

# **Predicting Dewatering Requirements of an Open Pit within a Subpermafrost Groundwater System with Highly Variable Recharge through Taliks**

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## **Abstract**

A series of field hydrogeological studies was conducted for a copper project in southern Siberia (Russia) to characterize a subpermafrost groundwater system; its hydraulic parameters, water level regime, and recharge/discharge conditions from/to surface-water bodies through open taliks, which are developed under river valleys. A proposed deep open pit will result in excavation of the upper part of the subpermafrost bedrock aquifer, which is transmissive and characterized by highly variable, seasonal water level fluctuations up to 90 m. The conceptual hydrogeological model is based on limited testing completed in deep coreholes using the IPI packer system and more than two years of water level monitoring data in numerous piezometers. A 3-D numerical groundwater model was developed and calibrated in the transient state to match observed highly variable seasonal changes in water levels and stream flows. A detailed stream-routing package was used to reproduce surface-water flows as a source of recharge to the subpermafrost groundwater system based on precipitation, evaporation, and stream flow data. The field data show that seasonal changes in stream flows result in significant variations in water levels, creating the largest natural stress to the groundwater system. A groundwater model, calibrated to this large recharge stress, is more reliable than a model based only on the results of short-term hydrogeological testing. The calibrated model was used to predict passive inflow to the proposed open pit and active dewatering requirements, in order to reduce residual passive inflow to a manageable amount under severe winter conditions.

## **Hydrogeological Setting**

An open pit copper project is proposed in southern Siberia (Russia) in a region where continuous permafrost dominates and local taliks occur, underlying valleys of rivers and creeks (Figure1). The territory is characterized by permafrost that in cross-section is thickest under the mountain ridges and

thinnest at bottoms of the river and creek valleys, where it locally pinches out completely (Figure 2). The thickness of permafrost at the ridge ranges from 400 to 500 m to 800 to 1,000 m. In the river valleys and small intermountain depressions the permafrost thickness decreases to 10 to 150 m.

Topographically, the project is situated in an area of surface water recharge and groundwater flow path.

Hydrogeological conditions in the project area are represented by two major aquifers:

- alluvial sediments in continuous open taliks, and
- fractured metamorphic Lower-Proterozoic rock within two water-bearing horizons (subpermafrost and open taliks below alluvium).

The aquifer of alluvial sediments in continuous taliks in the river and creek valleys includes saturated alluvial and glacio-fluvial sediments. Based on the flow pattern and degree of isolation from the ground surface, the aquifer is classified as an unconfined aquifer with porous media. Hydraulic conductivity values vary between 200 m/day and 450 m/day. The water levels of these aquifers have significant seasonal variation of up to 27 m. During the summer period, the depth to groundwater is a few meters, whilst during the critical winter period the aquifer dries out completely within the proximity of the project.

The bedrock aquifer consists of two water-bearing horizons – subpermafrost, and open taliks below permeable alluvium. Water-bearing strata are represented by metamorphic sandstone and siltstone with total thickness of about 3 km. Based on the collected and available hydrogeological data, the thickness of the fractured rocks that comprise the subpermafrost aquifer is in the order of 250 m (more than 400 m in open taliks). The hydraulic conductivity of the fractured rocks is up to 1.9 m/d. Below this fractured zone, the hydraulic conductivity of metamorphic rocks decreases with depth. Seasonally, the amplitudes of groundwater heads fluctuate by 50 to 90 m under the permafrost and by as much as 134 m in the continuous talik zone. Based on the groundwater flow pattern, the aquifer water is classified as fracture-vein water. The depth to groundwater depends on the elevation of the permafrost base.

The subpermafrost aquifer is classified as confined in most places, while within continuous taliks it is unconfined. The groundwater levels range from 50 to 180 m above the permafrost base. The proposed mine pit would be located 0.5 to 3 km west of River N, which in combination with large precipitation provides significant recharge to the subpermafrost aquifer through the continuous open taliks during the warm part of the year. The river has no constant water flow. The high flow occurs during the snow melt period (end of May to first half of June) and in the summer, during prolonged rain storms. The annual average river flow is about 1 to 1.5 m<sup>3</sup>/s in the proximity of the proposed pit and 3.5 to 4 m<sup>3</sup>/s at the northern boundary of the study area with maximum flow up to 7.3 m<sup>3</sup>/s measured in June.

Groundwater flows out to surface-water bodies to the north, west and south, where open taliks connect them hydraulically with the subpermafrost aquifer.

## Hydrogeological Characterization

Hydrogeological testing of the aquifers has met with difficulties, including:

1. Presence of thick permafrost zone everywhere outside of river valleys and very deep subpermafrost groundwater system;
2. Confined regime of subpermafrost aquifer with water levels above permafrost base, causing very quick freezing of water in coreholes (forming of ice caps) that limits the time for hydrogeological testing;
3. Significant fracturing of metamorphic rocks and inability to stress groundwater system sufficiently by testing in small-diameter coreholes, and technical limitations in drilling of large diameter wells;
4. Very cold winter conditions, remote area, and inability to conduct hydrogeological study during winter time when water levels are low and relatively steady in time; and
5. Significant changes in water levels during the warm season when natural hydraulic stresses significantly exceed possible stress by hydrogeological testing (pumping or injecting).

Initial hydrogeological studies were conducted in 1974 to 1976 and 1984 to 1985 during two phases of exploration of this copper deposit, and include areal geophysics (structure and permafrost delineation), 12 single-well pumping tests, and temperature surveys in boreholes. Hydraulic conductivity values measured in the bedrock groundwater system varied from 0.005 m/d to 22.5 m/d, with geometrical and arithmetical mean values of 0.7 m/d and 3.7 m/d, respectively. The large variability in hydraulic conductivity values reflects the fracture control of the permeability of the bedrock groundwater system.

In 2011 to 2012, as part of the Feasibility Study, SRK conducted hydrogeological tests in five coreholes, locations of which are shown in Figure 1. Two coreholes were drilled in the subpermafrost aquifer (one from underground developments and one from the ground surface) and three were drilled within the open talik in the valley of River N (one in alluvial sediments and two in fractured bedrock). Packer isolated testing (both injecting and airlifting) was completed in two bedrock coreholes drilled in the open talik area using the IPI packer system. Results of the hydrogeological testing are shown in Figure 3, and indicate the presence of high hydraulic conductivity fractured metamorphic sandstone to the depth of about 400 m.

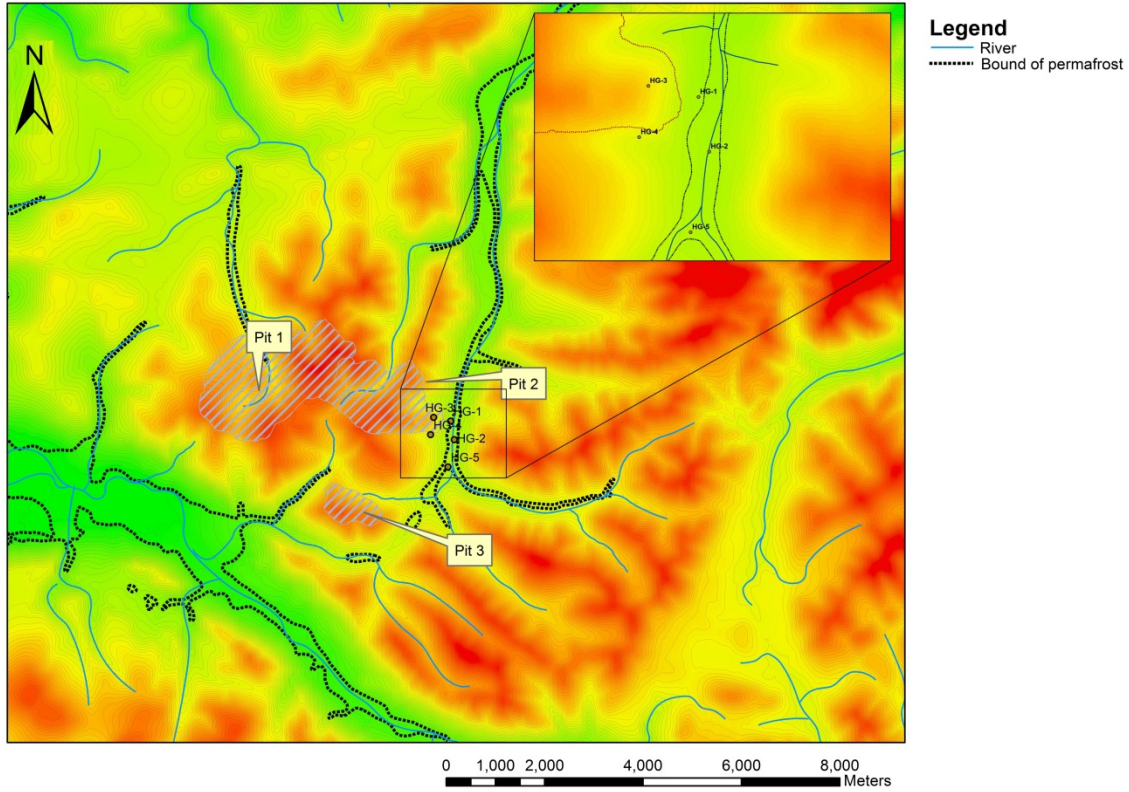


Figure 1: Permafrost-hydrogeological map of project area

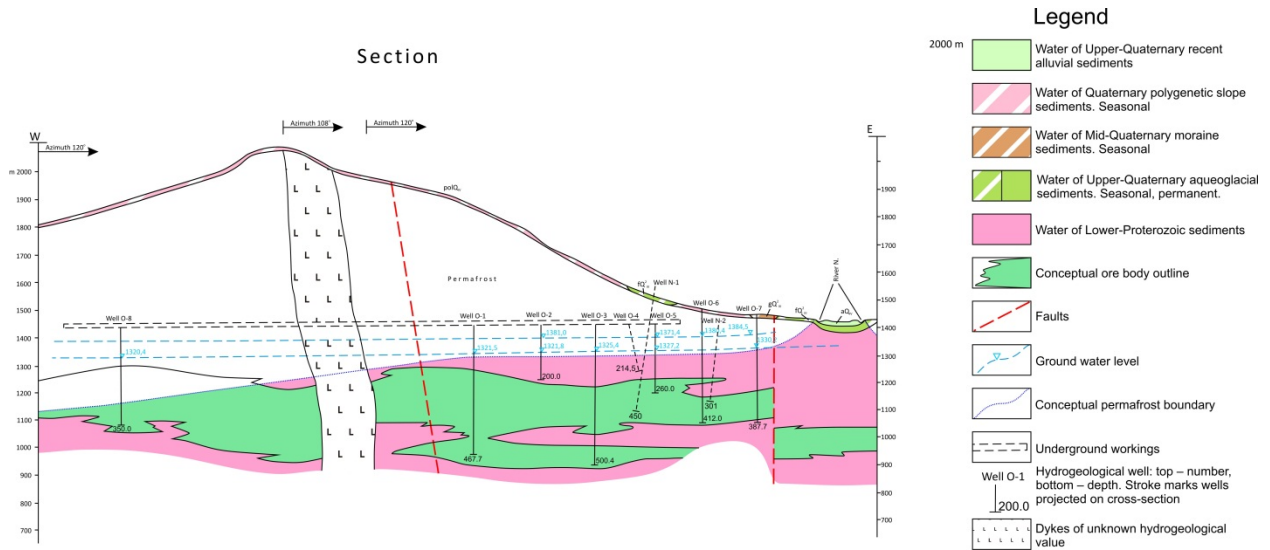
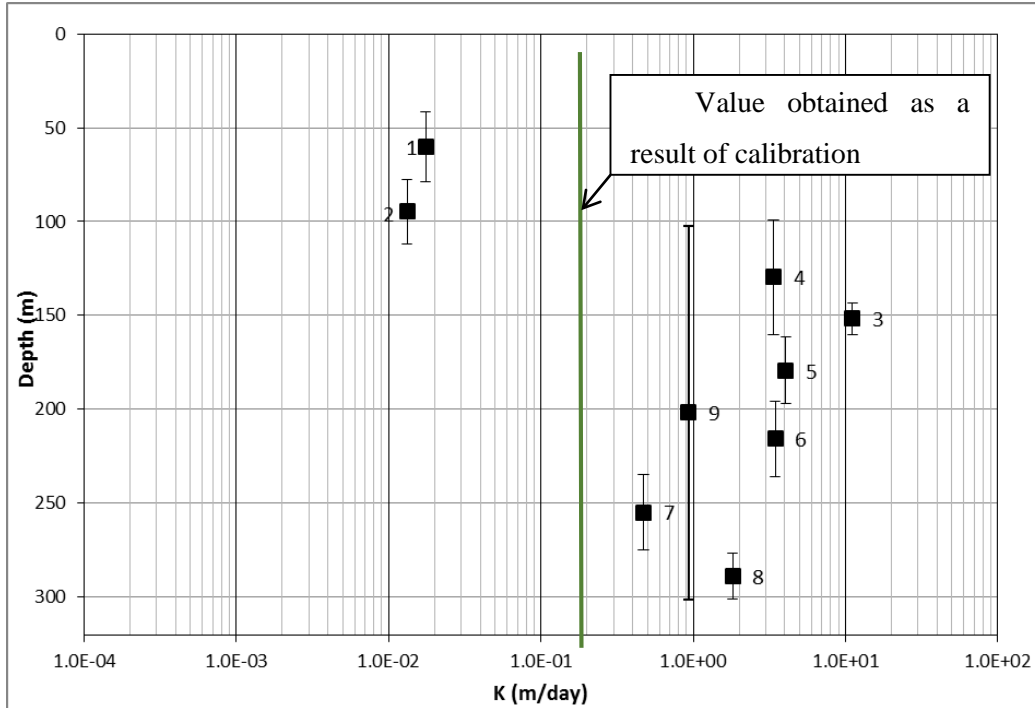


Figure 2: Conceptual hydrogeological cross-section



**Figure 3: Measured hydraulic conductivity in two bedrock coreholes completed within open talik during 2011 to 2012**

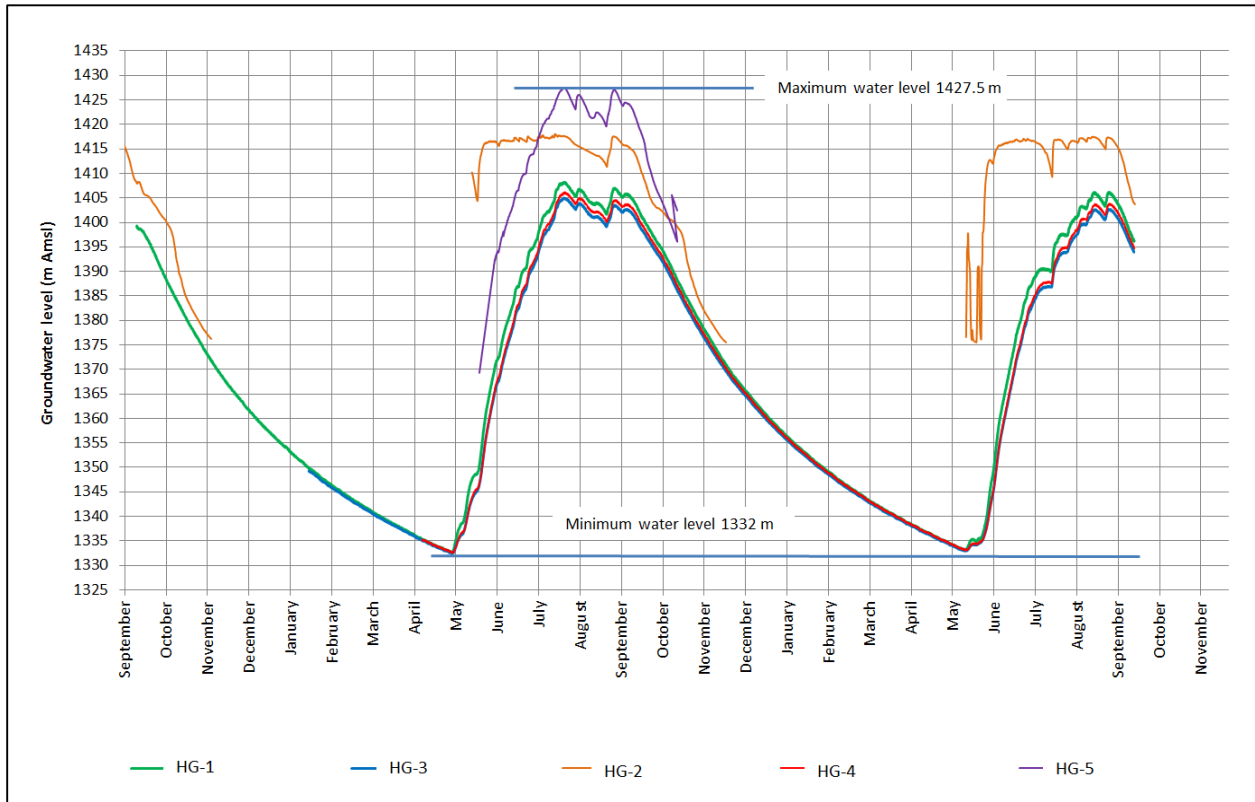
It should be noted that interpretation of the completed tests was difficult and questionable in cases where significant natural changes in water levels during testing exceeded the ability to stress the bedrock groundwater system in small diameter coreholes. It was observed that natural hydraulic stress to the bedrock groundwater system (rising water levels during snowmelt period in May to June and their lowering from October to April during frozen conditions) is significantly larger than stresses applied during hydrogeological testing.

The effect of the large snowmelt and recharge of surface water into the bedrock groundwater system through the open talik below River N during a relatively short period of time was considered by the authors to constitute a big, natural “injection test,” and the lowering of water levels during following freezing conditions as a groundwater “recovery” after this test.

Four coreholes were used for monitoring of water levels within the transmissive bedrock groundwater system (subpermafrost aquifer and bedrock aquifer within the open talik) and one within the alluvial sediments. Level TROLL pressure and temperature transducers were installed in these boreholes to record data every 4 hours. Transducers in two coreholes within the subpermafrost aquifer have direct cable connections, allowing for data downloads regardless of ice caps forming in these holes.

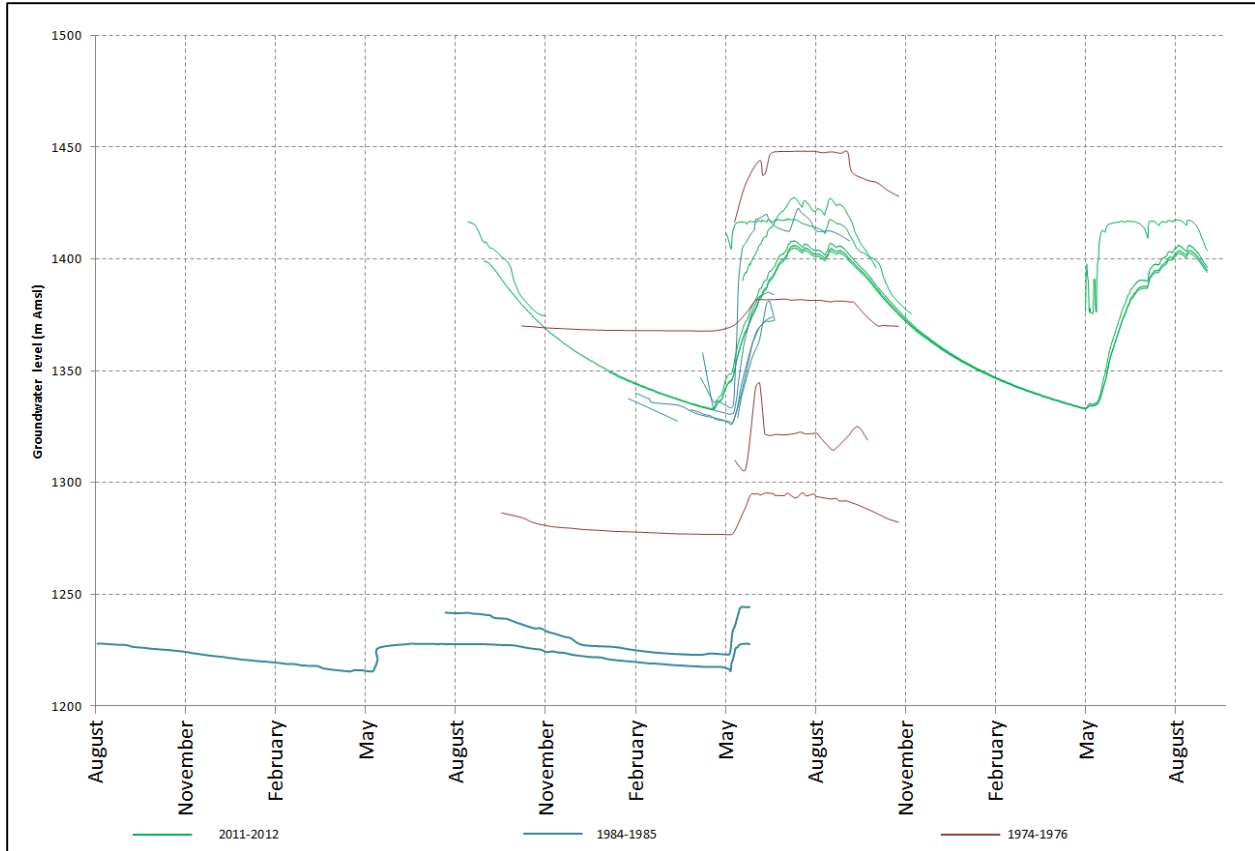
This monitoring technique made it possible to ascertain the hydraulic interconnection between the alluvial sediments of River N and the bedrock, as well as to fully understand the fluctuations of water

levels and temperatures throughout the year. Graphs showing changes in groundwater-level elevations measured in four bedrock coreholes and one alluvial monitoring well are presented in Figure 4.



**Figure 4: Measured seasonal variations in groundwater-level elevation**

Groundwater level data collected by the pressure transducers were used to verify average hydraulic conductivity of the bedrock groundwater system and to evaluate groundwater inflow to the proposed open pit, which will penetrate the subpermafrost aquifer at a later stage of mining. The seasonal variations in water levels result from large recharge events originating from snow and ice melt, and the focusing of the recharge in narrow taliks through otherwise continuous permafrost. Figure 5 presents the curves of groundwater level fluctuations observed in 1974 to 1976, 1984 to 1985, and 2011 to 2012. These curves show that groundwater-level fluctuations for different years of observations are similar.

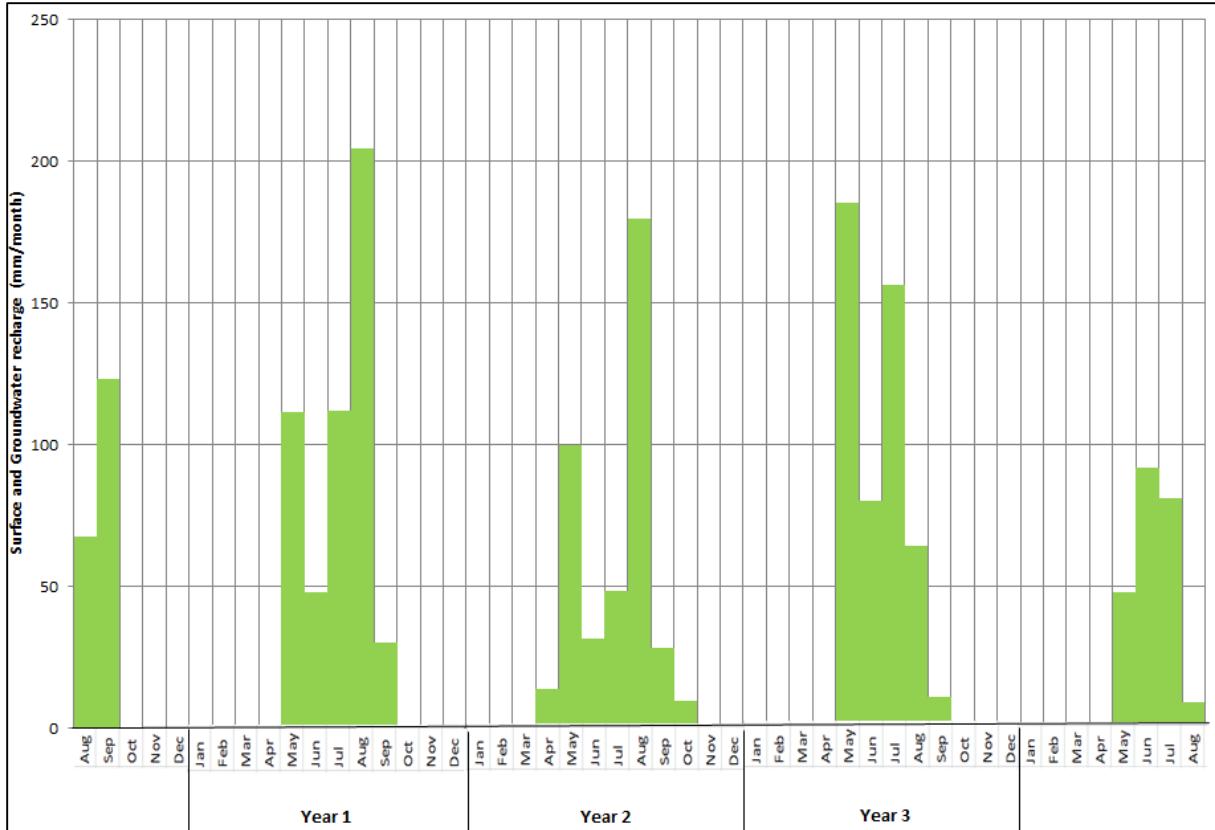


**Figure 5: Historical fluctuation groundwater level elevations in subpermafrost aquifer**

## Numerical Groundwater Modeling

Hydrogeological conditions of the project area were reproduced by the regional groundwater flow model calibrated to measured seasonal groundwater-level fluctuations and to components of the surface water and groundwater balance (recharge/discharge). This allowed for the refinement of the hydrogeological parameters of the subpermafrost aquifer and the saturated bedrock within the open talik zone.

Simulation of recharge to the subpermafrost aquifer through the continuous open taliks is a critical element of the model, and requires that recharge does not exceed the amount of water available in both the river and the alluvial aquifer as it changes drastically during the year. Realistic estimation of variable recharge in time is quite difficult. The groundwater flow model was constructed using the “Stream Routing” feature of MODFLOW, allowing for the estimate of recharge to the alluvial sediments from watercourses (based on flow volume in watercourses and discharge of groundwater to them). The recharge from the watercourses simulated by the Stream Routing package do not exceed the amount of water available within the catchment area, taking into account the annual precipitation and evaporation. Simulated distribution of annual recharge used for transient calibration of the model is shown in Figure 6.



**Figure 6: Distribution of annual recharge for transient model calibration**

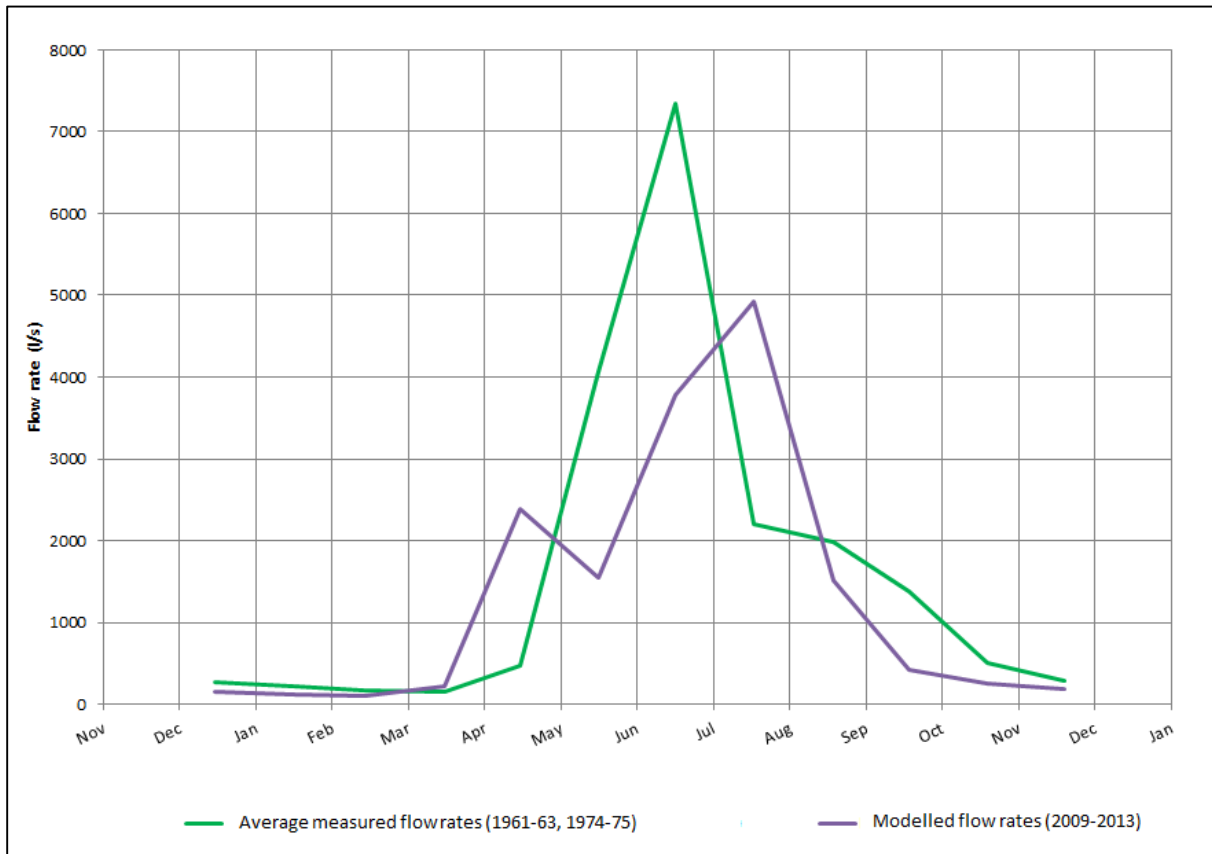
The model calibration to seasonal fluctuations of groundwater levels in the subpermafrost aquifer and alluvial sediments also provides a means for realistic reproduction of the recharge flux into the bedrock aquifer through the open taliks. Verification of components of the surface flow balance was carried out by comparing modelled data with the results of monitoring of the average flow of River N at the gauge station installed downstream (north of the proposed pit).

Realistic assessment of groundwater inflow into mine developments requires the model to reproduce reasonable redistribution of the groundwater flow between the alluvial and the bedrock aquifers during pre-mining conditions. In order to do this, the authors believe that the amount of water remaining in the alluvial sediments of River N at the very end of the recharge period should compare well to the amount simulated in the model. Data from the River N flood-ice study was used for this purpose. The flood-ice study indicates that ice mound formation takes place from November to May (approximately 181 days), with an average flow rate of about 200 l/s. The modelled flow rate for the River N during the same time period was relatively close, 173 l/s.

According to Figure 7, the modelled river flow rates during a low water season have a relatively good correlation with the measured rates. This indicates that during the recharge period (May-September), the amount of water accumulated within the alluvial sediments and subpermafrost aquifer is



close to the actual value, and similar discharge rates suggest that there is a good correlation between the modelled transmissivity and storage parameters and the actual ones. Some simulated flow rates during the recharge period are different from the actual values, which is likely due to the difference in precipitation regimes during the modelled years (2009 to 2013) and during the monitoring periods (1961 to 1963, 1974 to 1975). However, the order of magnitude of the flows is similar. The catchment area of the close, relatively small creek was not taken into account, which could also explain the difference in flow rates.

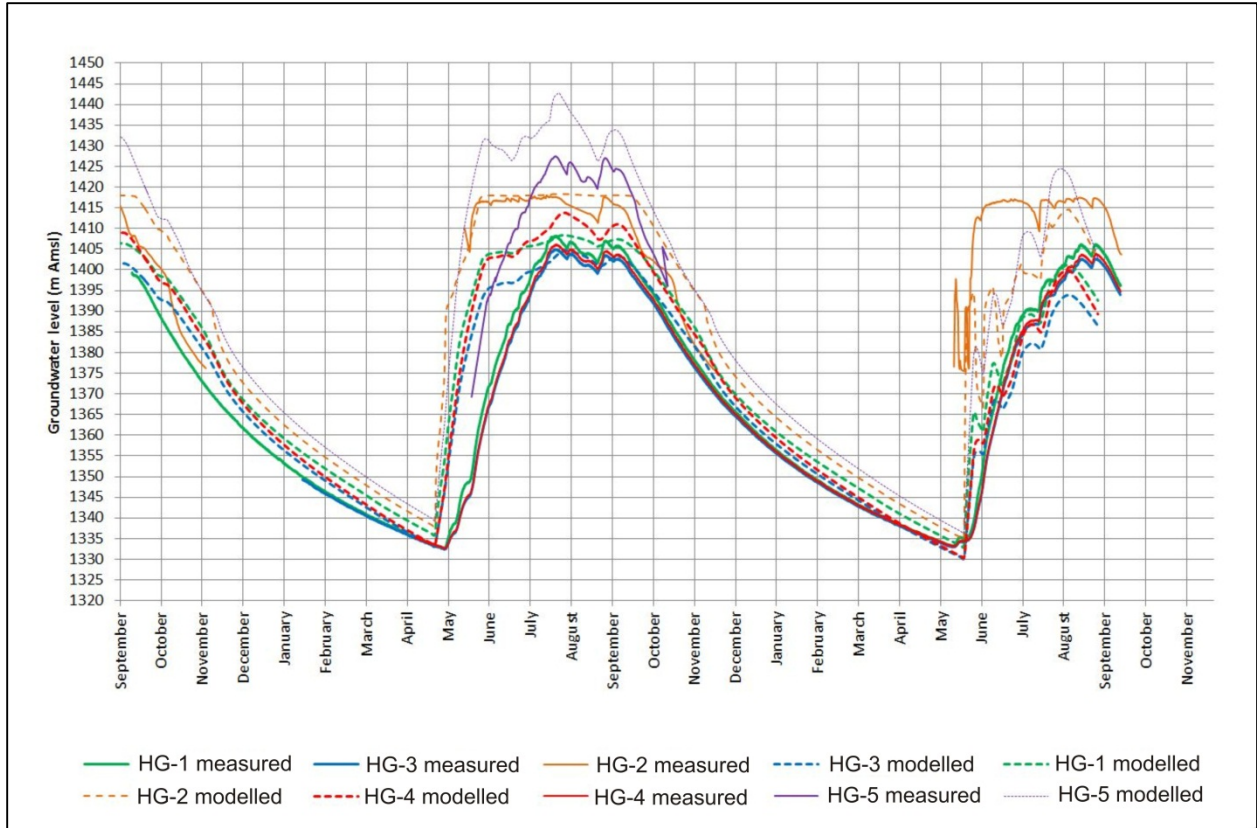


**Figure 7: Measured vs. modelled flow rates in River N**

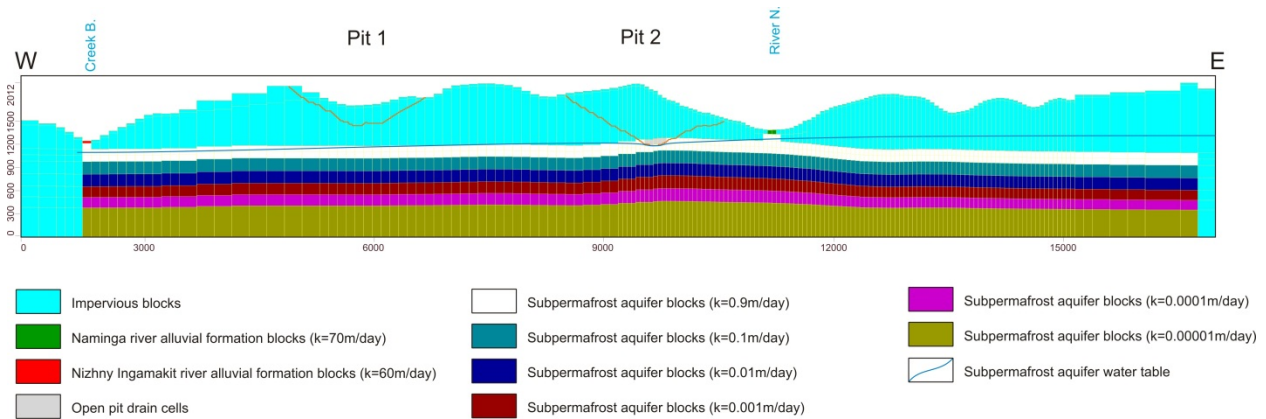
Transient model calibration results, showing groundwater fluctuations over a period of 3 years, are presented in Figure 7. The authors believe that there is a good correlation between measured data and model results, especially for the seasonal groundwater level decrease phase.

As mentioned above, raising water levels was a secondary objective of the model calibration due to the complexity of simulating all recharge elements of the aquifers (alluvial sediments and bedrock formation).

Lowest (in early May) and highest (late July to the middle of the recharge season) modelled water levels, direction of groundwater flows, recharge and discharge areas are shown in Figure 8. Calibrated values of hydraulic conductivity values are shown in Figure 3 and Figure 9.



**Figure 8: Results of transient model calibration to groundwater level fluctuations**



**Figure 9: Modeled west-east cross-section shown calibrated hydraulic conductivity values**

### Prediction of Dewatering Requirements

The 3D numerical groundwater flow model, calibrated to highly variable seasonal changes in measured groundwater monitoring data, was used to predict passive inflow to the proposed pit (when the subpermafrost part will be excavated) and active dewatering requirements. Maximum passive inflow into the open pit is predicted to be as much as 2,000 m<sup>3</sup>/h during the summer and up to 865 m<sup>3</sup>/h during

winter.

The predicted maximum total pumping rate from dewatering wells installed around the lower benches of the pit within the subpermafrost aquifer is about 2,770 m<sup>3</sup>/h in the summer of the last year of production, with residual passive inflow into the pit of about 25 m<sup>3</sup>/h. As the pit progresses into the subpermafrost aquifer, there is a general trend towards increased inflow, both minimum in winter, and maximum in summer.

## Conclusions

A large number of mineral deposits are located in far north regions, and subject to harsh climatic and ground conditions. They require sophisticated economical and technical assessment for future mining operations. Even where water occurs on the surface for only a few months per year due to low ambient temperatures for the most of the year, groundwater can turn mining operations in to a challenging, potentially cost-prohibitive exercise when not assessed properly. Studying the water related aspects of a site in these types of conditions can sometimes be even more challenging. The authors of the article had a unique chance to participate in a hydrogeological characterization and assessment of dewatering requirements for one such site, facing a shortage of hydrogeological characterization data due to:

- the presence of a thick permafrost layer that significantly limited the time spent on each aquifer test;
- the inability to conduct low flow rate airlift tests and injection tests in small diameter coreholes fractured hydraulically conductive bedrock;
- the significant natural groundwater fluctuations that masked aquifer test drawdowns; and to
- the cold temperatures and short field seasons.

A distinct feature of the hydrogeology of the project area, seasonal high amplitude groundwater fluctuations, was used to compensate for the limits of the hydrogeological characterization studies to properly evaluate dewatering requirements. Average hydrogeological parameters were defined by the numerical groundwater model during calibration to significant fluctuations in groundwater levels and historical surface water flow rates. Assessment of dewatering requirements was completed based on the calibrated model using hydraulic parameters successfully estimated using monitoring data.