Hydrogeological data collection and interpretation at arctic mines in the continuous permafrost zone

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ABSTRACT
Groundwater data collection and interpretation at existing and proposed mines in the Precambrian Shield of the Canadian arctic (western Nunavut and Northwest Territories) are discussed based on literature review and recent hydrogeological testing at proposed mine sites. The Canadian Environmental Assessment process requires the collection of baseline groundwater data and predictions of mine inflow quantities and potential impacts on groundwater quality and quantity during the construction, operation and closure phases of the mine. This portion of the Precambrian Shield is in the continuous permafrost zone. The presence of permafrost tends to reduce the potential for groundwater inflows into mines but presents a number of technical issues for: a) collection of hydrogeological data, b) interpretation of ground water flow systems, c) prediction of mine inflow volumes, and d) assessment of potential groundwater quantity/quality impacts on local water resources.

RESUME
Des issues concernant la collecte de quantité d'eaux souterraines et des données de qualité dans les mines existantes et proposées dans les roches précambriennes de bouclier de l'arctique Canadien (Nunavut et Territoires du Nord-Ouest) sont discutées, basées sur la revue de littérature et le récent essai hydrogéologique fait aux emplacements proposés de mine. Le processus d'évaluation environnemental Canadien exige la collecte des données sur des états d'eaux souterrains de ligne de base ainsi que des prévisions des quantités d'apport de mine et tous les impacts potentiels sur la qualité et quantité d'eaux souterraines pendant la construction, l'opération et les phases de fermeture de la mine. Cette partie du bouclier précambrien est une zone continue de pergélisol. La présence de pergélisol tend à réduire le potentiel pour des apports d'eaux souterraines dans des mines mais présente un certain nombre d'issues techniques pour: a) la collection de données hydrogéologiques, b) l'interprétation des systèmes d'écoulement d'eaux souterraines, c) la prévision des volumes d'apport de mine, et d) l'évaluation de la quantité et qualité d'eaux souterraines et l'impact potentiel sur les ressources d'eau locales.

1 INTRODUCTION

A number of new mines in western Nunavut and the adjacent area of the Northwest Territories are being developed due to the recent global demand for commodities (Figure 1). This paper is based on hydrogeological testing conducted for environmental impact assessment (EIA) and mine permitting at the Zinifex High Lake and Izok proposed poly-metallic mines in Nunavut and considers other published hydrogeological information for the Snap Lake, Ekati, Diavik diamond mines and the closed Lupin gold mine.

All of these existing and proposed mines are in the Canadian Shield Precambrian metamorphic rocks, although the local rock types vary between mines. Overburden deposits are generally very thin on this portion of the Canadian Shield.

Mean annual air temperatures in this area are approximately –10 to –15 degrees centigrade and the ground is continuously frozen to depths of 200 to 500m (i.e. continuous permafrost). Only the upper 1 to 7m melts during the brief summers. This shallow zone is known as the “active layer”. The presence of continuous permafrost significantly affects how hydrogeological data is collected and interpreted. Permafrost lowers the hydraulic

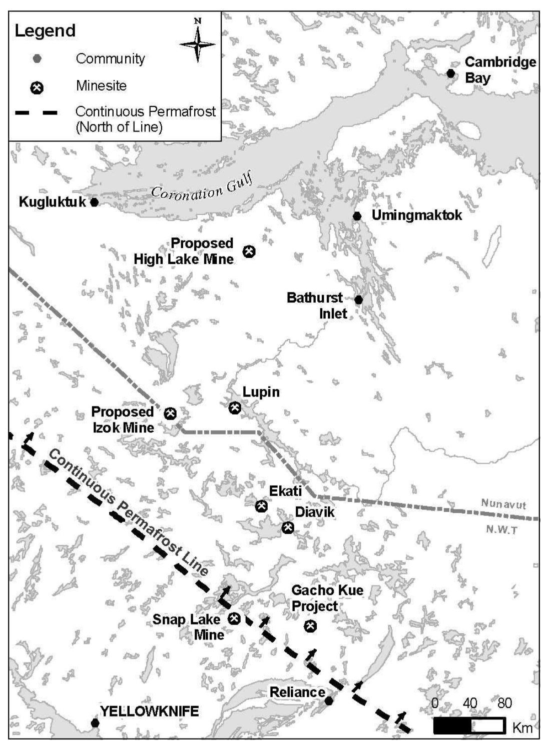

Figure 1. Location of mines in and near Western Nunavut

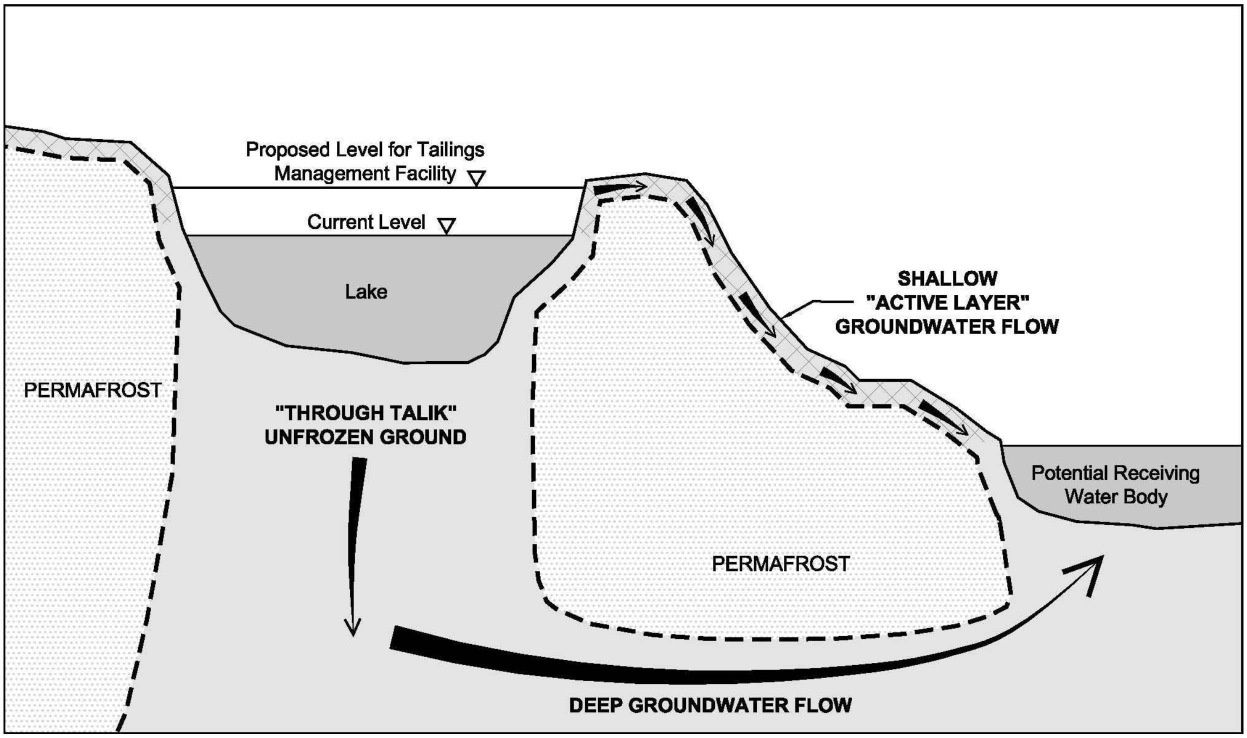

Figure 2. Schematic cross section showing shallow “Active Layer” and deep “Through Talik“ groundwater flow pathways

conductivity of the rock and soil by several orders of magnitude or more. Frozen zones are often interpreted to be impermeable for the purposes of mine inflow and contaminant transport calculations.

This paper discusses technical issues and methods for hydrogeological data collection and interpretation in:

a) the shallow “active layer”;
b) “talik” unfrozen zones below lakes; and
c) the deep groundwater flow system below continuous permafrost.

2 SHALLOW ”ACTIVE LAYER” DATA COLLECTION

The ground is generally frozen from late September to late June but the upper 1 to 7 m melts during the summer months. Shallow groundwater flow within the shallow “active layer” only occurs during July, August and early September. EIA baseline data collection requires assessment of the shallow, seasonal “active layer” groundwater flow system as well as the deeper regional groundwater flow system below the bottom of the permafrost.

Due to the thin seasonal nature of the active layer, shallow groundwater flows into open pit mines are generally small and are managed as part of seasonal surface runoff. However, the active layer can provide a seasonal pathway for contaminant movement away from tailings management systems, which are often constructed in lakes to facilitate water cover systems to prevent oxidation and formation acid rock drainage (ARD). If a lake is dammed to raise water levels then the active zone will become thicker and form a more significant contaminant pathway, for several years until the permafrost surface aggrades (Figure 2).

Global warming scenarios must be considered in environmental impact assessments. Global warming may cause the active zone to be thicker or unfrozen for longer periods and could make contaminant transport through the active layer more significant at some locations.

The thickness of the active layer ranges from 1 to 7 m depending on the latitude, season, recent weather, the presence type and thickness of vegetative cover, peat and organic soils insulation, slope aspect and orientation and human disturbance. The installation of thermistor strings in boreholes with data loggers is required to identify the seasonal depth and location of permafrost for the EIA process and for mine/facility design. Permafrost information can be as important as rock type and geological structure for determining groundwater mine inflow quantities or contaminant pathways/transport times from potential contaminant sources such as tailings management facilities.

The active layer depth increases gradually over the summer months as the shallow permafrost melts. The water table elevation often declines along with the declining permafrost depth and is often less than 0.5 m from the top of the permafrost. Thus both the groundwater level and thickness of the saturated active zone varies over time and accurate interpretation of the shallow groundwater flow directions and velocities is difficult. Typically shallow groundwater monitors are installed in the upper 3 to 7 m with screens that extend to near surface. During the summer melt period, water levels and depth to permafrost are measured and water quality samples are taken when possible. There is a limited amount of water in these shallow wells for well purging and water quality sampling. During the rest of the year the active layer is frozen and it is not possible to obtain meaningful data on flow or quality.

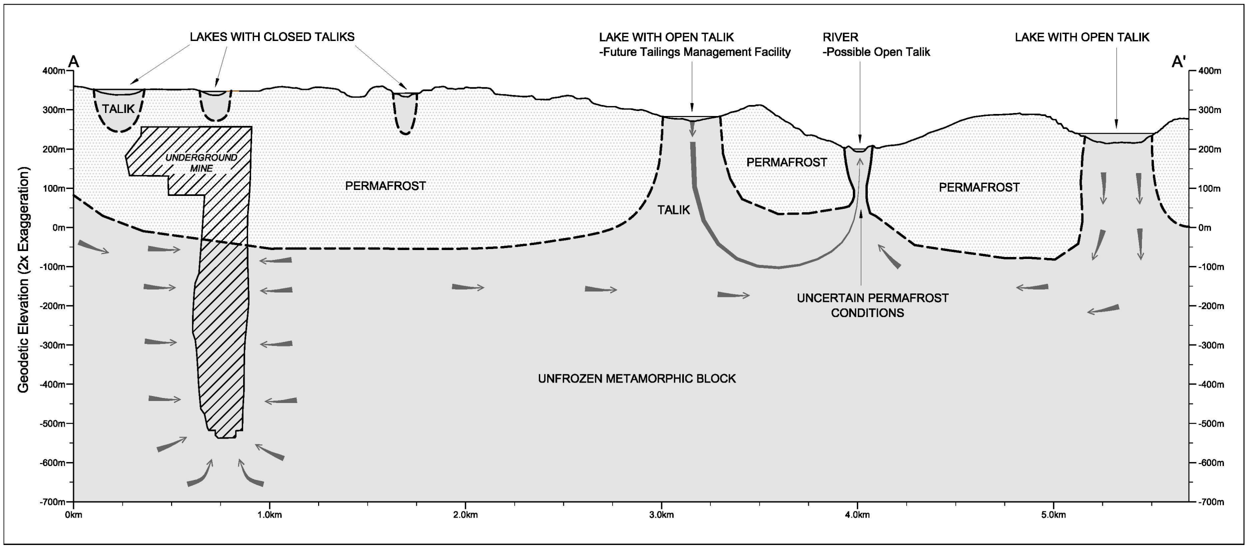

Figure 3 Schematic cross section showing taliks and potential deep groundwater flow pathways to underground mine and from tailings management facility (former lake) to river.

3 LAKE "TALIK" HYDROGEOLOGICAL DATA COLLECTION AND SIGNIFICANCE

The Canadian Shield in this area has numerous lakes. Lakes that do not freeze to the bottom during winter (those greater than 2 m deep) have melt zones below them known as "taliks". Knowledge and understanding of talik groundwater flow is very important for assessing groundwater inflows into mines and for assessing potential contaminant transport in the deep regional flow system.

If taliks are not hydraulically connected then they are called "closed taliks". If they are connected to other melt zone features that allow continuity of groundwater flow then they are known as "open taliks". If they penetrate through to the deep regional groundwater flow system below the continuous permafrost then they are known as "through taliks" and are significant for interpreting regional groundwater flow systems (Figure 3).

If lakes are sufficiently wide (0.2 to 0.5 km) then they may have "through taliks" that extend through the full depth of the continuous permafrost to the deep groundwater flow system below the permafrost. The potential existence of "through taliks" below lakes can be theoretically calculated with geothermal models that consider the mean annual temperature over the quaternary time scale, the size and depth of the lake and adjacent water bodies, the geothermal gradient at depth, the quaternary history of the location and the type/ density of snow cover.

Due to the numerous lakes in the Precambrian Shield, it is common for mine workings to be below a lake basin. Mines that are near or below larger lakes can have significant groundwater inflows if the unfrozen rock in the talik has permeable fracture zones (Bieber *et al.*, 2006).

The hydraulic conductivity of rock formations within taliks is usually the most sensitive and important parameter for predicting groundwater mine inflow quantities for underground mines below lakes or open pit mines that intersect lakes. The hydraulic conductivity of the rock mass is generally determined by drilling boreholes from the lake ice during the March to May period when the ice is thick enough to support the drill rig and there is sufficient daylight. Typically constant head permeability tests are conducted in specific depth intervals isolated by inflatable packers (Johnson and Mills, 2006). Tests can be conducted with a single packer system used at the bottom of the borehole as drilling proceeds or with a double packer system after the borehole has been completed to its' complete depth.

Water quality samples can also be collected from different depth intervals using the inflatable packer system but if the hydraulic conductivities are low it can be expensive to pay the diamond drill hourly rate while the boreholes are being purged and sampled. Hydraulic heads at different depths can also be measured from packed off intervals.

Permanent groundwater monitoring installations are generally not installed into taliks from lake ice due to difficult access after the ice has melted and the potentially damaging effects of shifting lake ice. If there has been underground test mining below the lake then there may be an opportunity to collect better groundwater flow and quality data from permanent borehole installations installed below the lake.

4 DEEP GROUNDWATER FLOW DATA COLLECTION AND INTERPREATION

The deep regional groundwater flow system below the 200 to 500m of continuous permafrost is hydraulically connected to surface via "through taliks" below larger lakes. Data collection from this deep groundwater zone is difficult and expensive for most projects because boreholes drilled from land will often freeze within a day.

On a few EIA projects, hydraulic conductivity data has been collected using inflatable packer systems in boreholes drilled below the base of the permafrost (Johnson and Mills, 2006). These tests are usually conducted in mining exploration diamond drill boreholes. The boreholes are typically drilled with a heated brine solution to avoid freezing and loss of the drill rods in the borehole. Hydraulic conductivity values at depths below 300m tend to be low. It can be difficult and time-consuming to obtain valid hydraulic conductivity data for zones below the permafrost.

Hydraulic head information over time can be obtained by installing vibrating wire piezometers below the bottom of the permafrost. However, if they are installed at too shallow a depth they will freeze and will not work.

Due to the depth and cost of installing and testing deep boreholes below the permafrost, it is unusual to have sufficient data to construct a map of the deep regional groundwater flow system. The elevations of larger lakes with "through-taliks" (that provide hydraulic connection to the deep groundwater flow system below the permafrost) are often used to estimate regional groundwater flow directions because of the difficulty in obtaining adequate hydraulic head measurements for the deep flow system

In areas of continuous permafrost, groundwater recharge does not occur on an aerial basis proportional to annual precipitation and it generally does in temperate areas. Areas of continuous permafrost do not allow recharge to the deep groundwater system below the permafrost except via through taliks below the larger lakes. The ground surface, streams and smaller rivers have permafrost below them, which prevents downward flow to the deep system. Recharge to the shallow flow system only occurs during the short summer period.

Lakes that are fed by streams and small, shallow rivers that freeze to the bottom during winter have no inflows or outflows during winter. Therefore, winter is the most sensitive time (low flow period) for assessing mine dewatering drawdown impacts on levels in nearby lakes or rivers that have through taliks.

Digital 3D groundwater flow modelling is often used to assess a) mine inflow volumes (which may require treatment prior to discharge) b) potential mine dewatering drawdown impacts on nearby lake levels and c) potential contaminant migration from tailings facilities or from mines after closure. For mines situated below unfrozen lake taliks these models can be constructed in a similar manner to non-permafrost areas. Adjacent permafrost areas are usually assumed to have a very low or negligible hydraulic conductivity.

However, groundwater flow models in continuous permafrost cannot be calibrated by using typical methods such as fitting to the existing water table contours with annual recharge estimated from annual precipitation, runoff and evapotranspiration data. As noted above, recharge to the groundwater flow system is restricted by the presence of permafrost and is not defined by a clear relationship to precipitation or catchment area.

5 DEEP GROUNDWATER QUALITY DATA COLLECTION

Boreholes and mines that penetrate below the base of the continuous permafrost may have inflows of deep groundwater that may be saline and very old. Sampling of deep saline groundwater from boreholes installed through 200 to 500m of permafrost is very difficult. The drill rods can freeze in the hole in less time than it takes to flush the drilling brine from the borehole interval prior to collection of groundwater samples. The hydraulic conductivity of crystalline bedrock at these depths is typically very low and the borehole may freeze in less time than it takes to collect a representative sample. Emerson *et al*. (2006) reported some success in sampling deep groundwater below the permafrost from surface using a multi-level sampling device containing anti-freeze. The most representative deep groundwater quality samples have been collected from underground mine workings that extend below the permafrost.

The occurrence of very old, brines in a number of places on the Precambrian Shield suggests that these deep flow systems are very sluggish and slow moving under natural conditions (i.e. pre-mining) (Frape and Fritz, 1987). Research projects for assessing permafrost impacts on nuclear waste disposal (Ruskeeniemi *et al*. 2002), (Ruskeeniemi *et al*. 2004) and for assessing biological conditions below permafrost are being conducted at existing and proposed arctic mine sites in Nunavut.

6 CONCLUSION

Despite significant data collection challenges, hydrogeological investigations for environmental impact assessments of proposed new mines and scientific investigations at existing mine sites are yielding information on the deep and shallow groundwater flow systems in the remote, continuous permafrost region of western Nunavut and adjacent areas of the Northwest Territories, Canada.

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