requirements place demands on the computational infrastructure as the models need increasingly higher spatial and temporal resolutions.

Three papers apply numerical simulation to assess the safety of nuclear waste repositories under climate cooling scenarios. For a site in Forsmark, Sweden, **Bosson et al.** investigate groundwater flow and solute transport under

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hypothetical climate and permafrost conditions. The presence of permafrost greatly diminishes vertical groundwater flow, compared with non-permafrost situations. With permafrost, the taliks and sea bottom provide passages for recharge and discharge, and for contact between shallow and deep groundwater. Tracking of particles that reach and are carried further by deep groundwater reveals that they spend much time travelling horizontally beneath the permafrost. However, taliks and unfrozen seabeds offer vertical pathways for exchange of flow and solute between the deep and shallow groundwater, which increases with decreasing permafrost.

Vidstrand et al. model groundwater flow in crystalline rocks of the Fennoscandian Shield, Sweden, beneath the moving margin of an ice sheet, focusing on the changes in groundwater flow as climate changes. The very long time scale of radiological safety requires consideration of the deep-seated groundwater systems during glaciation and deglaciation because the highly dynamic drainage systems of ice sheets and glaciers will also affect these deep systems. Under glacial conditions, permafrost in front of the glacier limits groundwater flow and water is discharged in taliks. As a glacier advances, pressure exerted by the ice sheet causes the permafrost to thaw. Successive reduction of the permafrost is accompanied by recharge of fresh meltwater beneath the ice, flushing saline groundwater from fractures in the bedrock. Orders of magnitude difference in Darcy velocity of flow can be caused by local variations in geological structure and hydraulic properties.

The safety of nuclear waste storage is also assessed by **Grenier et al.** for a sedimentary basin like that of the Paris Basin in northeastern France. They simulate transient thermal evolution in a cold dry glacial period, using generic topographic settings of a river and a plain. Under cooling scenarios, conductive heat transfer alone closes a talik within several centuries, but including advection from the river to the plain, talik closure is delayed on the millennium time scale. Depending on talik position, groundwater flow varies from a reduction of recharge to its complete cessation.

Frampton et al. model the effects of surface warming on permafrost degradation and subsurface flow. Several rates of warming are applied to a hypothetical subsurface configuration comprising two adjacent soils of different properties. Over a 10-year simulation period, seasonal variability of flow diminishes gradually, but the minimum flow increases notably, primarily during winter and spring. Groundwater discharge first increases as permafrost thaws but declines later when ground ice storage undergoes depletion.

Wellman et al. study the impacts of climate, lake size, and groundwater flow on the evolution of lakes in permafrost areas of Yukon Flats in Alaska. Numerical simulations of heat and water fluxes over centuries suggest that a lake that loses water downward from the active layer is relatively fast in developing a through-going talik that links supra- and sub-permafrost aquifers. A lake that gains water from upward movement of sub-permafrost groundwater does this more slowly, whereas a lake without any water gain or loss takes the longest time to form a talik through the permafrost. Once connected, the feedback of heat convected by groundwater enhances permafrost thaw.

Simulation of groundwater by **McKenzie and Voss** further highlights the role of heat advection by groundwater flow in permafrost thaw. Applied to a hypothetical undulating topography with a nested groundwater-flow system under climate-warming scenarios, the model shows that heat transport greatly accelerates the thaw, compared with thawing due to heat conduction alone. For patchy permafrost, thaw is quicker near zones of high permeability but low-permeability patches preserve permafrost for an extended time. Introducing seasonal temperature fluctuation gives rise to non-linear interaction of annual freeze–thaw with groundwater flow, but the effect on permafrost thaw is local rather than regional. Where taliks already exist below deep lakes, permafrost thaw proceeds faster than the no-lake situation only after the taliks break through the permafrost.

In conclusion

We end by referring the reader back to an earlier assessment. Williams and van Everdingen (1973) wrote the first review paper on groundwater investigations in permafrost regions of North America for the Second International Conference on Permafrost. They addressed many of the topics that have been included in this special issue including permafrost and movement of groundwater, availability of groundwater, icings, pingos and artesian pressures, influence of permafrost on water quality, methodology, studies of basin hydrology, investigations for pipeline projects, hydrologic model studies, and research needs. The paper did consider increasing demands on groundwater from growing communities and expanding industrial use, but not the potential consequences of a changing climate and the possible effects of degrading permafrost. In these 40 years, our instruments, our models, and even our methods of analyses have become much more sophisticated, giving us better capabilities to help our societies protect and utilize limited resources. Still, we owe much to those pioneering researchers, who began the studies that now allow us to gauge changes, and understand processes and potential impacts.

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