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Literature review of groundwater flow in permafrost

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SSM perspektiv

Bakgrund

Strålsäkerhetsmyndigheten (SSM) granskar Svensk Kärnbränslehantering AB:s (SKB) ansökningar enligt lagen (1984:3) om kärnteknisk verksamhet om uppförande, innehav och drift av ett slutförvar för använt kärnbränsle och av en inkapslingsanläggning. Som en del i granskningen ger SSM konsulter uppdrag för att inhämta information i avgränsade frågor. I SSM:s Technical note-serie rapporteras resultaten från dessa konsultuppdrag.

Projektets syfte

Konsultuppdragets syfte är att sammanställa forskningsläget när det gäller grundvattenflöde under permafrostförhållanden. Följande frågor är därvid av intresse:

- Är huvudprocesserna relaterade till grundvattenflöde under permafrostförhållanden klarlagda?
- Finns data tillgängliga för de betydelsefulla grundvattenflödesrelaterade parametrarna?
- Är befintliga modeller för grundvattenflöde under permafrost på relevanta skalor byggda på konceptuella modeller som är väl förankrade i processförståelsen? Har dessa bekräftats med fältdata?
- Vilka aspekter av grundvattenflöde under permafrostförhållanden kräver ytterligare forskning?

Slutrapporten från konsultprojektet (denna Technical Note) är ett av flera externa underlag som SSM kommer att beakta i sin egen granskning av SKB:s säkerhetsredovisningar, tillsammans med andra konsultrapporter, remissvar från en nationell remiss och en internationell expertgranskning av OECD:s kärnenergibyrå (NEA).

Författarens sammanfattning

Strålsäkerhetsmyndigheten har gett i uppgift att sammanställa kunskapsläget gällande grundvattenflöde under permafrostförhållanden. I synnerhet ska studien beakta om (i) huvudprocesserna relaterade till grundvattenflöde under permafrostförhållanden är klarlagda, (ii) lämpliga fältdata finns tillgängliga och (iii) om nuvarande modeller på ett lämpligt sätt återspeglar de konceptuella modellerna. Studien bör även föreslå områden för framtida forskning om grundvattenflöde under permafrostförhållanden. Studiens avsikt har varit att ge information utöver den som SKB sammanställt genom att identifiera studier som inte direkt är kopplade till SKB:s arbete inom området men som är lämpliga för att klarlägga grundvattenflöde under permafrostförhållanden.

Litteratursökningar har genomförts med sökmaskinen SCOPUS och har fokuserat på artiklar och publicerade litteraturgenomgångar. Sökningarna resulterade i en stor mängd litteratur kopplad till permafrost och grundvatten. Litteraturgenomgången fokuserade på att hitta studier som beaktar in- och utströmning från, respektive till, grundvatten som ligger under permafrostlager i periglaciala områden eftersom sådana studier närmast berör grundvattenflöde genom permafrost.

Representativa studier kan indelas i flera olika kategorier. Dessa innefattar modelleringsstudier som fokuserar på grundvattenhydrologi i samband med (i) inlandsisar, (ii) periglaciala områden gränsande till inlandsisar och (iii) grundvatten ovanpå permafrostlager. Modellerings- och fältstudier som beaktade öppna talikar (ofrusna förbindelser mellan grundvatten under permafrostlager och ytvattenförekomster såsom sjöar och åar) identifierades också, liksom studier som rapporterar fältobservationer av inströmning till grundvattnet genom heltäckande permafrost.

Litteraturstudien kommer fram till att man har en hyfsad förståelse av huvudprocesserna som styr grundvattenflöde i porösa medier under permafrostförhållanden och i samband med talikar. Fältdata kan insamlas med tillgängliga metoder för att stödja modellerna. De befintliga modellerna återger i vissa fall flöde genom sprickigt berg på ett missvisande sätt. Modellerna antar att vatten i sprickorna och i det omgivande berget har samma temperatur, vilket innebär att frusna förhållanden i bergmassan leder till att flöde i sprickor i stort sett utesluts. Med detta antagande blir den beräknade inströmningen till permafrostområden i stort sett noll förutom där talikar upprätthåller ofruset ytvatten.

Fältobservationer av betydande årstidsberoende uppströms inflöde till kalkstensområden trots tjocka permafrostlager pekar tydligt på att flöden i sprickigt berg kan motstå frusna förhållanden i berggrunden. De studerade områdena återspeglar inte fullt ut förhållandena i Forsmark med platt topografi och sprickig granit, men observationerna pekar på att forskning på området kan vara berättigad för att bättre förstå hur flöde i sprickor möjligtvis kan upprätthållas under permafrostförhållanden. I synnerhet krävs mer forskning för att (i) karakterisera möjligheten att upprätthålla temperaturskillnader mellan flödande sprickor och omgivande berg, (ii) karakterisera frysning och töande i flödande nätverk under föränderliga klimatförhållanden och (iii) mäta relevanta sprickegenskaper i befintliga permafrostområden.

Projektinformation

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SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) applications under the Act on Nuclear Activities (SFS 1984:3) for the construction and operation of a repository for spent nuclear fuel and for an encapsulation facility. As part of the review, SSM commissions consultants to carry out work in order to obtain information on specific issues. The results from the consultants' tasks are reported in SSM's Technical Note series.

Objectives of the project

The objective of this project is to compile the state of the knowledge regarding groundwater flow under permafrost conditions with the following questions being of interest:

- Are the main processes related to groundwater flow under permafrost understood?
- Is there field data available for the most important groundwater flow related parameters?
- Are models of groundwater flow under permafrost conditions on relevant scales built on conceptual models that are well founded on process understanding? Have they been corroborated with field data?
- Which are the main aspects of groundwater flow under permafrost conditions that needs further research?

The final report from this consultant project (this Technical Note) is one of several documents with external review comments that SSM will consider in its own review of SKB's safety reports, together with other consultant reports, review comments from a national consultation, and an international peer review organized by OECD's Nuclear Energy Agency (NEA).

Summary by the author

The Swedish Radiation Safety Authority (SSM) assigned the task of compiling the state of the knowledge with respect to groundwater flow in permafrost conditions. In particular, the study was to consider whether (i) the main processes related to groundwater flow in permafrost were understood, (ii) appropriate field data was available, and (iii) current models appropriately represent the conceptual models. The study was to provide suggestions for future research related to groundwater flow in permafrost. The intent of the study was to provide complementary information to work considered by the Swedish Nuclear Fuel and Waste Management Company (SKB) by identifying studies not directly related to SKB's work but useful for understanding flow under permafrost conditions.

Literature searches were performed using the SCOPUS search engine, focusing on articles and review papers. The searches identified a voluminous body of literature related to permafrost and groundwater. The review focused on identifying studies that considered recharges to and discharges from subpermafrost groundwater in periglacial zones, as such studies most directly consider groundwater flow through permafrost.

Representative studies were identified in several categories, including modelling studies that focused on groundwater hydrology associated with (i) ice sheets, (ii) periglacial zones outside ice sheets, and (iii) suprapermafrost groundwater. Modelling and field studies that considered open taliks (thawed conduits between subpermafrost groundwater and surface water bodies such as lakes and streams) were also identified, as well as studies with field observations that identified recharge occurring through continuous permafrost.

The review suggests that the main processes related to groundwater flow under permafrost conditions and within taliks are reasonably well understood for porous media, and field data supporting the models can be obtained using established methods. The current generation of models may misrepresent flow through fractured rock under some circumstances, however. The current generation of models assume that water in fractures and in the surrounding bulk rock exist at the same temperature, thus frozen conditions in the surrounding rock implies that flow through fractures is essentially eliminated. With this assumption, calculated recharge into permafrost zones is essentially zero in current models except where surface waters maintain open taliks.

Field observations of substantial seasonal upland recharge into carbonate units despite thick permafrost zones provide a clear indication that flows within fractured hard rock can withstand subfreezing conditions in the host rock. The study locations with these field observations are not completely representative of lowland fractured granite at the Forsmark site, but the observations do suggest that further research may be warranted to better elucidate how fracture flows might be maintained through permafrost. In particular, further research is needed to (i) characterize the potential for maintaining temperature differences between flowing fractures and the surrounding rock, (ii) characterize freezing and thawing in flowing networks under changing climatic conditions, and (iii) measure relevant fracture properties in existing permafrost zones.

Project information

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1. Introduction

1.1. Task description

This assignment concerns a literature study on groundwater flow under permafrost conditions. The state of the knowledge shall be compiled with the following questions being of interest.

- Are the main processes related to groundwater flow under permafrost understood?
- Is there field data available for the most important groundwater flow related parameters?
- Are models of groundwater flow under permafrost conditions on relevant scales (e.g., km scale) built on conceptual models that are well founded on process understanding? Have they been corroborated with field data?
- Which is (are) the main aspect(s) of groundwater flow under permafrost conditions that needs further research?

The Swedish Nuclear Fuel and Waste Management Company (SKB) has carried out work in this field and also compiled information from the literature for its work, e.g., Vidstrand et al. (2010). This assignment will aim at providing complementary information, (e.g., by identifying studies not directly related to SKB's work), yet useful for understanding groundwater flow under permafrost conditions.

While this study does not directly address the safety assessment, safety assessment issues that may come up under the subsequent review of SKB's licensee applications will be considered in guiding the compilation. Such questions include the potential reduction in groundwater flow under permafrost conditions compared to unfrozen conditions and the possible increase in groundwater flow due to the presence of taliks and preferential flow paths that may have to be accounted for in the safety assessment.

1.2. Background

Based on the task description, the current study focuses on conditions that may permit communication between subpermafrost groundwater and the surface. Communication may take the form of either recharge from the surface or discharge to the surface. The study focuses on communication in a periglacial region (i.e., not under an ice sheet or glacier), recognizing that recharge under an ice sheet may drive discharge. Recharge through permafrost may provide a means for dilute waters with adverse chemistry to penetrate to the repository horizon, with potentially adverse influences on repository performance. Discharge through permafrost may provide a pathway for released radionuclides to reach the accessible environment.

By definition, permafrost consists of a rock or sediment that has been continuously below the freezing point of water (0 °C) for more than 2 years. Permafrost zones are classed as continuous (generally requiring mean annual temperatures below −5 °C) or discontinuous. A permafrost zone acts as an aquiclude, with the frozen medium exhibiting effective hydraulic conductivity orders of magnitude smaller than the unfrozen medium, because ice preferentially blocks the largest pores in a porous medium and any remaining liquid water is only present in thin films.

Permafrost zones are bounded at depth because of geothermal heat moving to the surface and may be bounded above by a seasonally thawed and frozen active layer. Permafrost zones also may be in part bounded by a talik, simply defined as a zone remaining above the freezing point that is bounded below or laterally by permafrost.

The tight coupling between hydrology and temperature when temperatures are near the freezing point of water exerts a tremendous influence on hydrologic processes. Ice is much less mobile than liquid water and substantial energy is bound up as latent heat during the freezing process. In liquid water, energy is transported through both advection and diffusion, whereas energy transport within ice is limited to diffusion. Because of this tight coupling, the boundaries of permafrost zones may be strongly influenced by flowing water. Further, the freezing point of water is influenced by salinity and by pressure to a small degree. The boundaries of permafrost zones tend to be mutable under changing thermal and salinity conditions, and under changes in the tremendous pressures exerted by ice sheets.

1.3. Site conceptual model

Ice sheets have covered Scandinavia in past glacial cycles, and thus are considered likely to form again in future glacial cycles. In the last cycle, an ice sheet expanded from northern Sweden into northwest Russia and the northern parts of the British Isles, Germany, and Poland, profoundly altering the hydrology of the Forsmark site relative to present conditions. At the Forsmark site, periglacial conditions have been experienced because of an ice sheet expanding out of and receding to northern Sweden. Recharge and, especially, discharge may be influenced by the presence of an ice sheet or glacier. Accordingly, it is useful to review the SKB conceptual model for ice sheet hydrology to provide context for the study.

Vidstrand et al. (2010) present a conceptual model of groundwater conditions under periglacial and glacial conditions, considering the evolution of groundwater, as influenced by the presence of an ice sheet under advancing and retreating conditions. Hartikainen et al. (2010) elaborate on the conceptual model. In the SKB conceptual model, developed to perform bounding calculations, an advancing ice sheet is associated with permafrost in the periglacial region because of low air temperatures, and permafrost extends some distance under the ice sheet. A retreating ice sheet is associated with submerged conditions at the tip of the ice sheet (i.e., a proglacial lake). The presence of permafrost greatly reduces the hydraulic conductivity within the permafrost zone; in two Vidstrand et al. (2010) hydraulic conductivity models, the hydraulic conductivity is reduced by 10 orders of magnitude as the temperature drops from 0 °C to −1 or −1.5 °C. Groundwater recharged under the ice sheet discharges through taliks in the advancing case, and discharges to the proglacial lake in the retreating case. Vidstrand et al. (2010) also consider advancing scenarios without permafrost, in which case groundwater discharges in advance of the ice sheet.

In broad terms, the hydrological system associated with an ice sheet varies with position within the ice sheet and with the stage of ice sheet development because of couplings between hydrology, temperature, ice thickness, sea level, and isostatic level. Land surface topography is modified, perhaps modifying periglacial drainage patterns, because development of an ice sheet depresses the underlying and surrounding land surface towards the ice sheet center while simultaneously lowering the sea level.

The temperature and pressure conditions at the base of an ice sheet profoundly affect groundwater hydrology; groundwater recharge may occur when the base is wet (i.e., liquid water exists), but may be prevented when the base is frozen. An advancing ice sheet typically overruns permafrost formed by the cold periglacial environment. A sufficiently thick ice cover provides sufficient insulation that, over time, geothermal heat may thaw the permafrost underlying the ice sheet. The coupling between pressure and freezing point also influences the groundwater pressure (or head) distribution under ice sheets. In the same way that water tables tend to follow topographic gradients, water tables under ice sheets tend to follow the ice sheet topographic distributions. Accordingly, groundwater tends to flow towards the edges of the ice sheet towards discharge points. These factors may lead to a groundwater flow system that recharges under warm portions of the ice sheet, discharges near the edge of the ice sheet, and is isolated from the ice sheet in intermediate regions. In such a system, substantial upward pressure gradients may develop in periglacial regions near ice sheets (Bockgård, 2010).

Water, energy, and lithologic processes proceed on different time scales. Because of these different time scales, the periglacial hydrologic system is likely to exhibit hysteresis, in the sense that periglacial hydrology near a retreating ice sheet has a different organization from periglacial hydrology near the preceding advance. One important difference is that a retreating ice sheet exhibits a net export of meltwater rather than a net increase in ice mass, thus the periglacial environment will be wetter overall. Proglacial lakes at the tip of the ice sheet are more likely compared to advancing conditions. The Vidstrand et al. (2010) conceptual model includes this hysteresis in moisture by including a proglacial lake only during retreat. Depending on relative rates of advance and retreat, ice sheet duration, and position with respect to the ultimate ice sheet edge, one can infer that the permafrost zone may be warmer and thinner during retreat. However, groundwater discharge pathways through permafrost that were maintained by flowing water during the advance may have frozen while covered by the ice sheet, thereby discharge may occur at different locations for a given ice sheet position during an advance and the subsequent retreat.

1.4. Literature search methods

The literature review was performed exclusively using the SCOPUS search engine. This search engine includes journal articles and some conference proceedings and books, but does not include reports, such as the SKB reports. The search engine provides citation information, an abstract where available, and references where available (thus some reports can be indirectly identified from reference lists). It is possible to create a list of all references in documents identified in a search (a first-order list), but it is not possible to create a second list from these references (a second-order list). It is possible to develop a search by combining previous searches (e.g., excluding search results identified for particular authors from a general topic search). It does not appear possible to import an externally generated list of references (e.g., the bibliography from an SKB report) to create search lists for further processing. The list of search results can be exported in a format suitable for word processors or spreadsheets.

The literature on groundwater flow in permafrost has grown exponentially in recent years, thus it was necessary to adaptively develop keyword searches to identify relevant papers. For example, a keyword search on "permafrost" provided 7,658 hits and a keyword search on "talik" provided 84 hits. It proved useful to develop one search for any keyword in a list of keywords pertaining to cold regions, develop another search for any keyword in a list of keywords pertaining to groundwater hydrology, and then develop a combined search requiring that the document contain a keyword from both lists.

A representative list of 207 references was developed using a keyword search focused on identifying groundwater flowing through permafrost. The keyword search (aufeis OR talik OR permafrost) AND (groundwater discharge OR groundwater recharge) accomplished this goal. This is by no means an exclusive list; searching on (permafrost OR periglacial OR ice sheet OR glacier) AND (groundwater OR hydrology OR infiltration OR recharge OR discharge OR hydraulic conductivity) generated a list of more than 2,100 references, far beyond the scope of this review task. A large set of relevant references is undoubtedly present in reports and conference proceedings not identified by the search engine. Representative papers from the developed reference list are used to provide examples of the current literature.

The list of references was pruned by eliminating books and conference proceedings. Articles written in languages other than English were pruned, eliminating a number of particularly relevant articles written in Russian. For future research on this topic, it may be important to find ways to at least scan the Russian literature.

The list of references was examined to estimate what was in common with SKB work. All references in the most recent and relevant SKB reports (Vidstrand et al., 2010; Vidstrand and Rhén, 2011; Boulton et al., 2001; Vidstrand, 2003; Jansson et al., 2007; Hartikainen et al., 2010; SKB, 2010; and Jansson, 2010) were compared with the list of references, as were any journal papers authored by one of the authors of the five most recent reports (Vidstrand et al., 2010; Vidstrand and Rhén, 2011; Hartikainen et al., 2010; SKB, 2010; and Jansson, 2010) and all references in the papers.

2. Key literature

The literature describing groundwater flow in permafrost zones falls into several general categories. At the largest scale, ice sheet models consider couplings between some combination of ice sheet dynamics, permafrost, groundwater, salinity, sea level change, and isostatic compensation. At smaller scales, models exist that consider hydrothermal couplings with respect to thaw lakes, streams, and other landscape-scale processes. Observations of groundwater discharge also exist, suggesting couplings between groundwater and the surface.

2.1. Periglacial groundwater models

2.1.1. Ice sheet models

SCOPUS identified 107 articles or review papers considering ice sheets and groundwater. Ice sheet models can represent the conditions at the Forsmark site over a complete glacial cycle, including periglacial conditions during intervals when the ice sheet is not above the site.

Vidstrand et al. (2010) considered four representative models for groundwater flow systems under the influence of permafrost in the context of ice sheet dynamics (Lemieux et al., 2008a,b,c; Hartikainen et al., 2010; Walsh and Avis, 2010; and Cohen et al., 2010). The study by Hartikainen et al. (2010) is a site-scale study; the other studies consider much larger scales. Vidstrand et al. (2010) also cited a number of highly influential papers considering groundwater flow systems below ice sheets (e.g., work by Boulton and coworkers collected in Boulton et al., 2001, 2007a,b, as well as Piotrowski, 1997a,b and van Weert et al., 1997). The latest work provides a sense of the state of the art in modelling with respect to communication between subpermafrost groundwater and the surface at large scales.

The Lemieux et al. (2008a,b,c) model considers all of Canada and the northern United States. In this 3-D model, the periglacial region is assumed to have a water table at the ground surface, based on observations that the water table in Canada is rarely more than a few tens of meters from the ground surface. The groundwater model uses an external model (the Glacial Systems Model, developed by Tarasov, Peltier, and coworkers) to provide descriptions of ice sheets, permafrost thickness, and proglacial lake water levels as boundary conditions. Hydraulic conductivity is assumed to drop by 6 orders of magnitude when permafrost develops.

The Harikainen et al. (2010) model considers vertical cross sections through the Forsmark site. The model considers surface conditions (e.g., air temperature, topographic features, water bodies, vegetation, and snow) to estimate surface temperatures. The model considers subsurface conditions, such as thermal and hydraulic properties of bedrock and soil, geothermal heat flow, convective heat flow due to groundwater, heat generation from the repository, and salinity exclusion. Taliks are predicted to develop under lakes.

The Walsh and Avis (2010) model focuses on groundwater flow and radionuclide transport under various glacial scenarios, including specified taliks. The scenarios were abstracted from a simulation run of the Glacial Systems Model. The Cohen et al. (2010) model focuses on freshwater flow to the continental shelf from New Jersey to Maine under glacial conditions. Like the Lemieux et al. (2008a,b,c) model, the Cohen et al. (2010) model assigned the water table elevation to the ground surface and accounted for permafrost by reducing hydraulic conductivity.

Other models considering groundwater flow near ice sheets appear to have comparable or simpler descriptions of flow conditions in the periglacial region. Bense and Person (2008) consider idealized vertical cross sections, (i) assuming the water table is at the ground surface, (ii) reducing hydraulic conductivity where permafrost exists, (iii) calculating permafrost thickness based on modelled temperature distributions, and (iv) not specifically representing taliks or lakes. The Bense and Person (2008) study is notable for considering co-evolution of permafrost with groundwater flow. McIntosh et al. (2012) assume the water table is at the ground surface outside an ice sheet, without explicitly considering permafrost. Person et al. (2012) review 15 models considering ice-sheet hydrologic interactions, and conclude that such models typically specify permafrost distributions as boundary conditions rather than calculated from internal state conditions.

2.1.2. Periglacial groundwater modelling

Holmén et al. (2011) developed a 3-D finite difference single-continuum groundwater model for the Paris basin to consider groundwater flow over a glacial cycle. The model assumes that an ice sheet is not present and assigns surface boundary conditions of temperature and potential recharge. This model considers coupled water and energy balances, considers local topography and overland flow redistribution to estimate recharge, and calculates permafrost thickness using internal state variables. Fifty-year time steps are used over a glacial cycle, with some cells using locally smaller time steps. The Holmén et al. (2011) model represents a good example of the state of the art with respect to surface boundary conditions in medium-scale periglacial groundwater modelling.

2.1.3. Shallow (suprapermafrost) groundwater models

Numerical models considering shallow groundwater are rapidly developing. Such models typically consider fine space and time scales, such as a site scale with variability within a year. Ground surface temperatures typically vary widely over a year, making it particularly challenging to represent the freezing and thawing process numerically.

Several models appear to characterize current practice. Bense et al. (2009) consider reactivation of subpermafrost groundwater pathways under warming climates using a vertical cross section model of an idealized hillslope. Bense et al. (2009) considered coupled water and heat balances, but applied mean annual temperatures at the surface. Ge et al. (2011) and Frampton et al. (2011) considered similar hydrological systems, adding vapour transport, and considered sinusoidally varying air temperatures. The simulators for the two last models are capable of 3-D simulations, but such simulations are extremely computationally demanding. Because of computational demands, more detailed physical representations appear to be generally limited to 1-D simulations (e.g., Westermann et al., 2011; Scherler et al., 2010).

Local recharge into fractured bedrock is amenable to modelling at this scale, considering seasonal dynamics, at least with a 1-D model.

2.2. Taliks and conduits

Taliks predictably form under lakes and streams. In some cases, taliks may penetrate the underlying permafrost, in which case it represents a conduit between subpermafrost groundwater and the surface. When convective flow maintains a talik, the size of the talik may be sensitive to the flow rate because of energy constraints.

SCOPUS identified several papers related to taliks that are not available in English. These papers were not reviewed, but may provide relevant information. In particular, Mikhailov (2010) discusses taliks in river valleys, as influenced by convection.

2.2.1. Thaw lakes

SCOPUS identified 65 articles or review papers considering thaw lakes. Ice sheet hydrology models do not consider thaw lakes, which typically exist at a small scale relative to the model grid. Thaw lakes may not be experienced at the Forsmark site, because thaw lakes typically form in ice-rich sediments above permafrost and these conditions may not exist during a glacial cycle at the site. Nevertheless, thaw lakes represent an example of how surface waters can develop taliks in permafrost.

Thaw lakes are thought to initiate after thawing has left a depression. Once the lake water reaches a sufficient depth, the bottom of the water column remains unfrozen year round. Under such conditions, the lake bottom also remains unfrozen in a so-called thaw bulb, and may experience annual temperatures several degrees above freezing. The amount of heat flowing from the lake into the surrounding permafrost determines the equilibrium size of the thaw bulb. Thaw lakes may grow radially, as heat is exported to the surrounding banks. In some cases, the underlying talik may penetrate the underlying permafrost, allowing rapid drainage of lake waters through the lakebed (e.g., Yoshikawa and Hinzman, 2003). Drained areas of the lakebed then develop permafrost. This process may be cyclic, although development of a new lake may not occur at the center of the previous lake (Jorgenson and Shur, 2007).

Thaw lake models (e.g., Rowland et al., 2011; Plug and West, 2009; West and Plug, 2008; Ling and Zhang, 2004, 2003) use coupled heat and water balances to estimate talik dynamics. These models typically consider vertical cross sections.

2.2.2. Proglacial lakes

SCOPUS identified 326 articles or review papers considering proglacial lakes, of which 9 also considered groundwater. Some of the ice sheet models consider proglacial lakes as surface-water features that directly communicate with groundwater, with model calculations typically identifying the lake as a groundwater discharge location.

Two models were identified that model groundwater interactions with proglacial lakes. Both of the models consider site-specific scenarios. Flowers et al., 2007, uses a combined shallow-ice and groundwater model to consider meltwater from the Langjökull ice cap in Iceland, estimating that groundwater discharging to the lake carried 70 percent of the meltwater. Hoaglund et al. (2004) modelled modern and Pleistocene groundwater exchanges in the Michigan Basin, and suggest that groundwater recharge below a confining unit in the sedimentary basin was localized to the region of an ice sheet and proglacial lake. The Hoaglund et al. (2004) study appears to be an example of elevated pressures developing under an ice sheet driving recharge from one aquifer to another across a confining unit, rather than a challenge to the conceptual model that a proglacial lake is a groundwater discharge point.

2.2.3. Streams

SCOPUS identified 49 articles or review papers considering permafrost AND groundwater AND river. Streams and rivers are too small to directly represent large-scale ice sheet models, but the common condition of an imposed talik with a water table at the ground surface provides some indication of the hydrological impact that a large river might have on groundwater. Further, studies of baseflow in streams provide indications of groundwater recharge.

Most of the identified papers that considered groundwater and stream interactions focussed on changing streamflow dynamics as a result of different groundwater discharge patterns under thawing permafrost (e.g., Niu et al., 2011; Lyon and Destouni, 2010; and Walvoord and Striegl, 2007). These papers typically focused on changes in suprapermafrost groundwater dynamics.

2.2.4. Aufeis and recharge

SCOPUS identified 56 articles or review papers considering aufeis. Aufeis (icings or naledi) can be spectacular examples of groundwater recharge and discharge in permafrost zones. Aufeis represents groundwater discharge manifested as frozen layers forming above river ice. Aufeis is commonly due to suprapermafrost groundwater, which may be pressurized during seasonal freezing of the active layer. More rarely, aufeis may be due to perennial subpermafrost groundwater discharging to a stream at sufficient rates to preclude freezing to the bottom of the stream. Lauriol et al. (1991) determined that aufeis in the Yukon tends to be associated with faulted calcareous terrains. Clark and Lauriol (1997) consider a 31 km^2 aufeis sheet in the upper Firth River in northern Yukon, Canada, concluding that it is maintained by groundwater recharge rates up to 100 mm/yr. Using geochemical techniques applied to thermal waters (16 °C), Clark et al. (2001) identify a subpermafrost component to groundwater discharge supporting aufeis in Big Fish River, northern Yukon, Canada, suggesting that the recharge occurred at high elevation in the nearby Richardson Mountains. These two study locations are within the continuous permafrost zone, and both feature discharge from exposed limestone units. Tolstikhin and Tolstikhin (1977) describe aufeis as occurring across the Arctic, indicating that aufeis areas as large as 80 km^2 occur in Siberia. Yoshikawa et al. (2007) describe springs and associated aufeis in the Brooks Range of Alaska, attributing 30,000 l/s of springflow to recharge in southern exposures of limestone in the Brooks Range. Yoshikawa et al. (2007) indicate that the springflow is predominantly from intra and subpermafrost aquifers, and that many of the springs survived the last glaciation. Although Yoshikawa et al. (2007) do not estimate a recharge area, most of the springs are mapped in the eastern Brooks Range with an associated area of limestone exposures approximately 30,000 km^2 (independently estimated using Google Earth), implying recharge from all sources is on the order of 30 mm/yr averaged over the limestone outcrops. Springs are rare in the central Brooks Range; Nunn et al. (2005) suggest that recharge in the central Brooks Range is expressed as deep groundwater flow that discharges in and near the Arctic Ocean.

Lack of aufeis does not necessarily indicate that substantial baseflow does not exist. Utting et al. (2012) describes groundwater discharge from carbonate bedrock into the Fishing River, Yukon, Canada. The channel remains open year-round, maintained by perennial groundwater discharge via a talik under the channel. Utting et al. (2012) estimate that recharge is approximately 120 mm/yr, despite a mean annual temperature of −9 °C and 90 m of continuous permafrost in the watershed. Utting et al. (2012) conclude that recharge likely occurs during summers in upland areas with shallow soil over highly fractured bedrock, and geologic structures focus the subpermafrost groundwater to the talik.

These studies suggest that groundwater recharge may occur in continuous permafrost zones when conditions focus flow into permeable conduits. Presumably, the subpermafrost water table is below the permafrost, allowing water to drain through an unsaturated zone without being retained within the permafrost zone and thereby freezing in place. Exposures of calcareous units are especially susceptible to recharge because karst features can develop; calcium is more soluble as temperatures drop, thus karst develops more rapidly in colder climates. The Forsmark site does not feature limestone units, but fault zones exposed at the surface may provide an analogous means for waters to recharge, even during periods of continuous permafrost.

3. Discussion

3.1. Summary of the literature

The literature suggests that subpermafrost groundwater may communicate with the surface when the energy balance is locally favourable. The near surface cryosphere typically features a mean annual temperature profile that increases with depth below the surface. Solar and atmospheric energy balances, modulated by topographic position, plant characteristics, and snow cover, maintain the surface temperature, and geothermal heat diffusing to the surface maintains the temperature gradient. Because the geothermal heat flux is usually steady over glacial durations, any changes to the temperature profile initiate at the surface and propagate to depth.

Locally favourable conditions for subpermafrost groundwater to communicate with the surface may arise from surface conditions that locally maintain a warm ground surface, geothermal conditions that locally maintain a warm base, or geologic conditions that permit preferential flow at sufficient rates to withstand the heat loss to surrounding permafrost.

When the mean annual temperature is only moderately below freezing, favourable topographic positions (e.g., south-facing slopes) may receive enough solar radiation or insulating snow pack to maintain thawed ground. Such favourable topographic positions communicate with the underlying groundwater as though located in a more temperate climate. On the other hand, permafrost can be locally maintained despite air temperatures slightly above freezing, given suitable topographic position and vegetation. Accordingly, recharge is likely to occur in a mosaic when mean annual air temperatures are at or moderately below 0 °C. Under favourable conditions (e.g., shallow soil over densely fractured bedrock), recharge has been observed to be a substantial fraction of annual precipitation, even with continuous permafrost and mean annual air temperatures of −9 °C (Utting et al., 2012; Clark et al., 2001).

Water bodies deep enough to maintain an unfrozen layer (e.g., lakes, rivers) maintain an underlying thawed zone, which may provide a potential conduit for exchange with subpermafrost groundwater. Warm seasonal stream flow also may provide sufficient energy to maintain an underlying thawed zone. Finally, geothermally produced heat diffuses through ice sheets and glaciers, thus the base of ice sheet and glaciers tend to be warmer than the surface and sufficiently thick covers will allow thawed conditions at and below the base of the ice.

Favourable geologic conditions also may maintain thawed conduits through permafrost, analogous to thawed zones around a stream or river. Circulation patterns initiated during warmer climates may be preserved by convection as permafrost develops. Such conditions require that flows are sufficiently large to overcome loss of energy to the surrounding frozen media. Natural conduits in karst environments are particularly favourable for developing flow pathways, because flowing waters will dissolve the pathways, but fault systems in hard rock also may serve as a conduit.

3.2. Insights based on the literature review

The review study was tasked with considering four main questions to guide the review:

- Are the main processes related to groundwater flow under permafrost understood?
- Is there field data available for the most important groundwater flow related parameters?
- Are models of groundwater flow under permafrost conditions on relevant scales (e.g., km scale) built on conceptual models that are well founded on process understanding? Have they been corroborated with field data?
- Which is (are) the main aspect(s) of groundwater flow under permafrost conditions that needs further research?

These questions are addressed below.

3.2.1. Are the main processes related to groundwater flow under permafrost understood?

In general, the main processes related to groundwater flow interacting with permafrost in porous media appear to be reasonably well understood. The literature is more concerned with computational issues and uncertainties in model parameterization than with characterizing the physical processes.

One exception is the situation where flow is confined to discontinuities (e.g., fractures or faults). This situation has been explored to a much lesser extent than flow and permafrost in a porous medium. A network of discontinuities is likely to be more hysteretic than a porous medium. In a porous medium, a talik maintained by flow can readily expand or contract to respond to changes in flow or energy balances. In a discontinuity network, the rock mass isolates individual discontinuities so that it may be much more difficult for flow pathways to expand than to contract.

Our understanding of groundwater flow interacting with permafrost is better at the scale of individual fractures than it is at the repository or site scale, and it is likely that the current generation of models can reasonably model flow in a network of discrete fractures passing through permafrost. However, modelling at the site scale or larger is not practical using a discrete fracture network because of the exorbitant computation burden, thus a continuum representation is necessary at the larger scales. It is not at all clear that current models appropriately capture the hysteretic interaction between flow and energy balances in fractures when the fracture system is represented as a continuum.

3.2.2. Is there field data available for the most important groundwater flow related parameters?

This study focused on groundwater flow in the context of exchange between subpermafrost groundwater and the surface in periglacial environments. Within this scope, two system characteristics related to both permafrost and groundwater appear to be important for representing groundwater flow at locations representative of the Forsmark site under potential periglacial conditions: (i) the characteristics of an active talik network; and (ii) the nature of flow through faults, fractures, and conduits.

Groundwater flow related parameters such as hydraulic conductivity are important, as is always the case when considering groundwater flow, and should always be considered part of site characterization regardless of the presence or absence of permafrost. The primary new parameterization imposed by permafrost relates to the frozen hydraulic conductivity relationship, but the different proposed relationships are likely to provide similar groundwater patterns at the kilometre scale.

The concept of an active talik network represents the network of open taliks allowing groundwater to communicate across a permafrost layer. An active talik network may influence subpermafrost groundwater flow patterns, in the sense that numerous closely spaced taliks may generate shallower or deeper groundwater flow patterns than widely spaced taliks. Talik networks do not, strictly speaking, represent a groundwater flow parameter but observations of talik networks can be used to constrain models. The usual groundwater parameters influence talik network characteristics, but may not be as important as in other groundwater situations. Taliks exist at temperatures close to the freezing point, thus talik dimensions are sensitive to the energy balance. Taliks adaptively adjust their boundaries by freezing or thawing to accommodate a given flow and energy balance, thus a different hydraulic conductivity may result in a different talik dimension without substantially influencing total flux.

Characterizing flow through discontinuities (e.g., faults, fractures, conduits) is uncertain even without considering permafrost. Unlike active talik networks, permafrost may make characterizing the hydraulic properties of discontinuities more challenging, because the relationship between flow and energy balances will inevitably make estimated properties dependent on the applied flows and sensitive to long-term climatic conditions. It may be difficult to estimate fracture properties at sites already experiencing permafrost, because only fractures in the active network experiencing flow under the current flow regime would be measurable using standard methods. This issue does not appear to have been discussed in the reviewed literature and should be considered for future research.

3.2.3. Are models of groundwater flow under permafrost conditions on relevant scales (e.g., km scale) built on conceptual models that are well founded on process understanding? Have they been corroborated with field data?

The current generation of models are built on conceptual models that are well founded on process understandings for some purposes. For example, uncertainties associated with ice-sheet processes and potential lake locations may dominate uncertainties with respect to groundwater flow near a potential future ice sheet. Groundwater flow is likely to be relatively well represented away from a permafrost zone, based on the vast experience with groundwater modelling in temperate zones. Exchange between subpermafrost groundwater and the surface in the periglacial region is likely to be adequately represented near large-scale features such as lakes, because taliks are dominated by lake effects rather than convection.

Flow through features at the subgrid scale (e.g., fractures, faults) that are maintained in an unfrozen state by convection may be less well represented in the current generation of models.

Current models representing porous media (e.g., sedimentary basins) may be better founded than models representing fractured rock (e.g., granite, limestone), because flow velocities are smaller in porous media and therefore water and energy balances are more closely tied together. Current models of fractured rock use an equivalent continuum approach to represent the fracture system, which implies that the fracture system and surrounding rock are in perfect thermal equilibrium. For example, the Vidstrand et al. (2010) model implements this approach by developing equivalent hydraulic properties for the set of discrete fractures within each grid cell, which consists of a control volume with side lengths ranging from 32 m to 512 m. Each grid cell is assumed to have a uniform pressure and temperature throughout the cell. In actuality, the interface between a flowing conduit and the rock face contacting the conduit will be in thermal equilibrium, but water in the conduit may maintain higher temperatures than in the bulk rock mass away from the conduit. In fractured media, it may be appropriate to consider the bulk rock and fractures as two interacting continua with separate temperatures in order to represent important aspects of the energy balance near fractures.

There have been few field studies considering groundwater hydraulics in permafrost zones, especially in fractured media. The available studies tend to be centrally focused on developing water balances or considering features such as thaw lakes, streams, and glaciers. In such studies, the detailed representation of groundwater hydraulic properties is secondary to the primary study goal. Accordingly, field verification of the interaction between flowing groundwater and permafrost has received relatively little field corroboration.

3.2.4. Which is (are) the main aspect(s) of groundwater flow under permafrost conditions that needs further research?

It is not clear that the current generation of models appropriately represent convective effects in subgrid features found in hard rock. The current generation of large-scale models assume that hydraulic conductivity is very small wherever permafrost exists, thus represent infiltration as essentially zero. However, recharge of 100 mm/yr has been observed through 90 m of continuous permafrost in limestone (Utting et al., 2012) and substantial discharges are found in many areas with limestone cropping out (e.g., Yoshikawa et al., 2007; Clark et al., 2001; Lauriol et al., 1991; Tolstikhin and Tolstikhin, 1977). Such large recharge conditions may be limited to karst and densely fractured units with substantial topographic relief (i.e., mountainous regions), thus recharge would likely be smaller under similar climatic conditions at the Forsmark site.

The set of observations suggest that flowing conduits developed during warmer climatic conditions may permit recharge and discharge through thick continuous permafrost. Taliks that remain open because of convective flow represent a strongly hysteretic process, in the sense that an interruption or reduction in flow may close the talik with substantial thaw required before the talik reopens. This implies that the state of each talik in a system of active taliks depends on conditions in the other taliks, thus the set of active taliks under permafrost conditions may be sensitive to the time history of climatic conditions.

Given these limitations on the current models, further research is needed on the appropriate representation of constitutive relationships and parameterizations to represent flow and energy balances in discontinuities. In particular, further research is needed to (i) characterize the potential for maintaining temperature differences between discontinuities and the surrounding rock, (ii) characterize the potential impacts of hysteretic freezing and thawing in flowing networks under changing climatic conditions, and (iii) measure relevant fracture properties in permafrost zones.

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