Kiggavik Project

Environmental Impact Statement

Tier 3 Technical Appendix 5D

Groundwater Flow Model

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1 INTRODUCTION

1.1 OVERVIEW

The Kiggavik Project is a proposed uranium ore mining and milling operation located in the Kivalliq region of Nunavut approximately 80 km west of the community of Baker Lake.

This document is a Technical Appendix to Volume 5, Aquatic Environment, of the Kiggavik Environment Impact Statement (EIS). The methodology used to develop the groundwater flow models is presented in this Technical Appendix, as well as the results of model calibration and simulation of pre-mining conditions. Two scenarios are presented; a scenario representative of the current permafrost conditions followed by a no-permafrost scenario simulating an extreme climate change that would result in a complete loss of permafrost.

1.2 PURPOSE AND SCOPE

Two three-dimensional regional groundwater flow models of the Kiggavik Project area were developed in support of the Kiggavik EIS. These flow models encompass a large area, including the Kiggavik and Sissons sites, considering as far as practical natural boundary conditions with limited artificial control of the calculated flow regime.

The models were developed using background information on geology, permafrost, hydrogeology and field investigations presented in the following document:

- Technical Appendix 5B - Geology and Hydrogeology Baseline

The ultimate goal of the groundwater flow modelling is to provide a predictive tool for future applications, such as inflow predictions towards future mining works and long-term flow predictions through decommissioning activities. The models, as presented in this Technical Appendix, have to be considered a "living tool" subject to improvements of both the conceptual and numerical parts. Immediate applications of the models are found in the following document

- Technical Appendix 5E - Prediction of Water Inflows to Kiggavik Project Mines
- Technical Appendix 5J - Tailings Characterization and Management

2 CONCEPTUAL GROUNDWATER FLOW MODEL

2.1 EFFECT OF TOPOGRAPHY ON FLOW

The groundwater flow pattern in the Project area is representative of topography-driven flow in low permeability bedrock.

The regional topography is expected to control the groundwater flow system under both current and post-decommissioning conditions. For the most part, the Project area has a gently rolling topography with a few low escarpments associated mainly with east-west trending faults In the Kiggavik area ground surface elevations vary from 140 m near Pointer Lake to 265 m at the peak of the hill northeast of the proposed accommodation and mill sites. In the Sissons area, ground surface elevations vary from 166 m near Andrew Lake to 215 m at the peak of the hill northeast of the End Grid area.

2.2 EFFECT OF HYDROLOGY ON FLOW

2.2.1 Recharge and Surface Drainage

Groundwater recharge in permafrost environment is considered negligible. Precipitation mainly reports to surface water courses and/or evaporates/sublimates. Surface hydrology is dominated by the snow melt in early summer, and is strongly affected by freezing and thawing of the ground. The shallow subsurface drainage occurs only in summer months, when the active layer thaws.

Surface water is abundant at times, particularly during the freshet, when permafrost strongly limits infiltration and when eight months of precipitation that has accumulated on the landscape melts over a period of several weeks. However, in winter there is little or no flow and only the deeper lakes contain significant water.

Ground topography near Kiggavik can be described as mostly flat or very gently sloping. The terrain has a series of low scarps, which run W-SW to E-NE. Drainage divides are in the higher land, north of Kiggavik site, and to the west. There are numerous lakes interspersed throughout the landscape, but there are relatively few defined drainage channels. Surface flow occurs along low elevation areas that act as broad drainage channels. The channels are often lined with boulders and short vegetation.

Many of the streams in the region cease to flow over the winter period until spring melt in late May or early June. The largest stream monitored as part of the Kiggavik Project hydrometric program (Judge Sissons Lake Outlet) drains an area of 658 km^2 and is believed to freeze to the base in winter. Streams in the Kiggavik Project area do not carry any flow for approximately 60% of the year. Very large rivers in the regional study area, such as the Thelon River, continue to flow year-round.

2.2.2 Lakes Potentially Supporting Open Taliks

2.2.2.1 General

To support a talik, a lake must be deep enough to maintain an unfrozen bottom throughout the winter. A two metre thick ice coverage is assumed to be developed in lakes at the Project site during the winter months (Prowse and Ommaney, 1990); therefore lakes must be greater than two metres deep to support a talik.

The depth of the talik formed beneath a lake is dependent on the size of the lake. When the size of a lake is above a critical value, the talik beneath the lake will be an open talik, which connects to the deep groundwater flow regime beneath the permafrost. Beneath smaller lakes, which do not freeze to the bottom over the winter, a talik bulb that is not connected to the deep groundwater flow system will form.

The unfrozen portions of surface water bodies must also be sufficiently large to support talik formation. An estimate of the minimum diameter of a circular lake or the minimum width of a strip-shaped or elongated lake that can support an “open” talik” has been derived (Burn, 2002).

For a circular lake the temperature at depth Z, T_Z, is given by (Burn, 2002)

$$T_Z = T_G + \frac{Z}{I} + (T_L - T_G)\left(1 - \frac{Z}{\sqrt{Z^2 + R^2}}\right)$$

and for an elongated lake is given by

$$T_Z = T_G + \frac{Z}{I} + \frac{(T_L - T_G)}{\pi}\left(2\tan^{-1}\left(\frac{H_P}{Z}\right)\right)$$

The criterion for formation of a talik is that

$$T_Z \geq 0, \ for\ all\ \ Z.$$

This equation can be solved graphically

The unknowns are defined as:

- Z= depth in m
- T_G= mean annual temperature (T_G<0) of undisturbed permafrost region
- T_L= mean annual temperature (T_L>0) of the lake
- T_Z= temperature under the centre of the lake
- I= geothermal gradient in m/°C (metres per degree Centigrade)
- R= radius of circular lake
- H_P = half-width of an elongated lake

It should be noted that these approximations may overestimate T_Z for small lakes (< several hundred metres across) due to the assumption of no horizontal temperature gradient (West and Plug, 2008) and the resulting use of the one-dimensional Stefan equation to solve for temperature in the vertical direction.

For the purpose of this assessment, T_L is assumed to be 4 °C and T_G is -8 °C. The latter value is an average based on an extrapolation to the surface of thermistor data trends from the Sissons area. A geothermal gradient of 32 m/°C is also assumed, which is the lowest (*i.e.,* most conservative) value estimated from all accepted thermistor records. Using the formulas described above to determine the minimum size of lakes supporting an open talik, a circular unfrozen lake requires a minimum radius of about 145 m to support an open talik, while an elongated lake requires a half-width of about 75 m. These calculations assume a mean annual lake temperature of 4°C and mean annual temperature of undisturbed permafrost of -8°C. Several lakes near the Project site satisfy both the minimum dimensional and depth requirements to support a talik extending to the deep groundwater flow system. Figure 2.2-1 and Table 2.2-1 indentify lakes that satisfy these requirements. Lakes that are large enough to support an open talik, but for which bathymetric data are unavailable are also identified.

Table 2.2-1 Lakes Potentially Supporting Open Talik Formation

Lake ID	Surface (km2)	mean Depth (m)	max Depth (m)	Estimated total volume (10^6 m3)	Average Lake elevation (masl)	Source Data For lake elevation
#1	2.59	na	na	na	182.3	#2
#2	1.08	na	na	na	158.1	#2
#3	1.16	na	na	na	182.6	#2
Aberdeen	>11.2	na	na	na	79	#1
Boulder	4.78	na	na	na	135	#2
Buzzard	3.19	na	na	na	160	#1
Caribou	3.41	1.4	2.7	4.91	136.9	#2
Cirque	0.056	2.6	4	0.146	211.3	#2
Escarpment	0.127	2.2	8	0.279	182.4	#2
Felsenmeer	0.208	2	6	0.423	222.8	#2
Fox	1.28	1.7	2.6	2.17	142.8	#2
Gerhard	10.73	na	na	na	185.1	#2
Jaeger	2.81	1.6	4	4.62	150.64	#2
Judge Sissons	95.5	4.6	20	439	132.4	#2
Lin	0.48	1.3	na	0.632	164.5	#2
Mushroom	0.32	1.89	8.9	0.59	173.2	#2
Pointer	3.93	1.39	2.9	5.45	141.9	#2
Ridge	0.167	2.3	7.1	0.384	230.7	#2
Rock	0.324	0.707	1.45	0.21	134.3	#2
Scotch	0.195	3.6	6	7.1	155.8	#2
Siamese	27.92	4.1	11.6	114.6	160.5	#2
Skinny	1.97	3.1	12	6.11	167.7	#2
Sleek	3.76	na	na	na	149.7	#2
Squiggly	6.38	6	14	38.3	213	#1
Willow	0.549	1.4	na	0.766	133	#2

Source data for lake elevation
#1 Canadian Digital Elevation Data (CDED), Gvt of Canada, Natural Resources Canada (www.geobase.ca)
#2 2008/2009 LiDAR survey

2.2.2.2 Case of Pointer Lake

Pointer Lake is a relatively shallow lake located downgradient from the proposed Main Zone, Centre Zone and East Zone Tailings Management Facilities (TMFs). As such Pointer Lake has the potential to be the primary receiving surface water body for potential constituents of concern originating from the TMFs. Under the current permafrost conditions the role of Pointer Lake is dependent on the hydraulic connection between the lake and the sub-permafrost groundwater flow system, which in turn is dependent on the presence of a talik below Pointer Lake.

Thermal modelling was performed to demonstrate the presence of a talik below Pointer Lake (see attachment A). The model was developed using the finite element model SVHEAT (SoilVision Systems Ltd., 2009) in steady state mode given the time scales involved with the formation of taliks under lakes. A simplified two dimensional section was used to represent the surrounding ground and Pointer Lake.

The thermal modelling suggests that the minimum width for having an opened talik is about 100 m (50 m half-width). Given the geometry of Pointer Lake, the site climate, and assuming that the conditions modelled are reasonable assumptions, the model confirms that an open talik is likely present under Pointer Lake when the water column is greater than 1.5 m.

2.3 EFFECT OF PERMAFROST ON FLOW

Historical thermal data were collected at the Project site from 1988 to 1991, and recent data was collected from 2007 to 2011 (see Figures 2.3-1 to 2.3-3). In these investigations, multilevel thermistor strings were installed in selected drillholes to determine the temperature profile of the ground beneath the Project site, and, therefore, the thickness of the active layer and the permafrost. The multilevel thermistor strings consist of temperature probes installed at regular intervals along the drillhole.

Multi-level-thermistor data collected from 2007 to 2011 indicate that permafrost extends to a depth of about 210 m to 230 m below ground surface in the area of the Main Zone, Centre Zone, and East Zone deposits. Data collected at Sissons indicate that permafrost extends to a depth ranging from 240 m to 260 m below ground surface in the area of the Andrew Lake and End Grid deposits. This is somewhat shallower, but generally consistent with data from historical thermistor installations, which suggests permafrost depths at the site ranging from 260 m to 280 m below ground surface.

Permafrost is considered to be virtually impermeable and ephemeral flow through the nominal active zone is considered negligible. The presence of the permafrost layer is expected to produce a confined flow system laterally continuous across the region, except under lakes that support open taliks. The hydraulic conductivity of the permafrost is low; a value of 1×10^{-12} m/s was assigned to the permafrost in the model to mimic an aquitard that does transmit very low volumes of water. Specific storage was assumed to be zero.

2.4 EFFECT OF GEOLOGY ON FLOW

The geology of the area, as it is relevant to the development of a conceptual and numerical regional groundwater flow model, consists of the following units:

- Overburden
- Basement rock
  - Metasediments
  - Intrusive granites
- Structural features (i.e, faults and dykes)

Overburden

Soils in the Project area are predominantly cryosols. The area is characterized by a shallow active layer (1 m to 1.5 m), shaped by various cryogenetic processes and resulting landforms such as hummocks and polygons. Soil types are mainly loamy basal tills, classified as Keewatin tills, very bouldery with sand/gravel/silt matrix. Overburden investigations suggest that overburden depths of up to 5.5 m are typical of the site. The overburden is typically heterogeneous, with variable hydraulic properties depending on the clay content and the abundance of boulders and large cobbles.

Under the current permafrost condition the overburden layer is only active during the summer when the soil has temporarily thawed and is not expected to interact with the deep groundwater flow system.

Under the completely melted permafrost scenario the surficial deposits are expected to show a high degree of hydraulic continuity with the surface water system, with shallow groundwater and lake water levels showing comparable fluctuations.

Basement rock

Competent rock comprises the majority of the rock domain. The hydraulic conductivity of the deep bedrock at the project site is low and is expected to decrease at greater depths as observed at other sites in the Canadian Shield.

- Basement host rocks in the vicinity of the Kiggavik deposits are composed of metasediments, and to a lesser extent altered granite and intrusive rocks. Uranium mineralization in the Kiggavik area is hosted for the most part in altered metasedimentary rocks (mainly metaarkose, metapelites and sericite schist), and to a much lesser extent in altered granite and intrusive rocks. There is no mineralization hosted in the Mackenzie diabase which cuts through Kiggavik.

- The Andrew Lake deposit is located in metasediments overlying granitic gneiss (banded metamorphic rocks) and granodiorite (an igneous rock). These formations have been strongly metamorphosed and altered, tectonized, and intruded. The rocks have gently dipping foliation, small scale recumbent folding, and low angle thrusting. The Andrew Lake deposit is located on a major east-northeast structure. This region has seen several episodes of hydraulic brecciation, mainly within the granite and syenite rocks, and to a lesser extent in the metasediment units. The subvertical faulting associated with the Andrew Lake deposit governs the extension of the mineralization.

- The End Grid deposit is located in an east-northeast sequence of metasediments, which are intruded by granite, porphyries, syenites and lamprophyres. It is related to the same major structure as the Andrew Lake deposit, but with a northeasterly trend. The mineralization within the deposit is controlled by horst and graben structures created by subvertical faulting.

A geology map including major structural features in the model domain is presented in Figure 2.4-1.

The deep groundwater flow regime was characterized during hydrogeological testing undertaken in deep boreholes drilled through permafrost to the unfrozen ground below (see Figures 2.3-1 and 2.3-2). A compilation of the hydraulic conductivity values derived from the tests conducted during the 2008, 2009, 2010 and 2011 field program is presented in Figure 2.4-2. Hydraulic tests conducted to data indicate that the hydraulic conductivity (K) of the rock at the Project site is low, with values ranging from less than 3.0×10^{-11} m/s to 1.0×10^{-6} m/s and a geometric mean of 2.7×10^{-9} m/s.

Figure 2.4-2 also compares the Kiggavik Project results to conductivity measurements from the Meadowbank Project (Cumberland Resources Ltd, 2005) and from a data set measured in metamorphic rock in Colorado, collected by Neretnieks (1993). The Neretnieks and the Meadowbank Project results are both considered to be reasonably representative of the Kiggavik deep rock mass. The dashed line in Figures 2.4-2 indicates a possible upper bound for the K values at depth. Hydraulic conductivities from the Neretniek and Meadowbank data sets range from $1x10^{-7}$ to $3x10^{-10}$ m/s at 200 m depth and $2x10^{-8}$ to $7x10^{-11}$ m/s at 300 m depth. The tests at Kiggavik fall within this range with the exception of one test measurement completed in 2009; AND09-03 was tested at $1x10^{-6}$ m/s between 297 and 327 mbgl.

Structural features

Several airborne geophysical surveys were conducted in the Project area for exploration purposes. Regional structures as shown on Figures 2.4-3 and 2.4-4 are mainly based on geophysical anomalies that were interpreted to be potential fault traces. Therefore the location of these regional features may not be accurate at the local scale.

A structural geology program was also conducted in the field during the nineties. The program focused on structural analysis of major fault systems with emphasis on hydrothermal events. The program included structural mapping at the outcrop level, regional mapping from airborne data and kinematic analysis. Two main phases of brittle deformation were identified during the program.

In competent bedrock environment enhanced permeability zones (i.e., zones of greater permeability than the surrounding rock) are frequently observed in association with open fractures, greater fracturing or larger fractures apertures that may be associated with structural features. When connected, enhanced permeability zones are considered to be of potential importance for governing the groundwater flow both prior to mining, during mining and after decommissioning. For instance if the mines were to intersect an enhanced permeability zone beneath permafrost, the dominant groundwater flow pattern induced during mining would likely be near parallel to the features.

Zones of enhanced permeability can be composed of sparsely spaced, highly permeable discontinuities within a lower permeability pseudo-matrix. Depending on the orientation of a borehole drilled within such a zone, none or many permeable fractures may be intersected and identification of these zones can be difficult with geotechnical logging and single well response testing alone. Fracture-enhanced permeability has not been observed to date in the Kiggavik Project area. Packer testing across several faults at Kiggavik site has not indicated an increased permeability in comparison to the bulk competent bedrock. Similarly injection tests completed across the cross cutting dykes at Main Zone did not indicate an enhanced permeability (MZ08-04 - test 2).

At some locations, faults logged in individual boreholes but not interpreted to extend laterally, intersected the test intervals, without translating to an increased hydraulic conductivity. Also geotechnical logging of boreholes has resulted in the local identification of fracture systems in both of the areas of the planned mines. These fracture systems may correspond to zones of enhanced permeability; however where fractures are in filled by fault breccias, veins or fault gouge this may not be the case.

2.5 HYDRAULIC HEAD DISTRIBUTION

Hydraulic head measurements were conducted at the Project site using vibrating wire piezometers successfully installed in four boreholes (END-09-01, ANDW-09-03, MZ-09-04 and GW-11-02) below the base of the permafrost. Estimates of static heads were also conducted from exploration boreholes showing artesian conditions (MZ-07-03, BONG-41, BONG-45 and BONG-52) and one borehole used for packer testing (MZ-10-01).

In general hydraulic heads measured beneath permafrost at the Project site are near to or above ground surface. Historical and recent observations suggest that flowing artesian conditions exist under the permafrost in several areas at the Project site. Typically artesian conditions occur in a hydrostratigraphic unit that is overlain and confined by units of lower permeability causing the hydraulic head in the unit to be above the bottom of the overlying confining layer. At the project site, the confining unit is the overlying permafrost above the deep unfrozen groundwater system. When the hydraulic head is above the ground surface, a well installed within the unit will flow indicating flowing artesian conditions.

2.6 DENSITY DEPENDENT FLOW

Saline groundwater is commonly found in deep and/or sub permafrost aquifers in the Canadian arctic. The Kiggavik site is at the upper limit of past marine influence, estimated to be 180 m elevation in upper Baker Lake region. Therefore the option of including density dependent flow in the model was evaluated. It was considered that modelling density dependent flow would introduce unnecessary complications to the numerical modelling. This option was not considered in this assessment for the following reasons.

- Hydrochemistry data collected to date suggest relatively fresh water below permafrost. The sub-permafrost groundwater sample collected in 2009 at MZ09-04 borehole shows concentration of major elements and total dissolved solids (e.g. chloride concentration of 1280 mg/l) that can be attributed to the natural calcium-sodium-chloride salinity of the deep bedrock. This water is only slightly brackish and is not expected to create significant density-dependent flow effects.
- The driving gradients between taliks and under permafrost are much greater than potential vertical density driven flow and most of the flow occurs laterally. Although flow of saline water below permafrost may occur at depth, density driven flow is unlikely to contribute significantly to the overall groundwater flow system.

2.7 SUMMARY

The Kiggavik Project lies within the Canadian Shield in an area of continuous permafrost. Permafrost depth is estimated to range from about 210 m depth in the area of the Main Zone, Centre Zone, and East Zone deposits to about 250 m depth in the area of the Andrew Lake deposit and End Grid deposit.

In areas of continuous permafrost, there are generally two groundwater flow regimes: a deep groundwater flow regime beneath permafrost and a shallow groundwater flow regime located in the active (seasonally thawed) layer near the ground surface. Because of the thick, low permeablility permafrost, there is little to no hydraulic connection between the two groundwater flow systems. The shallow groundwater flow regime at the Project site has little to no hydraulic connection with the groundwater regime located below deep permafrost.

In areas of continuous permafrost, the deep groundwater regime is connected by taliks (unfrozen ground) located beneath large lakes. Taliks are formed beneath lakes that do not freeze to the bottom in winter. If a lake is large enough, the talik extends down to the deep groundwater regime. The presence of the thick and low permeability permafrost beneath land located between large lakes results in negligible recharge to the deep groundwater flow from these areas. Smaller lakes generally have taliks that do not extend down to the deep groundwater regime and also do not influence the groundwater flow in the deep regime. Consequently, recharge to the deep groundwater flow regime is predominantly limited to areas of “open” talik beneath large surface water bodies.

Generally the driving force for groundwater beneath the permafrost is the elevation of lakes with “open” taliks. Groundwater flows from higher elevation lakes to lakes located at lower elevations. Therefore flow directions in the deep groundwater flow regime can be inferred from the elevations of the lakes supporting taliks (Figure 2.7-1 to 2.7-3). Groundwater flow in the area of the Main Zone, Centre Zone and East Zone deposits is inferred to be south towards Fox

Lake, Pointer Lake, Jaeger Lake, and Judge Sissons Lake. Groundwater in this area may also discharge to Sleek Lake, located to the southwest, and Scotch Lake, located to the southeast. In the area of the Andrew Lake, and End Grid deposits, the predominant groundwater flow direction is inferred to be southeast towards Boulder Lake, and Judge Sissons Lake. These groundwater flow directions have been inferred assuming that open taliks exist beneath lakes identified as large enough to support an open talik, and that on the regional scale the hydraulic conductivity of the bedrock beneath the permafrost is relatively homogeneous and isotropic.

Relatively competent rock comprises the majority of the rock domain. The hydraulic conductivity of the deep bedrock in the Project area is low and is expected to decrease at greater depths as observed at other sites in the Canadian Shield.

Hydraulic tests indicate that the hydraulic conductivity (K) of the rock at the Project site might be partially related to the rock type, with syenitic gneiss and granitic rock generally having a higher K than the metasediments. The majority of testing at the site indicates low hydraulic conductivity values on the order of 1×10^{-9} m/s with greater hydraulic conductivities of up to 10^{-6} m/s measured in a few boreholes. No correlation was found between areas of greater fracturing and intervals with greater hydraulic conductivity.

3 CURRENT PERMAFROST MODEL

3.1 MODEL DESIGN

3.1.1 Numerical Implementation

Two groundwater flow models have been developed, one based on the FEFLOW® v6.0 software (WASY 2010), and one based on the MODFLOW software (McDonald and Harbaugh 1988). FEFLOW (Finite Element subsurface FLOW system) is a computer program for simulating groundwater flow, mass transfer and heat transfer in porous media. The program uses finite element analysis to solve the groundwater flow equations of saturated or unsaturated conditions, as well as mass and heat transport, including fluid density effects and chemical kinetics for multi-component reaction systems. The MODFLOW software is an industry standard software application which incorporates a finite difference solution of the groundwater flow equations. The modular structure of MODFLOW consists of a Main Program and a series of independent modules. The modules are grouped in packages, each of which deals with a specific feature of the hydrologic system to be simulated. MODFLOW operates in conjunction with ZONEBUDGET (Harbaugh 1990) and MODPATH (Pollock 1998) to calculate subregional water budgets and three dimensional particle tracking pathlines, respectively.

The Kiggavik model presented in this section was developed under steady state conditions, neglecting density dependent effects. It was considered that the basement unit acts in a hydraulically similar manner as a porous medium and that the Equivalent Porous Medium approach is valid at the model scale. Hydrostratigraphic units were considered to have homogeneous material properties. The permafrost layer was treated as a homogeneous low permeability layer acting as a confining layer to the underlying rock mass.

3.1.2 Domain

The model domain is approximately 30 km wide and covers an area of 740 km^2 (Figure3.1-1). The Kiggavik and Sissons sites are at a minimum of 8 km from the external boundaries and 10 km from the northern part of Judge Sissons Lake. The proposed regional model encompasses a large area in order to obtain, as far as practical, unbiased predictions due to arbitrary boundary conditions. The extent of the model was selected based on observed topography, location and elevation of surface waterbodies, and surface water drainage patterns. Consequently, the model utilizes the following boundaries:

- o the western boundary was selected to include Gerhard Lake and Aberdeen Lake;
- o the eastern boundary includes Siamese Lake and Skinny Lake;

- the northern boundary includes Squiggly Lake and topographic highs located upgradient from the Kiggavik area; and,
- the southern boundary includes mainly Judge Sissons Lake.

3.1.3 Mesh

3.1.3.1 FEFLOW Model

The FEFLOW calculation code uses the finite-element method to solve the flow equations. This method requires definition of a mesh made of elements over which the calculations are performed. Although the model encompasses a large area, the model grid is sufficiently refined within the areas of interest to provide reasonable estimates of flow directions and volumes within the study areas, and more specifically, the Kiggavik and Sissons mining areas.

The model mesh consists of a total of 878,066 triangular elements. The finite element mesh was designed from triangular elements (Figure 3.1-1). It was refined to 20 m element size near the sites: Andrew Lake Pit, End Grid Underground, and the Main, Centre, and East Pits.

The model was sub-divided vertically into 15 layers (Table 3.1-1). Individual layers are defined by top and bottom planes (called slices in FEFLOW). Model slices are surfaces bounding a layer which contain the finite element mesh nodes. Each layer is the volume bounded by two slice surfaces. The layer contains the hydraulic properties such as hydraulic conductivity and storage.

The ground surface forms the top slice of the model. It is based on a 1 m LIDAR survey (LiDAR Services International, 2009; ArKeX, 2009), with accuracy of 30cm. Outside of the LiDAR coverage the topography was taken from regional digital topographic map with 5 m elevation contour interval.

The base of the permafrost was created by mirroring the ground surface topography at the depth corresponding to observed permafrost depths. It was generated using the 1 m contour digital terrain map (DTM) produced from LiDAR data. The DTM was smoothed with a low pass filter, translated vertically and then rotated by 3 degrees dipping south. This surface was used in the model as the base of permafrost across the entire model domain. Figure 3.1-2 shows the ground and permafrost surfaces used in the model.

The other model layers were defined to match as far as possible the underground development zones and the geometry of the Kiggavik TMFs. Intermediate layers were also introduced in the model to increase vertical discretization and reduce potential numerical instability issues.

Table 3.1-1 Model Layer Surfaces

Units in Taliks	Units Outside of Taliks	Layer #	Slice #	Description
Fractured rock	Permafrost		--- 1 ---	Ground elevation
		Layers 1 to 4	2 to 4	Slice 2, z= 5 mbgl (thin active layer) Slice 3, z=60 mbgl (for Post-Closure Model with partially thawed permafrost to depth 60 m) Slice 4 = 60.5 mbgl (buffer layer for abrupt K change)
		----------	--- 5 ---	Plane surface of constant elevation z=-100 mbgl (-68 masl) = End Grid Level 1
		Layer 5		
		----------	--- 6 ---	Base of permafrost (variable elevation)
	Fractured rock	Layer 6		
		----------	--- 7 ---	0.5 m below permafrost (buffer layer for abrupt K change)
		Layer 7 to 14	8 to 15	Plane surfaces of constant elevations Slice 8, z= 325 mbgl (-157 masl) = End Grid Level 3 Slice 9, z=450 mbgl (-282 masl) = End Grid Level 4 Slice 10 = 568 mbgl (-400 masl) 100 m spacing from slice 10 to slice 15 (z= -900 masl)

3.1.3.2 MODFLOW Model

The MODFLOW calculation code is based on a finite difference formulation of the underlying differential equations. The finite difference formulation is inherently mass conservative and therefore leads to straightforward water balance and flow pathline calculations. The main disadvantage of the formulation is that mesh refinement is less flexible.

The model mesh consisted of a primary grid of 300 by 300 grid blocks, with block size of approximately 120 m. The grid was refined in the Kiggavik area to a 60 m by 60 m mesh. The mesh was not refined in the Sissons area. Vertically, the model mesh had 14 layers which were constructed to be identical to the layers in the FEFLOW mesh. Figure 3.1-3 shows the MODFLOW mesh.

The discussion of boundary conditions and material properties in the following sections applies to both the FEFLOW and MODFLOW numerical models.

3.1.4 Boundary Conditions

As mentioned in the introduction, a motivation to develop the regional model was to avoid arbitrary boundary conditions that control the flow regime. Boundary conditions specified in the groundwater flow model under current permafrost conditions include constant head boundaries and no-flow boundaries.

Constant Head Boundary

Specified constants heads were assigned in Layer 1 over the areas of each lake supporting an open talik. A constant head boundary assumes an infinite source of water to the groundwater system, which is considered a valid assumption for this site as the surface water recharge into lakes is much greater than the flux from the base of the lake into low permeability fractured rock. Figure 3.1-4 shows a plan view of the boundary conditions assigned to Slice 1. These specified head boundaries were set to the average elevation of the lake that each boundary represents. The list of lakes with open taliks is presented in section 2, with associated lake elevations listed in Table 2.2-1.

No flow boundaries

With the exception of the boundaries with lakes (Judge Sissons Lake, Siamese Lake, Skinny Lake, Aberdeen Lake, Gerhard Lake, Buzzard Lake, # 1 Lake and #2 Lake), all the model limits were treated as “no flow” boundaries for all layers. As a result, the model is free to calculate groundwater divides that may or may not mimic the topography divides.

Recharge and Surface Drainage

Groundwater recharge from precipitation, seasonal active layer thawing and surface drainage were not simulated in the current permafrost model because permafrost prevents connexion of the surface water to the groundwater system, with the exception of the open taliks, which are already assigned with individual boundary conditions. Additional boundary conditions were introduced in the no-permafrost model to simulate surface drainage and recharge (see section 4.2).

3.2 MODEL CALIBRATION

3.2.1 Introduction

The purpose of the groundwater flow model calibration was to identify a set of model parameters that yields the most realistic description of groundwater flow while preserving the essential elements of the physical system. This set of model parameters is a combination of existing data and inferred parameters. The calibration process in groundwater modelling is nonunique, which means that there may be several sets of model parameters that provide an acceptable fit between observed and calculated data.

The parameters typically matched in a groundwater flow model calibration are the hydraulic heads, but also the direction of flow, and the water balance, if such data are available. The calibration parameters for a groundwater flow model typically include the spatial distribution of hydraulic conductivity, recharge, or discharge rates (*e.g.*, precipitation, or leakage), and boundary conditions.

The Kiggavik model was calibrated against measured and inferred hydraulic heads. An iterative, trial and error approach was used with iterations between the pre-mining and dewatering conditions calibrations. The following steps were followed

The key geological features were first introduced as zones of distinct hydraulic conductivity. A first calculation was made with an initial guess of the hydraulic conductivity values. The hydraulic conductivity values were then varied within the bounds determined from packer and slug tests with the objective of minimizing the difference between calculated heads and observed “pre-mining” heads.

3.2.2 Hydraulic Conductivity Distribution

A 3D view of the model layout and hydraulic conductivity distribution is shown in Figure 3.2-1. Taliks are visible as higher permeability zones that extend below the permafrost zone.

<u>Permafrost</u>

The permafrost was considered to be an effective aquitard, laterally continuous, except under lakes supporting open taliks. The permafrost was modelled with a very low hydraulic conductivity ($K_x=K_y=K_z=1\times10^{-12}$ m/s). Specific storage was assumed to be zero.

<u>Overburden</u>

This unit does not affect significantly the deep groundwater flow system as it has been shown to be discontinuous, shallow, and is only active during the summer when the soil has temporarily thawed. For the no-permafrost scenario, the overburden (active layer) was simulated as a 5m thick layer with hydraulic conductivity of 5×10^{-5} m/s, and specific storage (S_S) of 1×10^{-5} m^{-1}.

<u>Unfrozen Basement Rock</u>

The unfrozen rock “aquifer” was subdivided according to the following sub-geological units: Metasediments, Granite, Orthoquartzite, Syenite, Gneiss and Barrensland Group. Hydraulic conductivities for these units were estimated by calibration of the pre-mining groundwater model to the head elevations observed at Kiggavik, Sissons and Bong. Each unit was assigned a K value, homogeneous in the horizontal dimension.

At various sites in the Canadian Shield it has been shown that rock mass permeability decreases with depth (see for instance Ophori et al., 1996). Based on site measurements and measurements in similar deep basement rock, the hydraulic conductivity was assumed to decrease with depth to simulate a rock mass that is less fractured and with fractures that are less connected. A vertical anisotropy (Kx=Ky=Kz x 10) was also considered to represent a rock mass with more fractures connected in the horizontal direction than in the vertical direction.

Table 3.2-1 summarizes the calibrated hydraulic conductivity values for each unit.

Table 3.2-1 Calibrated Hydraulic Conductivity Distribution

Unit ID	Depth (m)	HYDRAULIC CONDUCTIVITY (m/s)						
		Permafrost	Granite	Meta-sediment	Gneiss	Ortho-quartzite	Syenite	Barrensland Group
K1	0-5	$1x10^{-12}$	$5x10^{-05}$	$5x10^{-05}$	$5x10^{-05}$	$5x10^{-05}$	$5x10^{-05}$	$5x10^{-05}$
K2	5-90	$1x10^{-12}$	$5x10^{-07}$	$5x10^{-09}$	$5x10^{-08}$	$1x10^{-07}$	$8x10^{-08}$	$3x10^{-07}$
K3	90-200	$1x10^{-12}$	$5x10^{-08}$	$5x10^{-10}$	$5x10^{-09}$	$1x10^{-08}$	$8x10^{-09}$	$3x10^{-08}$
K4	200-330	-	$1x10^{-08}$	$1x10^{-10}$	$1x10^{-09}$	$5x10^{-09}$	$3x10^{-09}$	$8x10^{-09}$
K5	330-1070	-	$1x10^{-09}$	$1x10^{-11}$	$1x10^{-10}$	$5x10^{-10}$	$3x10^{-10}$	$8x10^{-10}$

The major structural features shown in Figures 2.4-3 and 2.4-4 were included in the model to ensure conservative prediction of fluxes into mine workings and potential for transport of contaminant. Faults were simulated using quadrilateral 2D vertical discrete elements with a K of $1x10^{-7}$ m/s and a thickness of 10 m.

3.2.3 Storage Properties and Effective Porosity

Storage properties of the rock are not used under steady-state flow conditions. The values included in the model are presented in this section for reference purposes. The following storage parameters were used for transient modelling of mine inflows (see Appendix 5E), travel time and contaminant transport estimates (See Appendix 5J).

Specific storage

Permafrost

Specific storage was assumed to be zero.

Overburden

The overburden (active layer) was simulated as a 5m thick layer with specific storage of $1x10^{-5}$ m^{-1}.

Unfrozen Basement Rock

A specific storage of $1x10^{-5}$ m^{-1} was used for all layers and lithology units, with the exception of major structural features.

Effective Porosity

Overburden

An effective porosity of 0.2 was used for the overburden, described as bouldery loamy basal tills with sand/gravel/silt matrix.

Unfrozen Basement Rock

An effective porosity of 0.001 was used for the fractured bedrock. This low value is supported by the following observations.

- Data from 90 tracer experiments performed in low-permeability fractured media have been studied to explore correlations among parameters controlling flow and transport, including hydraulic conductivity and effective porosity (Guimera and Carrera, 2000). The results presented by these authors suggest that effective porosity values between 0.0001 and 0.01 cover the main data set, with a central value of about 0.001.
- These values are supported by the work conducted at the Yucca Mountain test site, Nevada (Bechtel SAIC, 2005). The value used in the assessment at Yucca Mountain was reported to be 0.0001 for granites that form the basement rocks beneath the alluvial basins at depths greater than 300 m (Smith, 2010, personal communication).
- A value of 0.003 was suggested for fractured bedrock in the Whiteshell Research Area (Ophori et al., 1996).

3.2.4 Pre-Mining Hydraulic Heads

The pre-mining simulation represents the groundwater flow regime prior to any mining at the Kiggavik Project area. Limited information corresponding to measured and inferred hydraulic heads was used to calibrate the groundwater flow model.

Tables 3.2-2 includes a comparison of observed artesian conditions and predicted hydraulic heads for the confined sub-permafrost layer for both the FEFLOW and the MODFLOW models. Figure 3.2-2 shows a scatter plot comparing calculated and observed heads for the FEFLOW model only. The figure includes only those predicted heads which were not artesian. Table 3.2-2 and Figure 3.2-2 indicate that the model simulates reasonably well the overall distribution of hydraulic heads in the Project area. Locally however the model underestimates the observed hydraulic heads. This is the case for instance in the END-09-01 and MZ-09-04 areas, where a decrease in the model hydraulic conductivity would be required to increase the calculated hydraulic heads and to better match the observed artesian conditions. It is considered however that given the uncertainty associated with the measurement of artesian heads decreasing the model hydraulic conductivity in these areas may result in a non-conservative model (ie hydraulic conductivity values too low).

Table 3.2-2 Predicted vs Observed Hydraulic Heads

Hole ID	Observation	Observed Head (masl)	Predicted Head (masl)	
			FEFLOW	MODFLOW
MZ-07-03	Observation from pressure transducer interpreted as artesian condition	> 187.9	202	204.5
MZ-08-04	Artesian conditions: ~4.5 L/s from the rods and casing annulus; low salinity of flowing water	> 177.8	201.5	204.5
MZ-09-04	Artesian conditions, constant flow for 44 hours + shut in test with packer in place; vibrating wire piezometer	215.5	202.2	204.6
MZ-10-01	During packer test	204.3	201.2	204.4
GW-11-02	Vibrating wire piezometer	> 172.0	198.2	203.9
BONG-41	Artesian conditions: ~2.5 L/s from the rods and casing annulus	> 160	197.3	
BONG-45	Artesian conditions: ~0.2 L/sec at 320m	> 160	197.4	199.3
BONG-52	Artesian conditions	> 155		199.2
END-09-01	Vibrating wire piezometer	175.5	168.2	168.2
AND-09-03	Vibrating wire piezometer	169.7	170.3	168.8

3.3 MODEL RESULTS

The calibrated steady-state head distribution beneath the permafrost for the pre-mining conditions is shown in Figure 3.3-1 and 3.3-2, for the FEFLOW model, and in Figure 3.3-3 for the MODFLOW model. The hydraulic head distribution reflects the surface elevation of lakes with open taliks. In the Kiggavik area, simulated groundwater flow in the unfrozen basement within the vicinity of the Main Zone and Centre Zone is in a south/southeasterly direction, confirming that Pointer Lake and Judge Sissons Lake act as points of bedrock groundwater discharge. In the area of the Andrew Lake and End Grid deposits, the predominant groundwater flow direction is towards the southeast and Judge Sissons Lake.

Areas of steep hydraulic gradients are simulated between Aberdeen Lake and Gerhard Lake in a manner consistent with the topography along the western boundary of the model. Steep gradients are also predicted in areas with metasediments, which are simulated with a lower hydraulic conductivity than the other basement rocks.

In some areas the model predicts hydraulic heads above the ground surface elevation, indicating artesian conditions (Figure 3.3-4). These predictions are generally consistent with the known artesian conditions.

3.3.1 Further Calibration

The calibration for the MODFLOW pre-mining model was carried one step further. The orthoquatzite conductivities were reduced by a factor 10 everywhere. The conductivities in the Kiggavik area were further refined. Four new conductivity regions were defined (see Figure 3.3-5). The southern two regions were given metasediment conductivities. The northern two were given orthoquartzite conductivities. Figure 3.3-5 shows the changes for the layers corresponding to K4 in Table 3.2-1. The equivalent changes were carried out in the other conductivity regions. Table 3.3-1 compares the heads predicted by the refined calibration to the calibration reported in Table 3.2-2. The calibration for the Bong-area wells has been substantially improved. Figure 3.3-6 shows the calibrated pre-mining steady state head distribution for the MODFLOW model with the refined calibration. The predicted heads are slightly higher to the north of the Kiggavik mining region and slightly lower in the Bong-area.

Table 3.3-1: Comparison of Model Calibrations.

Hole ID	Observed Head (masl)	MODFLOW Predicted Head as per Table 3.2-2 (masl)	MODFLOW Predicted Head as per Section 3.3.1 (masl)
MZ-07-03	> 187.9	204.5	203.3
MZ-08-04	> 177.8	204.5	203.0
MZ-09-04	215.0	204.6	203.6
MZ-10-01	204.3	204.4	203.0
GW-11-02	> 172.0	203.9	198.7
BONG-45	> 160	199.3	177.5
BONG-52	> 155	199.2	176.1
END-09-01	175.5	168.2	168.8
AND-09-03	169.7	168.8	169.7
Correlation Coefficient		0.44	0.74

4 NO PERMAFROST MODEL

4.1 INTRODUCTION

The effects of climate change on the project in the short and long term will depend on the degree and rate of warming. Climate change predictions are uncertain at the current time, but consensus on the degree of warming is beginning to become more accepted within the scientific community and the general public. Although the causes of climate warming are under debate at this time, the predicted warming trends are considered to be possible and are within typical climate variability in the long term. Increasing mean annual air temperatures will lead to significantly warmer weather in the summer months; increasing the number of days with air temperatures greater than 0 °C. It is expected that the primary effect this will have on the Kiggavik Project area will be to increase the number of days when precipitation will fall as rain, rather than snow, and the number of days available for melting existing or seasonal ice and snow, thus increasing the average surface temperatures and impacting permafrost distribution in the region. A compilation of the factors affecting global climate and a discussion of the cumulative effects of these factors are provided in Technical Appendix 4D (Baker Lake Long Term Climate Scenario).

The warming trend used for modeling purposes of the Project area considers a 5^{o}C rise in the mean annual surface temperature (MAST) over the next 100 years followed by a long-term plateau at 5^{o}C above the current MAST. This trend is considered to be conservative as it anticipates a greater temperature increase for the Baker Lake area than what is suggested based on the analysis and scenario presented in Appendix 4D.

Thermal modelling was performed to highlight the potential impact of climate change on the permafrost at the Kiggavik Project sites. Two different climate change scenarios were simulated based on this warming trend over 100 years; from a MAST of -7 °C to -2 °C and from a MAST of -6 °C to - 1 °C. Both cases consider the same 5 degree rise in temperature however they differ in what their starting values are. Figure 4.1-1 shows the warming trends and the corresponding computed change in permafrost depth in the Kiggavik area for the two climate change scenarios over 2000 years. The thermal model used to simulate the effect of climate change on permafrost is presented in Technical Appendix 5J (Tailings Characterization and Management).

Model results show that if the mean annual surface temperature rises the change is manifested as a reduction in depth of permafrost at the base, and not at the surface. Figure 4.1-1 shows that the warming trends will result in long term permafrost depths decreasing from about 220 m to either 90m from surface for the first trend (e.g., -7 °C to -2 °C) or 40m from surface for the warmer trend (e.g., -6 to -1 °C).

The major change in the hydrogeological system due to climate change will be how it affects the thickness and distribution of permafrost in the region. The increase in mean annual surface temperature will affect permafrost from both the top, in the active zone, and from the bottom due to the geothermal heat in the deep rock mass.

To assess the worst case potential from a groundwater flow and contaminant transport perspective a conservative approach was used and complete melting of permafrost was considered. The absence of permafrost would be a significant change to the groundwater flow system. With removal of the confining permafrost layer, piezometric levels would equilibrate to near ground surface levels, except in low topographical locations, which would act as discharge zones for the groundwater system. Surface components of the hydrological system would become connected to the underlying hydrogeological flow system across the region. This would have an effect on the pressure distribution and hydraulic heads.

The objective of the model presented in the following sections is to predict groundwater flow conditions in a very long term scenario, with the assumption that a warming trend greater than the 5^{o}C rise has melted the permafrost completely and that the hydrogeological system has stabilized to a new pseudo-equilibrium state. The ultimate objective of this model is to predict the potential change in solute transport from the Main Zone, Centre Zone and East Zone TMFs to potential receptors. This component of the assessment is presented in Technical Appendix 5J (Tailings Characterization and Management).

4.2 MODEL PARAMETERS

4.2.1 Hydraulic Conductivity Distribution

Under no-permafrost conditions the hydraulic conductivity distribution will change for units that were previously located in the permafrost layer. Therefore the hydraulic conductivity distribution presented in Table 3.2-1 was used to characterize basement units previously located in permafrost.

4.2.2 Recharge

As summers become warmer and wetter, lake evaporation and evapotranspiration conditions are typically predicted to increase. Although water losses typically increase the magnitude is not expected to compensate for the increases in precipitation. Therefore both runoff and recharge are expected to increase relative to the current permafrost conditions. However recharge is not expected to increase as much as precipitation because the thin soils and weathering profile and the underlying low permeability bedrocks will limit the infiltration rate.

To account for the expected change in hydrology groundwater recharge from precipitation was included as a boundary condition in the no-permafrost groundwater flow model. A maximum “reasonable” recharge rate was estimated by increasing the recharge rate in the model until the simulated hydraulic heads be equal or higher than ground surface in areas of the model located at sufficient distance from boundary conditions such as drains and lakes. This iterative process resulted in a recharge value of 15 mm/year. Any additional recharge above this value was found to cause unrealistic mounding of groundwater above ground surface. The calibration results are illustrated in Figure 4.2-1.

4.2.3 Lakes

The location of the lakes was not changed in the no-permafrost model, assuming no geomorphic changes to ground surface. The following four lakes however were removed from the model: Ridge Lake, Felsenmeer Lake, Escarpment Lake, and Mushroom Lake. These lakes were removed considering that, with thawing of the permafrost, they would likely drain into the underlying rock and become dry depressions rather than annual lake bodies. This assumption was based on the observation that the lake elevations are much higher than the surrounding groundwater head. Therefore it is reasonable to assume that these lakes may be "perched" on frozen ground.

4.2.4 Stream Channels

Drain boundary conditions were added along stream channels at the top surface of the no-permafrost model in order to prevent excessive mounding of the water table as a result of the applied recharge flux, particularly in areas away from lakes. The stream channels were simulated as drains allowing groundwater to exit the model but not recharge the model. This assumption is considered to be reasonable because the water table is close to ground surface and the drainage channels are the lowest points along topography.

The drains added to the model were selected to match topographical depressions and existing channels. Figure 4.2-2 shows a plan view of the drains used in the no permafrost model.

4.3 MODEL RESULTS

Contours representing the calculated water levels for the entire no-permafrost model are shown in Figures 4.3-1 and 4.3-2, for the FEFLOW model. The MODFLOW model results are presented in Figures 4.3-3 and 4.3-4. Compared to the current permafrost case (Figures 3.3-1 and 3.3-2) the simulated steady-state heads with the no-permafrost model show a stronger surface water impact on groundwater flow.

It should be noted that the MODFLOW and FEFLOW hydraulic head distributions are different for the no-permafrost scenario. This difference can be attributed to the fact that the FEFLOW model was run in fully saturated confined mode whereas the MODFLOW model was run in confined/unconfined mode, allowing the inclusion of an unsaturated zone in the upper layers. The MODFLOW model was also run in confined mode for comparison purposes. The resulting hydraulic head contours are shown in Figure 4.3-4 and can be compared to Figure 4.3-1.

It is considered that for the no-permafrost case the inclusion of an unconfined zone in the top layer of the model is a more realistic representation of the flow regime. For this reason the MODFLOW results were used in the contaminant transport analysis (Appendix 5J).

Figure 4.3-5 presents the results of a simplified particle path analysis conducted with FEFLOW, with particle paths associated with particles released throughout the Main Zone area. Figure 4.3-5 shows that in the no-permafrost model particles discharge to Pointer Lake. Figure 4.3-6 shows the results of a similar analysis conducted with MODFLOW/MODPATH for particle released throughout the Main Zone, Centre Zone and East Zone areas. Figure 4.3-6 confirms that over the long-term, in the no-permafrost scenario, particles are expected to discharge to Pointer Lake. This analysis is further developed in Appendix 5J (Tailings Characterization and Management).

5 CONCLUSION

5.1 KEY FINDINGS

The proposed model encompasses a large area, simulating groundwater flow on a regional scale in order to obtain, as far as practical, unbiased predictions due to arbitrary boundary conditions. The extent of the regional model was selected based on observed topography, location and elevation of surface waterbodies, and surface water drainage patterns.

A reasonable geological and hydrogeological database exists for the model study area including topography, climate, hydrology and geophysical data as well as exploration boreholes, ground temperature, pressure readings and hydraulic tests. This database was used to develop a conceptual groundwater flow model and to provide input parameters and calibration data to the corresponding numerical model.

The Kiggavik Project lies within the Canadian Shield in an area of continuous permafrost. Multi-level-thermistor data collected from 2007 to 2011 indicate that permafrost extends to a depth of about 210 m to 230 m below ground surface in the area of the Main Zone, Centre Zone, and East Zone deposits. Data collected at Sissons indicate that permafrost extends to a depth ranging from 240 m to 260 m below ground surface in the area of the Andrew Lake and End Grid deposits.

Under pre-mining conditions, the groundwater regime in the study area consists of two flow systems. A shallow groundwater flow system occurs in the active, seasonally thawed, layer near the ground surface. The deep groundwater flow regime comprises groundwater flow beneath permafrost. Because of the thick, low permeablility permafrost, the shallow groundwater flow regime at the Project site has little to no hydraulic connection with the sub-permafrost groundwater regime.

The groundwater flow pattern in the Project area is representative of topography-driven flow in low permeability bedrock. The deep groundwater regime is connected by taliks (unfrozen ground) located beneath large lakes. The driving force for groundwater beneath the permafrost is the elevation of lakes with “open” taliks, with groundwater flowing from higher elevation lakes to lakes located at lower elevations. Groundwater flow in the area of the Main Zone, Centre Zone and East Zone deposits is simulated to be south towards Pointer Lake then Judge Sissons Lake. In the area of the Andrew Lake and End Grid deposits, the predominant groundwater flow direction is simulated to be inferred to be southeast towards Boulder Lake and Judge Sissons Lake.

Relatively competent rock comprises the majority of the rock domain. The hydraulic conductivity of the deep bedrock in the Project area is low and is expected to decrease at greater depths as observed at other sites in the Canadian Shield. Hydraulic tests indicate that the hydraulic conductivity (K) of the rock at the Project site might be partially related to the rock type, with syenitic gneiss and granitic rock generally having a higher K than the metasediments. The majority of testing at the site indicates low hydraulic conductivity values on the order of 1×10^{-9} m/s with greater hydraulic conductivities of up to 10^{-6} m/s measured locally. No correlation was found between areas of greater fracturing and intervals with greater hydraulic conductivity.

Two groundwater flow models have been developed for this Project, one based on the FEFLOW software and one based on the MODFLOW software. The ultimate goal of the groundwater flow models is to provide a predictive tool for future applications, such as inflow predictions towards future mining works and long-term flow predictions through decommissioning activities. Immediate applications of the model are found in the following documents

- Technical Appendix 5E - Prediction of Water Inflows to Kiggavik Project Mines
- Technical Appendix 5J - Tailings Characterization and Management

The FEFLOW finite element formulation is considered to be better suited to situations were grids must be adapted to local structures. The FEFLOW model results were therefore used in the calculation of the water inflows to the underground mines (Technical Appendix 5E). The results of the MODFLOW-based numerical model were reported for the post-closure tailings characterization (Technical Appendix 5J).

5.2 FOLLOW UP PROGRAM

The three-dimensional flow models presented in this Technical Appendix are considered to be living tools subject to improvement of both the conceptual and numerical parts. The proposed groundwater flow models simulate in a realistic manner the pre-mining groundwater regime in the Kiggavik Project area. The flow models are also able to reproduce the distribution of artesian conditions and some hydraulic heads measurements in the Project area. However, the models are not capable of perfectly reproducing all conditions and have certain limitations, in particular due to the limited calibration data set.

Improvement of the calibration data set and improvement of the robustness of model predictions is part of the proposed followup program. The followup program would take place during operation and would include the installation of additional vibrating wire piezometers in the vicinity of the open pits to monitor the influence of pit dewatering activities, if any. The followup program would also include the installation of far-field piezometers downgradient from the proposed mines.

6 REFERENCES

6.1 LITERATURE CITED

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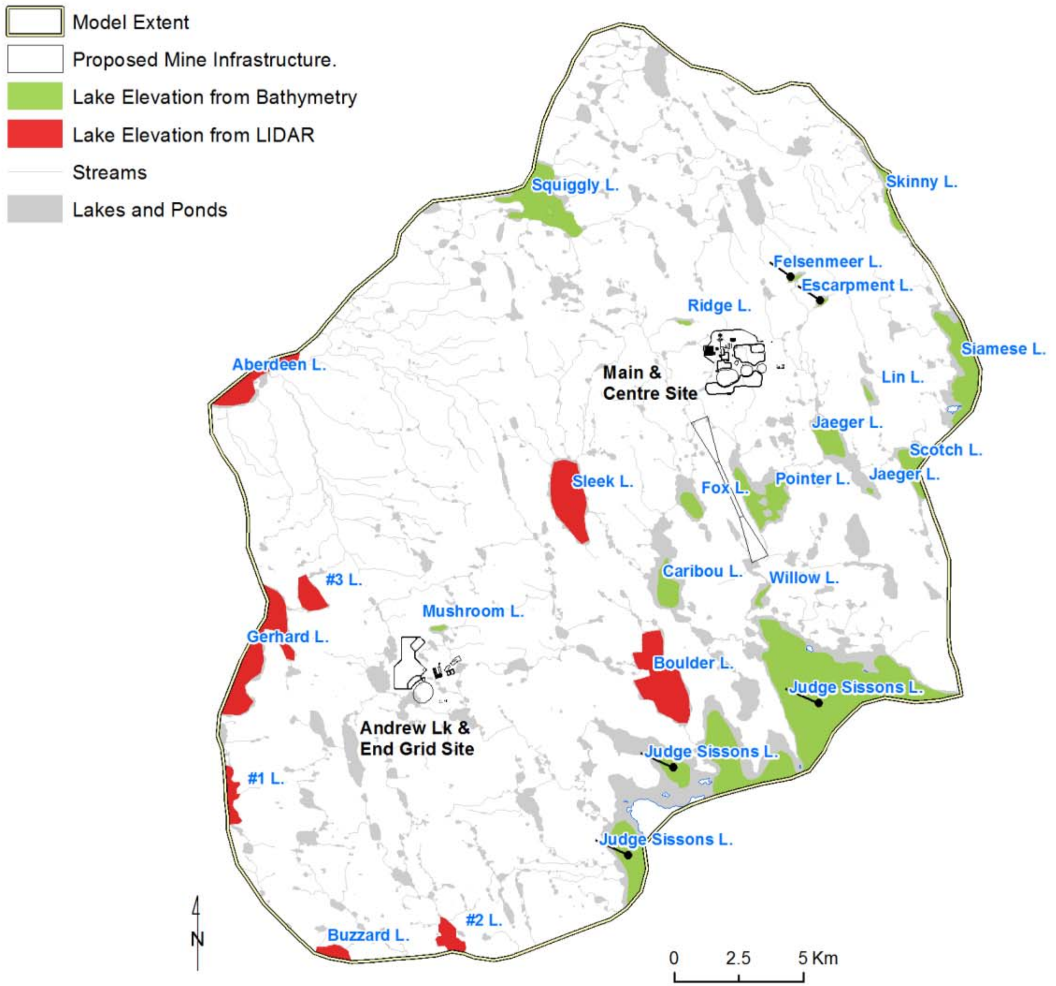
Figures

Figures



Technical Appendix 5D
Groundwater Flow Model
December 2011

Figure 2.2-1
Lakes potentially supporting open talik formation

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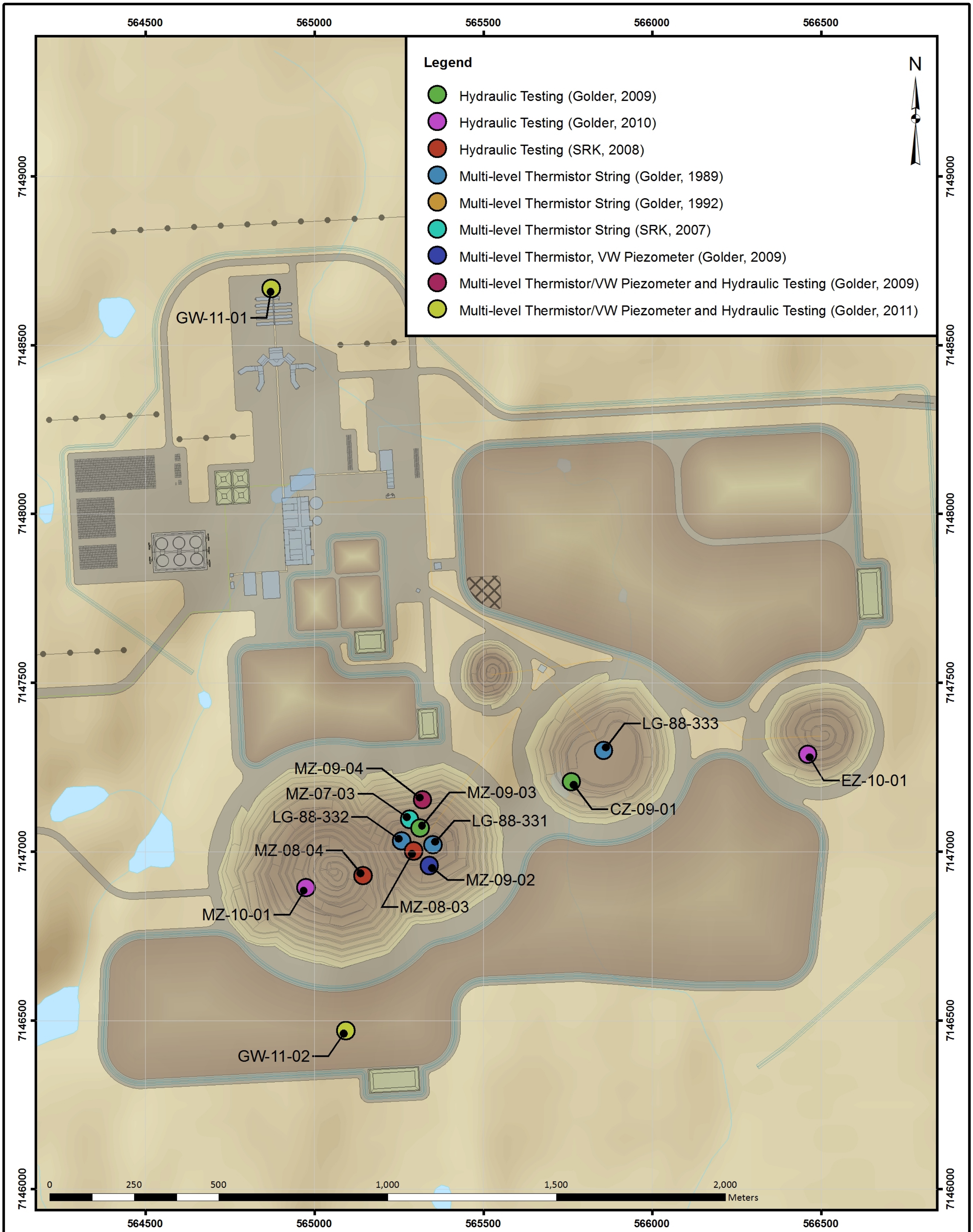

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FIGURE 2.3-1
THERMAL AND HYDRAULIC TESTING LOCATIONS
KIGGAVIK AREA

ENVIRONMENTAL IMPACT STATEMENT
APPENDIX 5D

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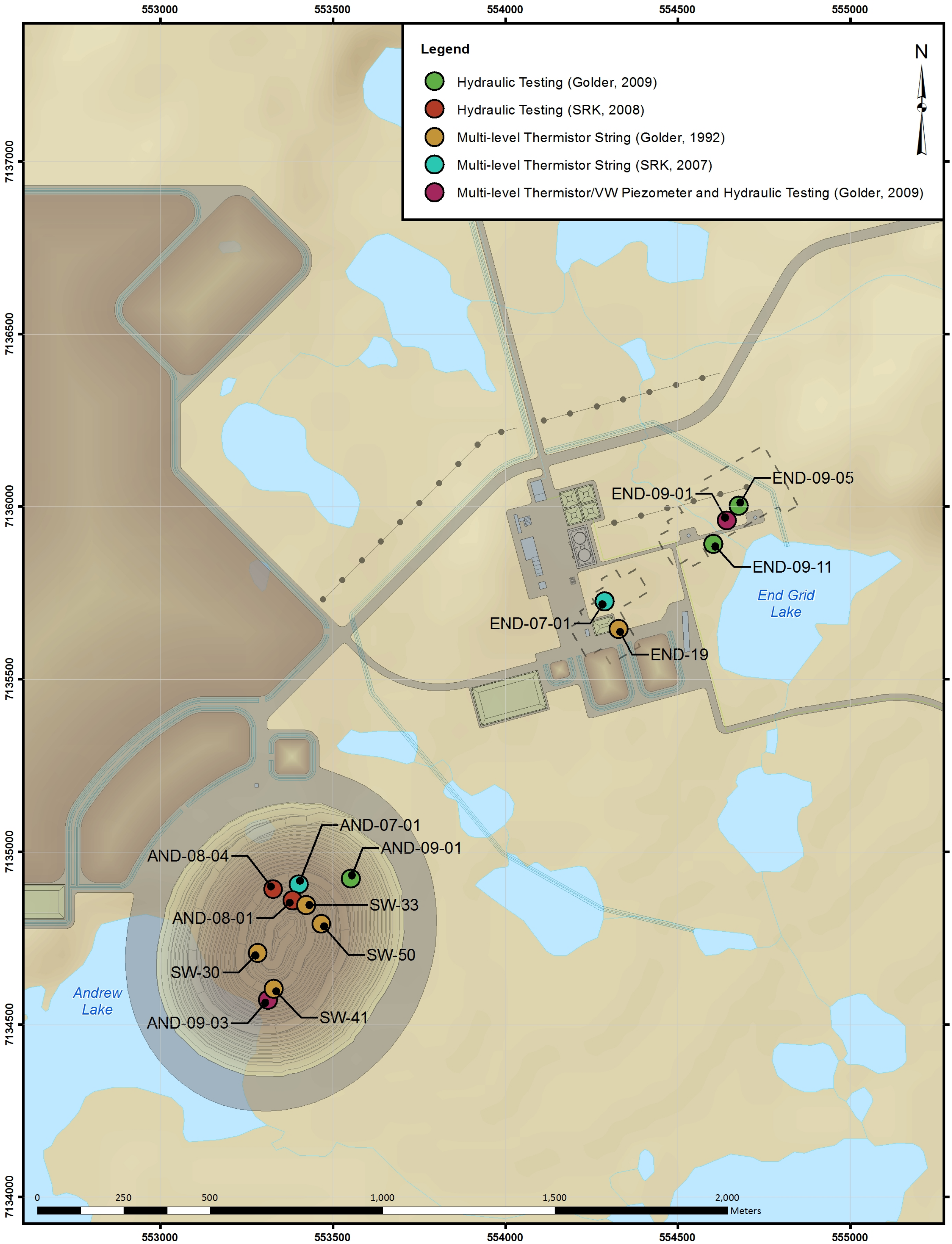

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Data Sources: *Natural Resources Canada, Geobase®, Nation Topographic Database, AREVA Resources Canada Inc.*

FIGURE 2.3-2
THERMAL AND HYDRAULIC TESTING LOCATIONS
SISSONS AREA

ENVIRONMENTAL IMPACT STATEMENT
APPENDIX 5D

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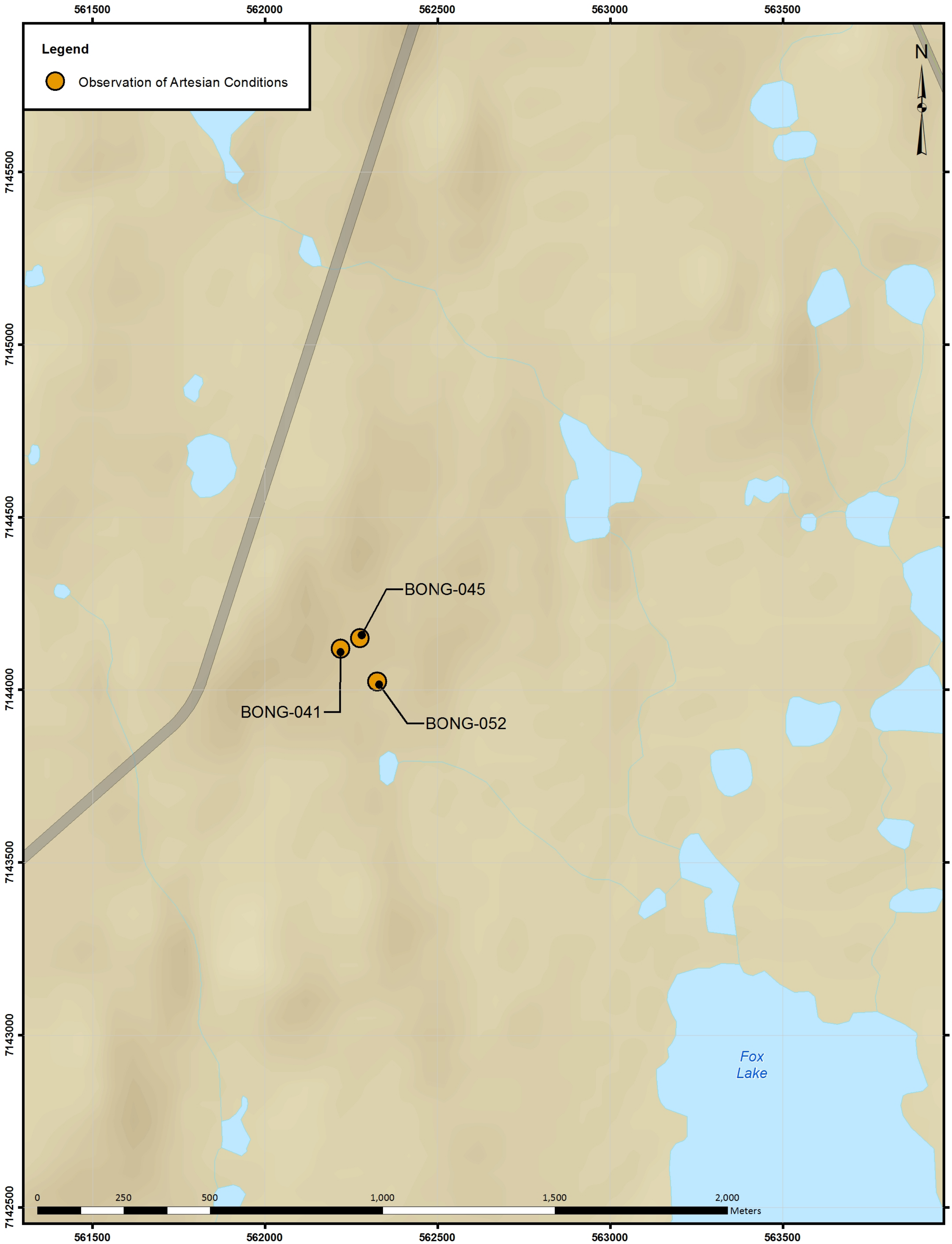

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Data Sources: *Natural Resources Canada, Geobase®, Nation Topographic Database, AREVA Resources Canada Inc.*

FIGURE 2.3-3
ARTESIAN EXPLORATION BOREHOLES
BONG AREA

ENVIRONMENTAL IMPACT STATEMENT
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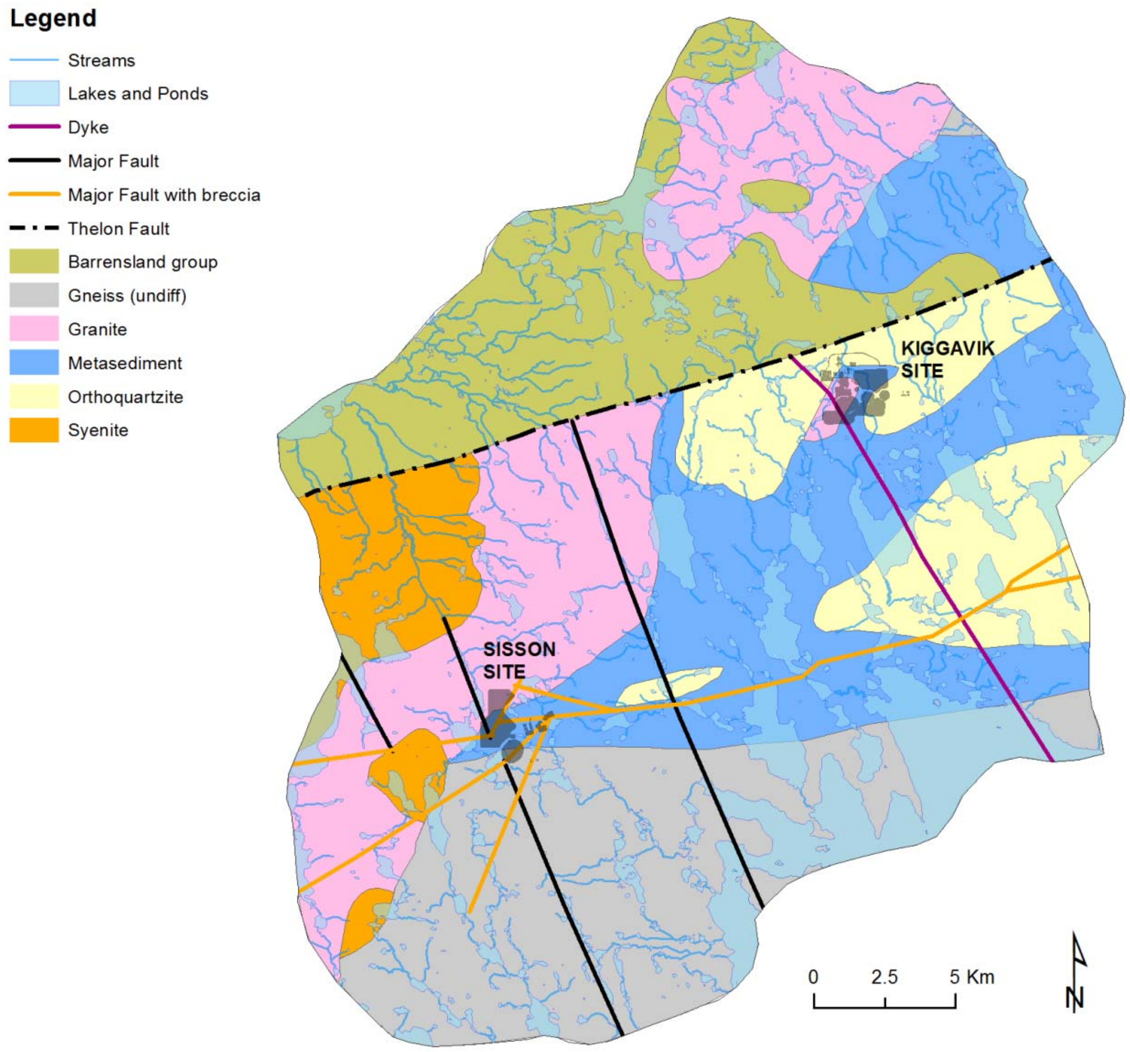

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Technical Appendix 5D
Groundwater Flow Model
December 2011

Figure 2.4-1
Geology map and major structural features in the model domain

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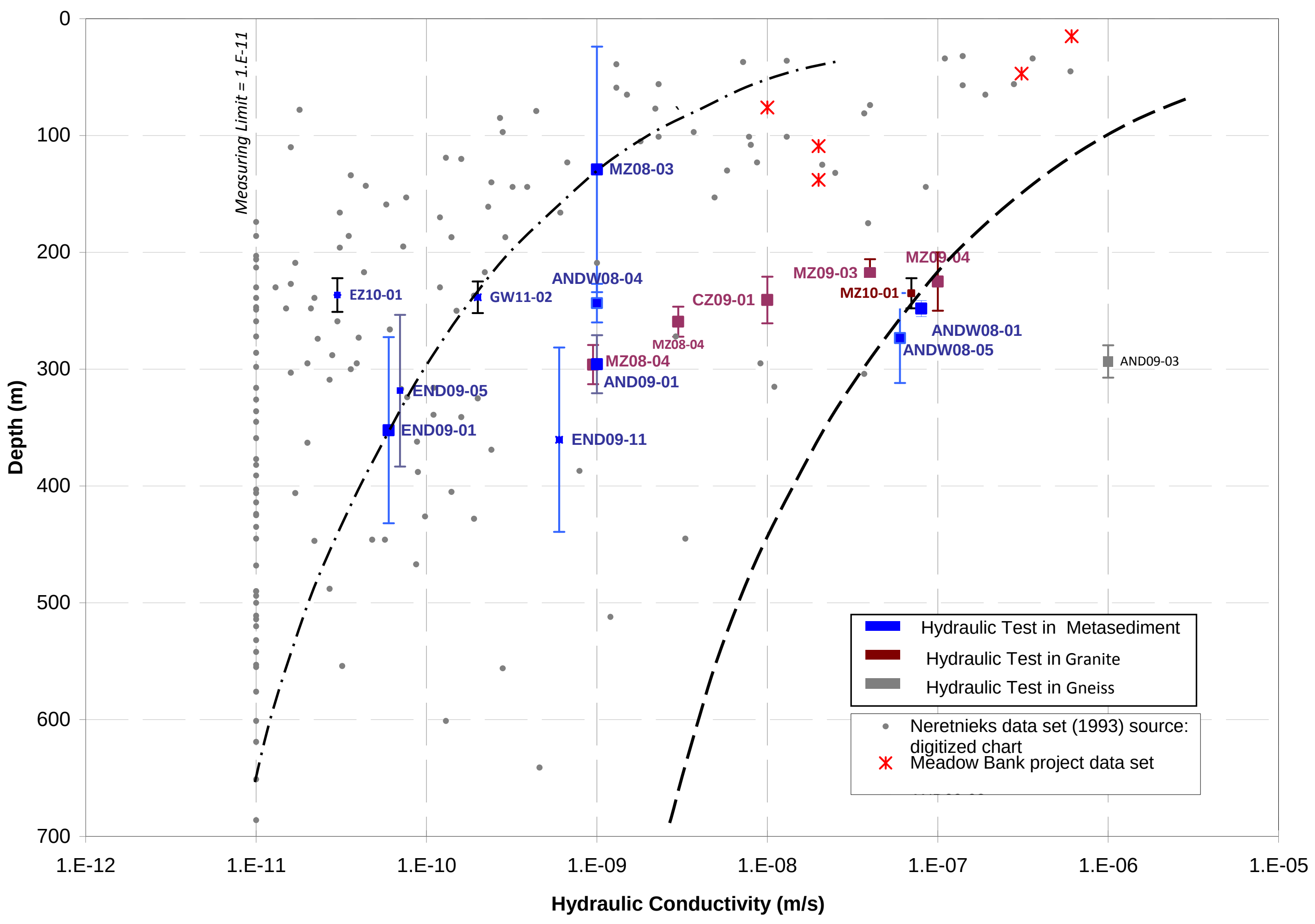

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Figure 2.4-2
Compilation of single well pressure response test results

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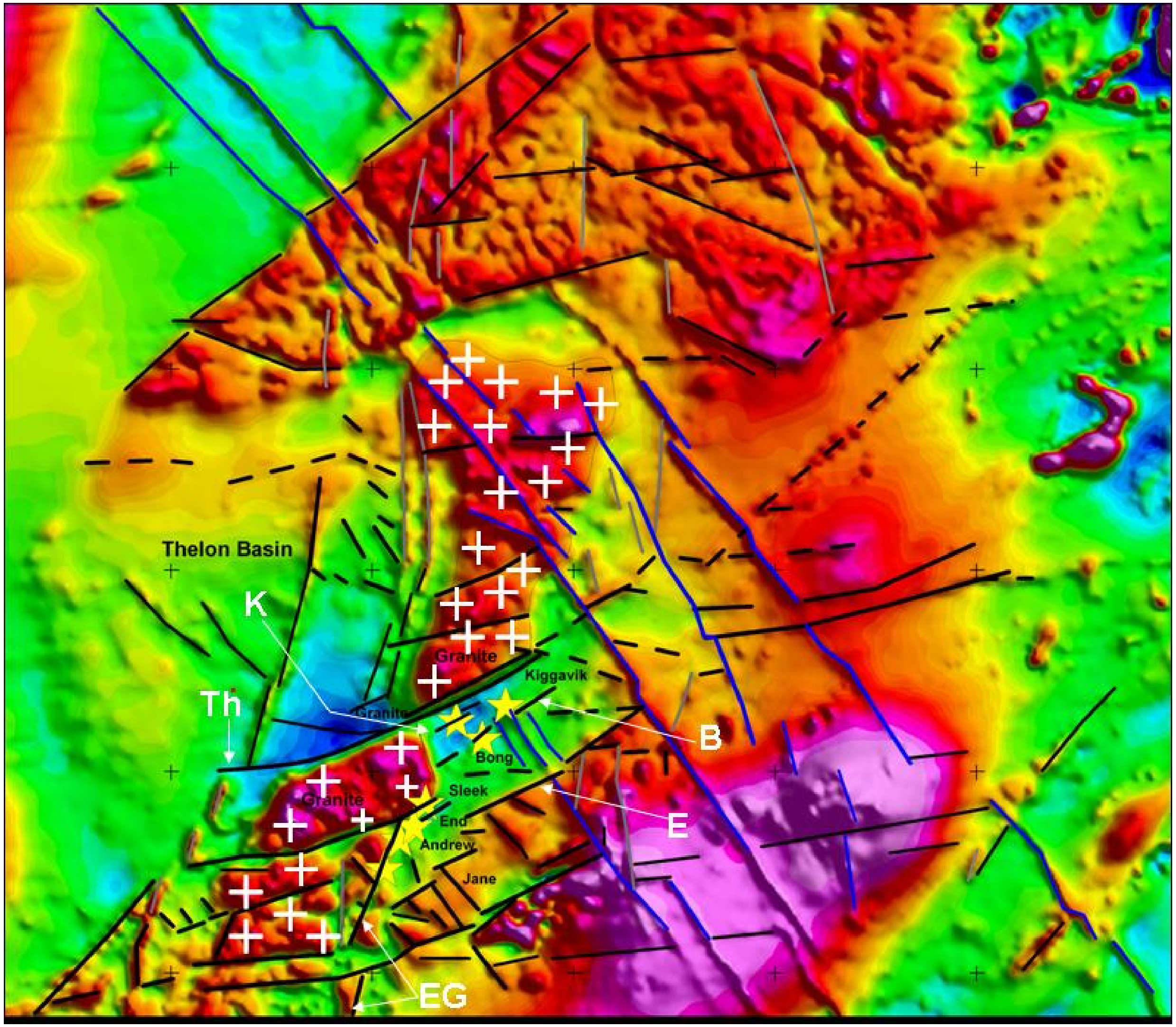

Black line: discontinuities which would belong to the dextral faults system (NE-SW, WSW-ENE, E-W, WNW-ESE striking-trend) and to the minor conjugate sinistral system (NW-SE)
Grey line: discontinuities which would correspond to the late faulting
Blue line: Discontinuities which would correspond to the diabase dykes
White cross: granite
Yellow stars ores bodies

Th = Thelon Fault
K = Kiggavik Fault
B = Bong Fault
E = End Fault
EG = End-Andrew-Jane-Alpha-Golf Fault

Airmag map from the regional magnetic survey performed by the Geological Survey of Canada

Figure 2.4-3
Structural interpretation of the Kiggavik Project area based on Airmap map

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Legend

- Mine Location Proposed
- Major Fault Line
- Major Fault Line (Quartz Breccia)
- Minor Fault Line
- Foliation
- Kiggavik Lease

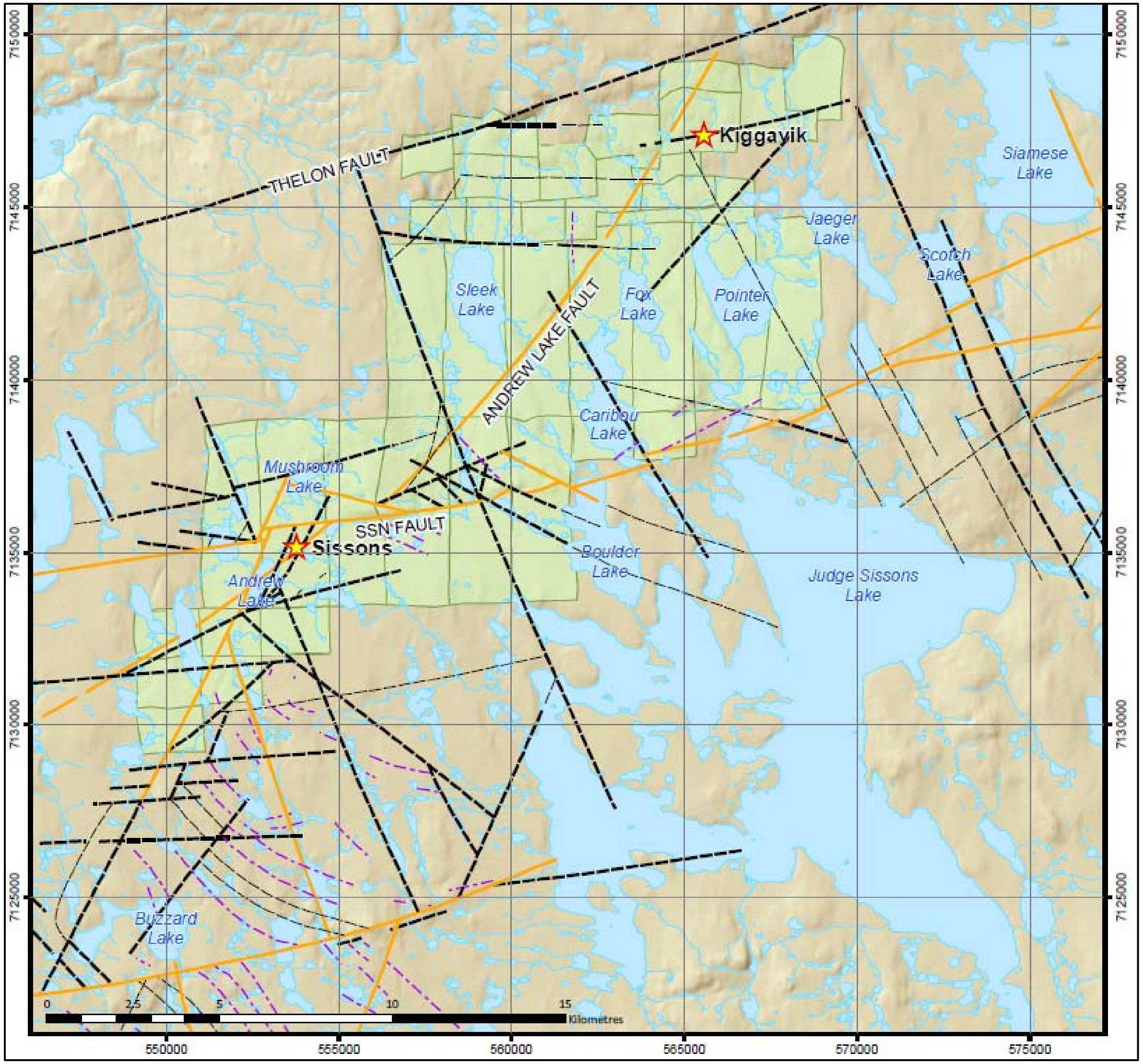

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Figure 2.4-4
Regional structures

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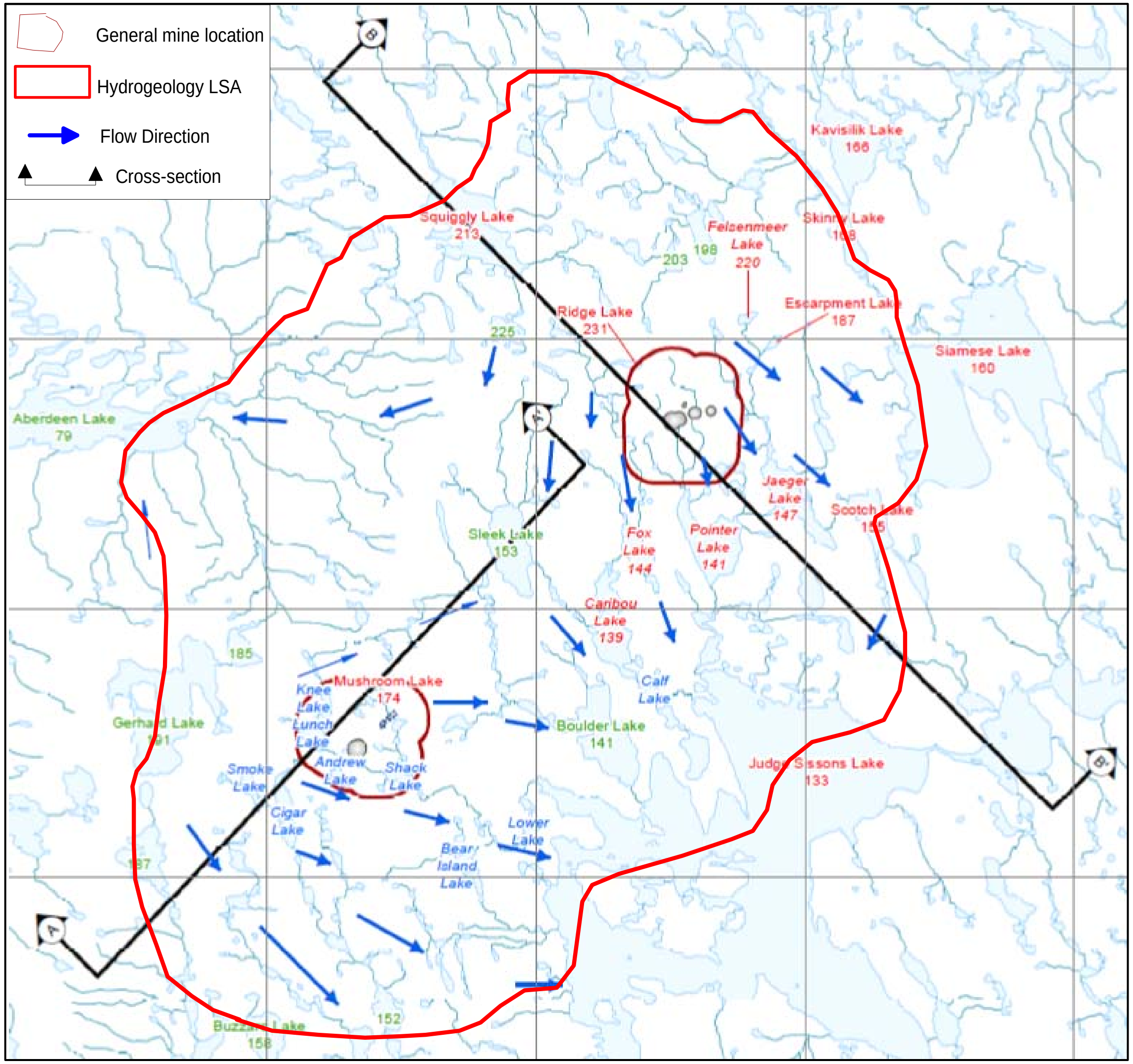

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Figure 2.7-1
Inferred groundwater flow direction

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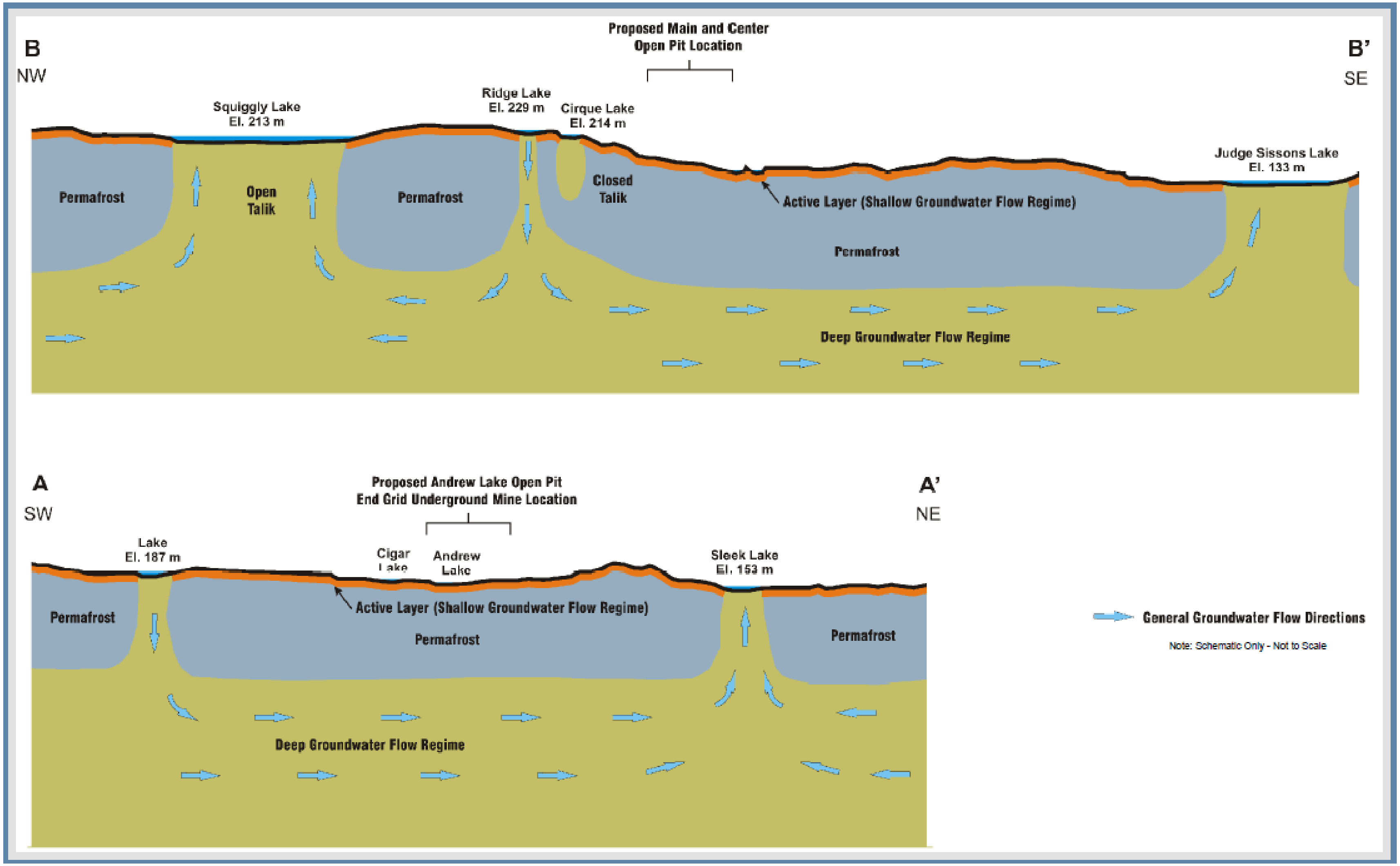

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Figure 2.7-2
Conceptual model of groundwater flow
Kiggavik and SIssons areas
Cross section view (1 of 2)

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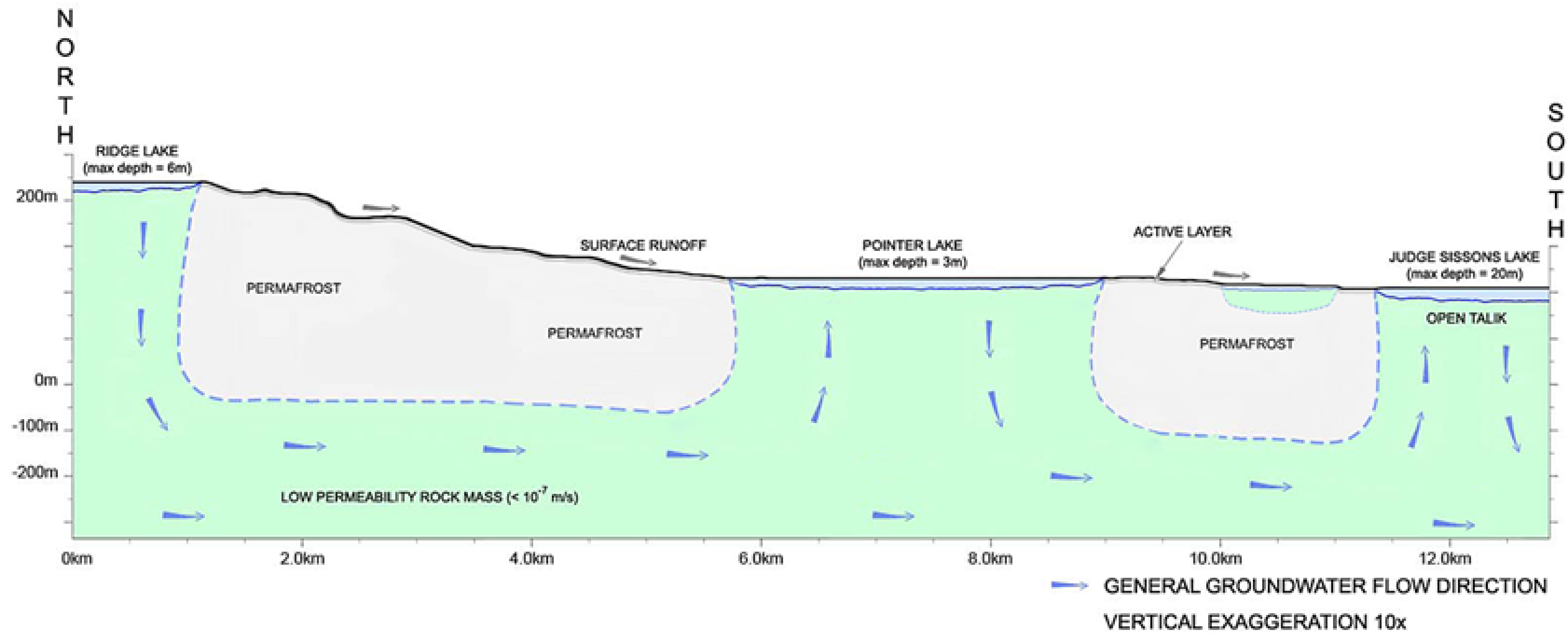

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Figure 2.7-3
Conceptual model of groundwater flow
Kiggavik area - Cross section view (2 of 2)

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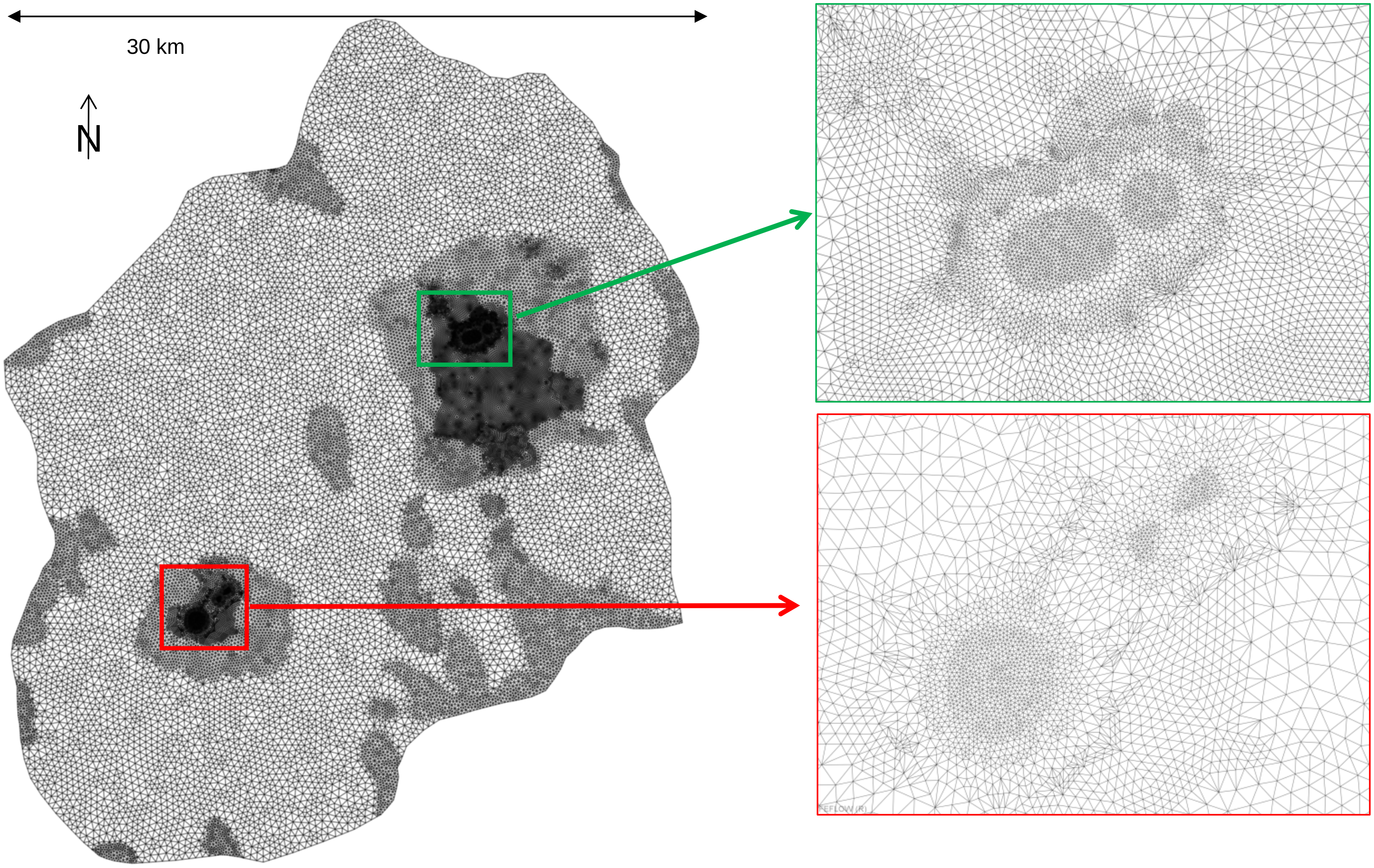

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Figure 3.1-1
FEFLOW Model mesh geometry (plan view)

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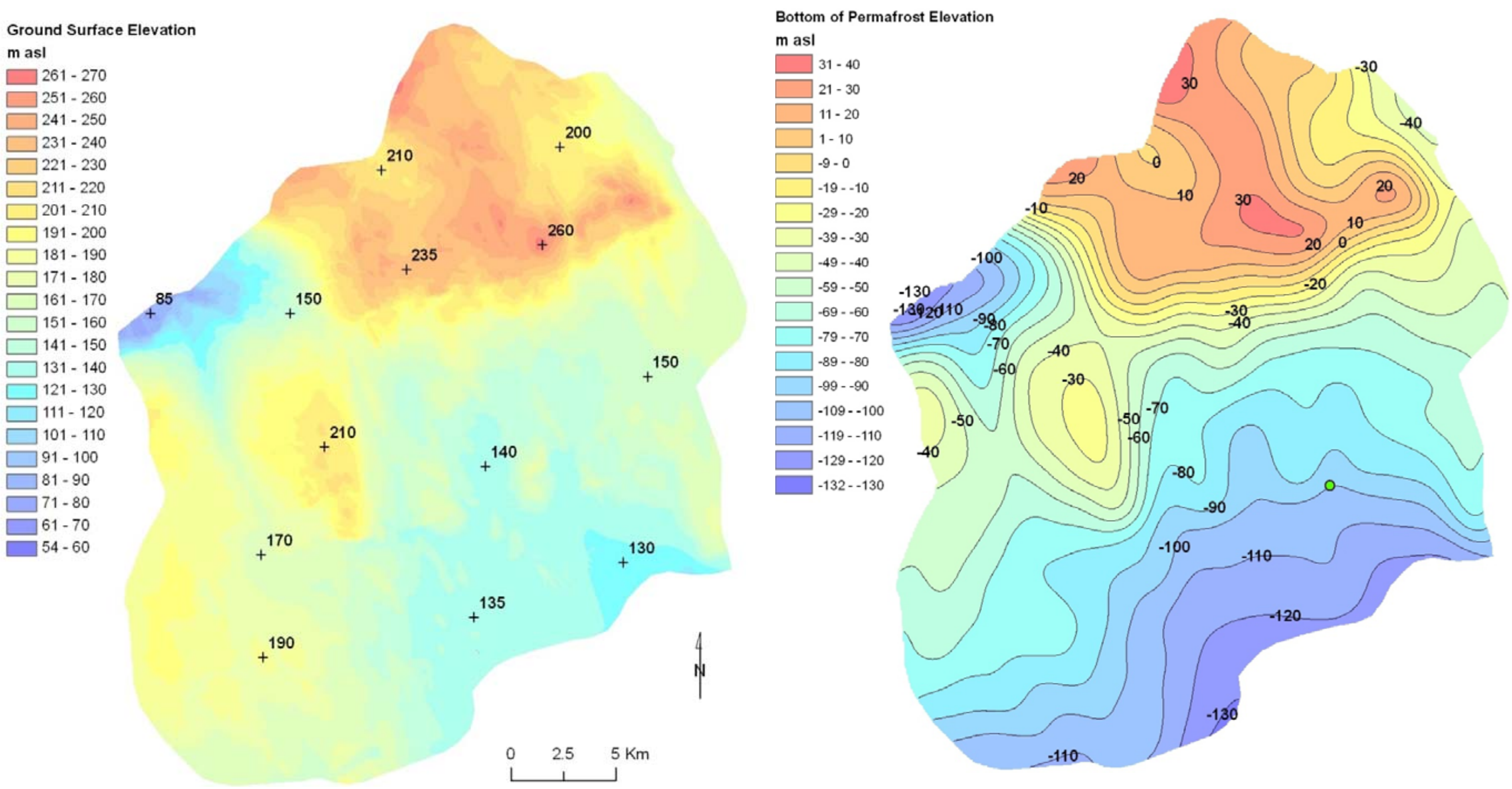

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Figure 3.1-2
Ground surface and permafrost elevations

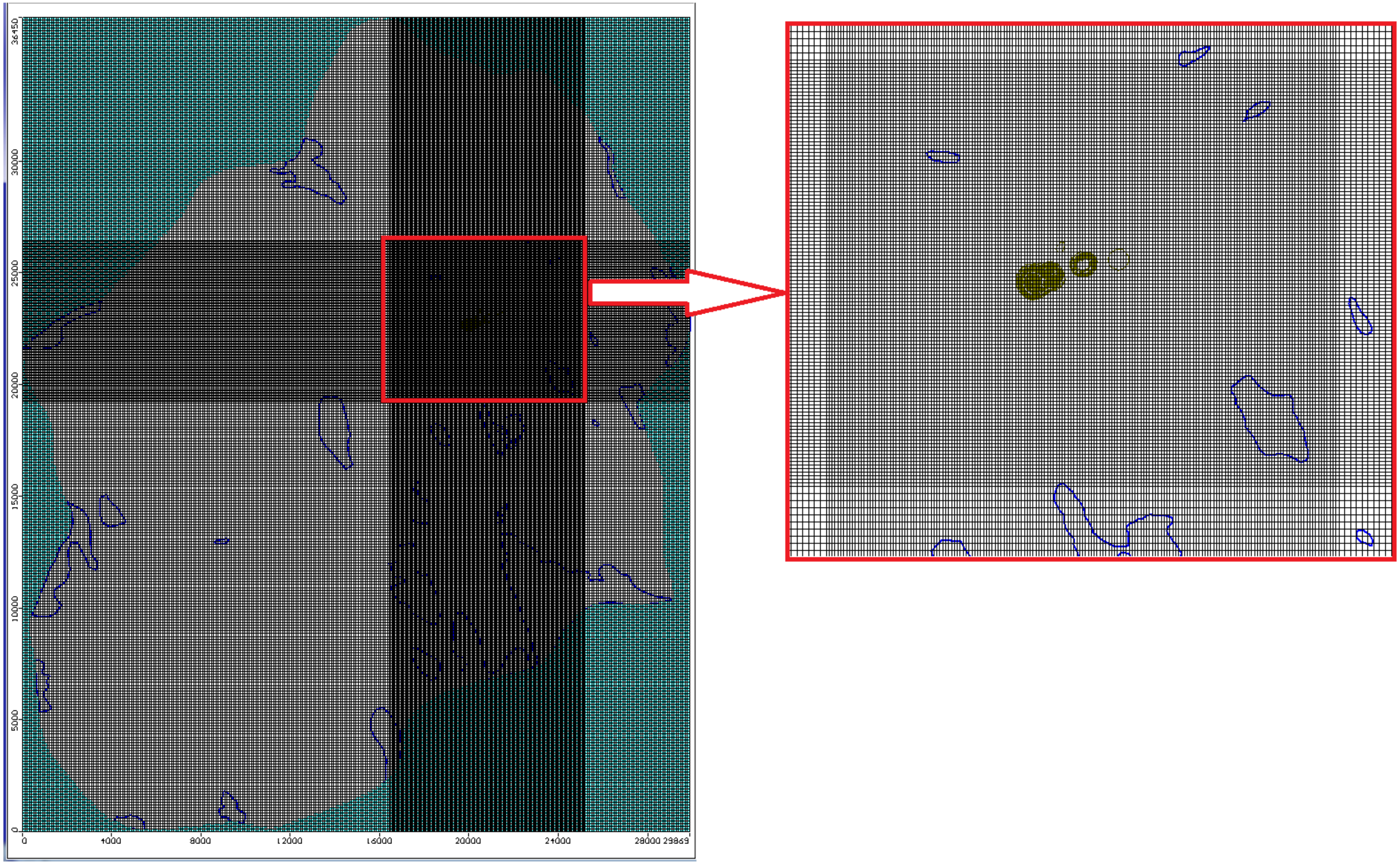

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Figure 3.1-3
MODFLOW Model mesh geometry

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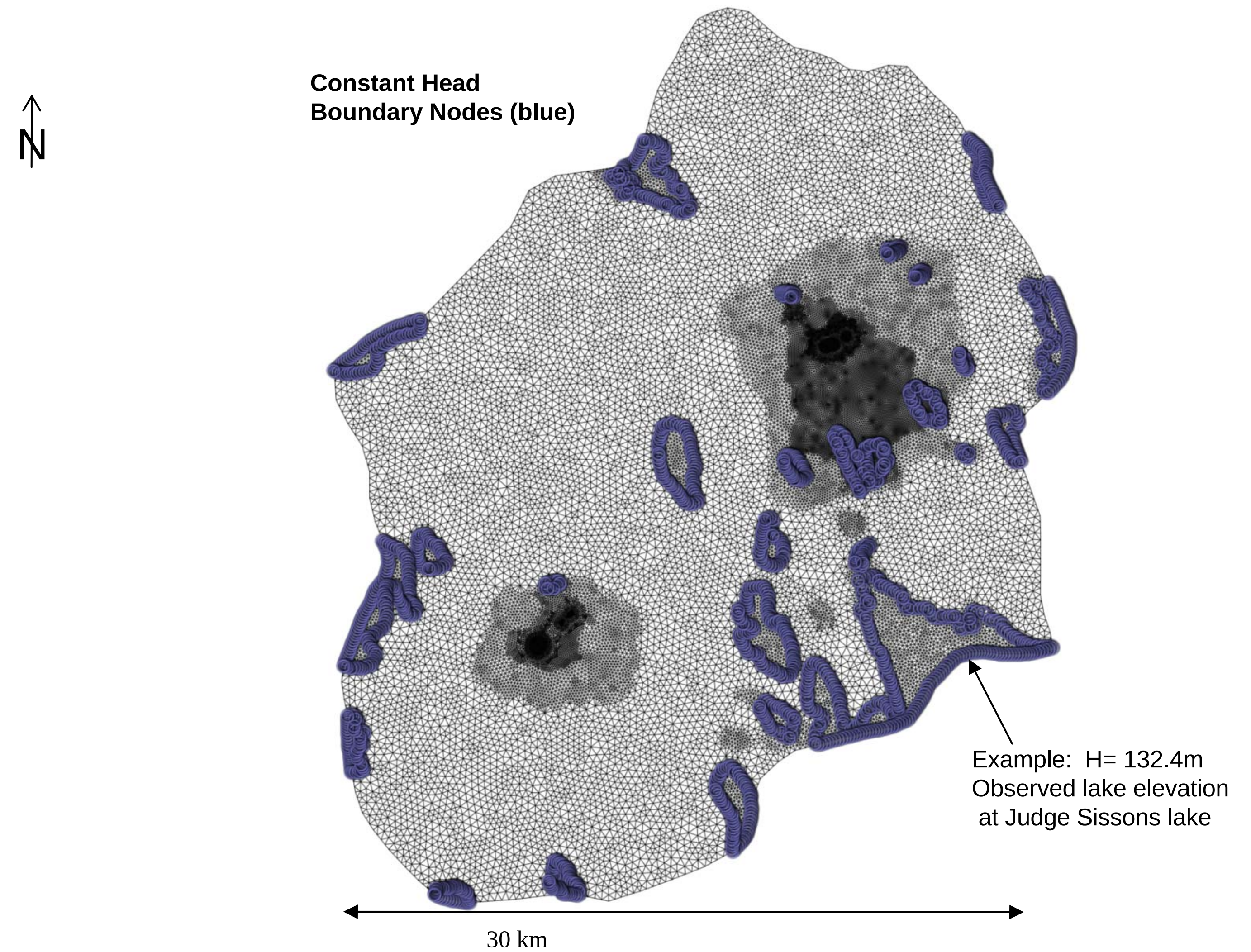

Figure 3.1-4
Boundary conditions in model slice 1

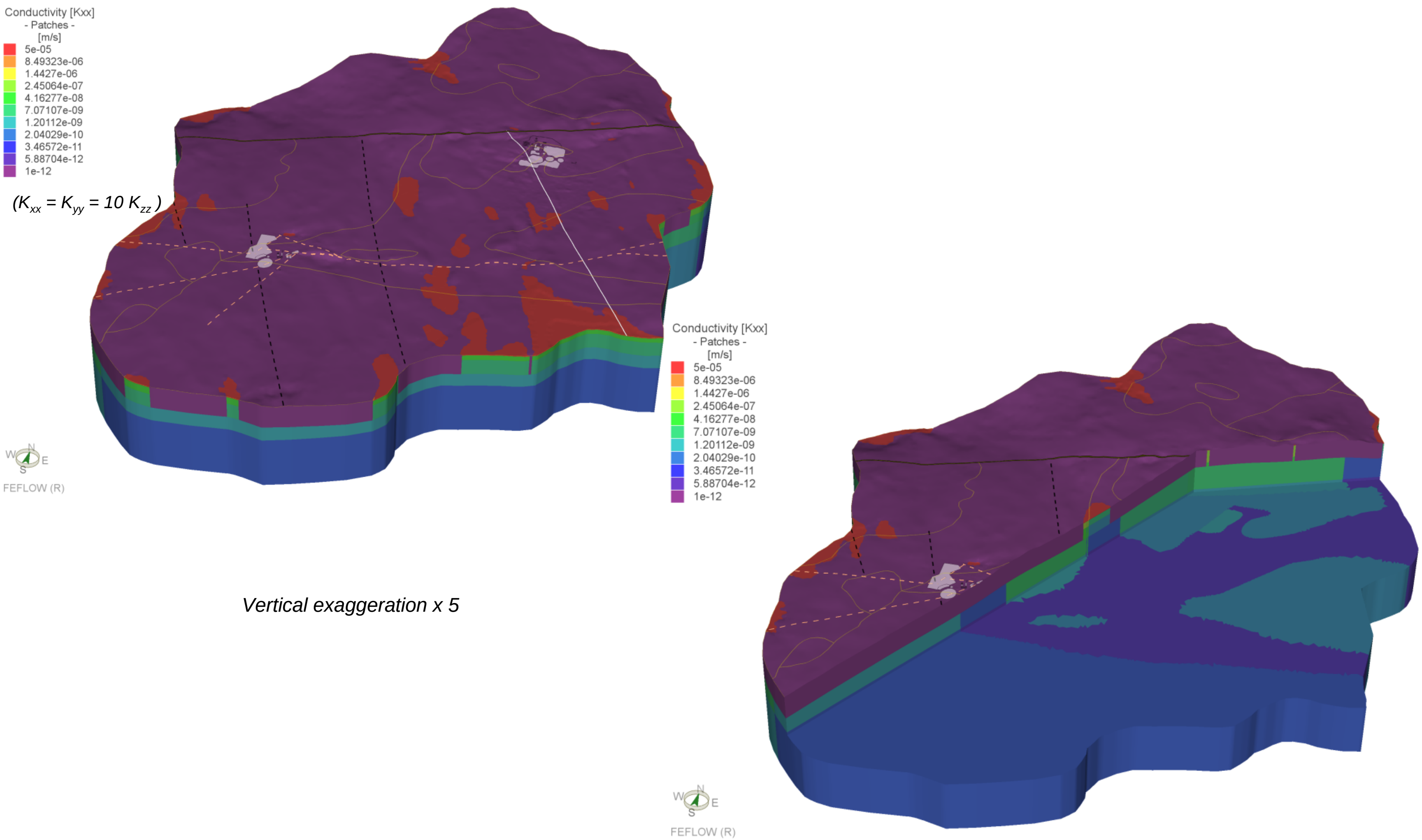

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Figure 3.2-1
3D view of model hydraulic conductivity distribution

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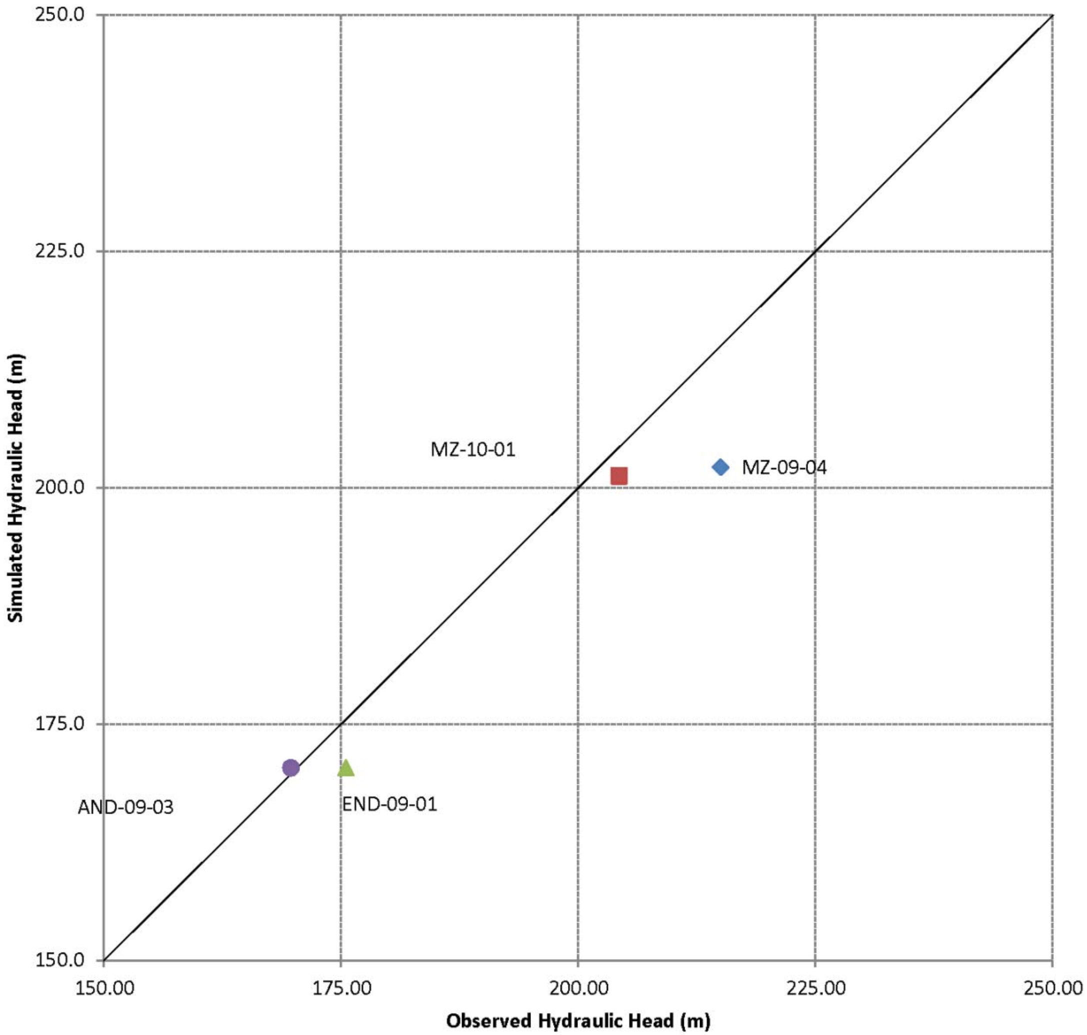

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Figure 3.2-2
Predicted vs Observed Hydraulic Heads

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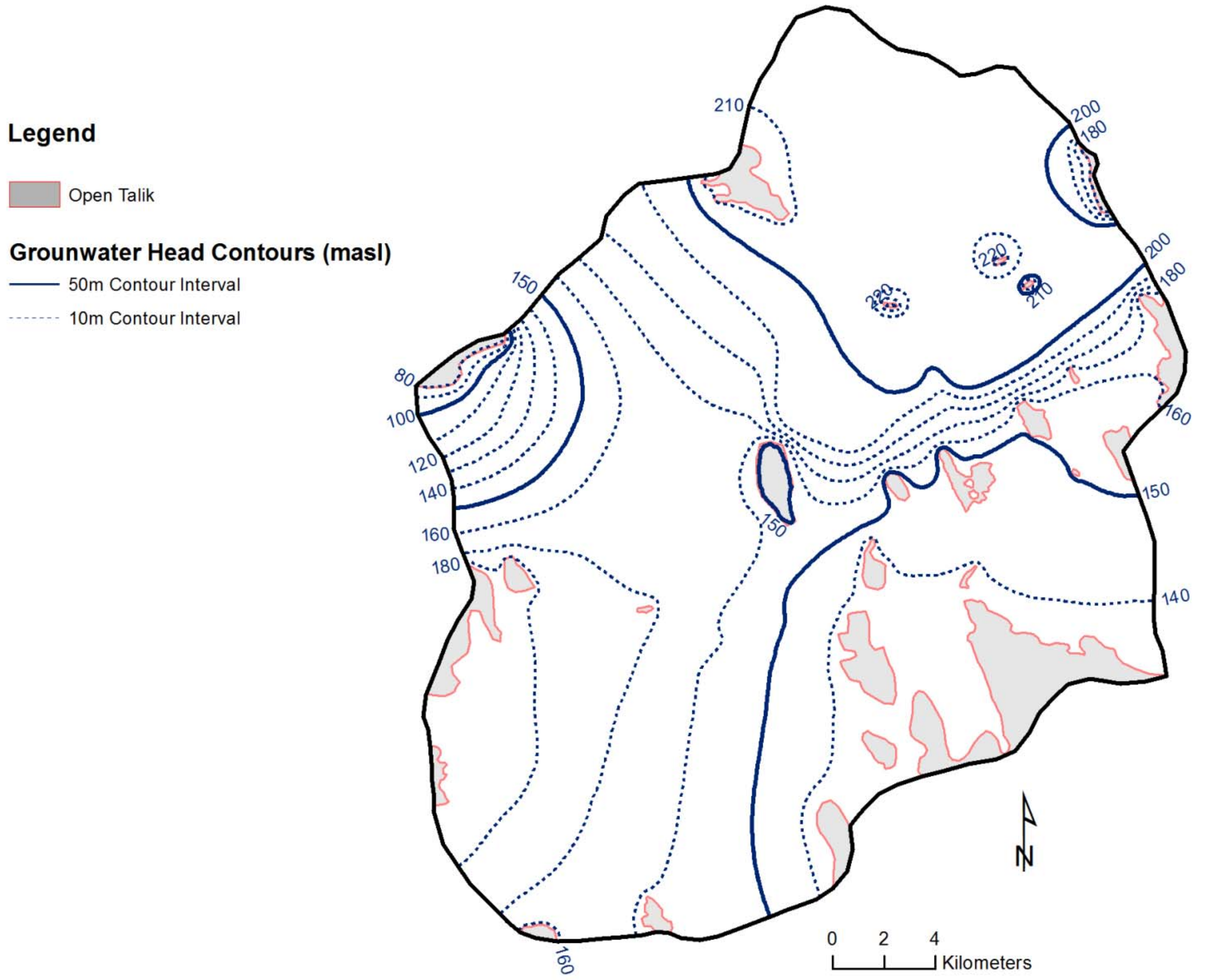

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Figure 3.3-1
Feflow Calibrated steady-state head distribution

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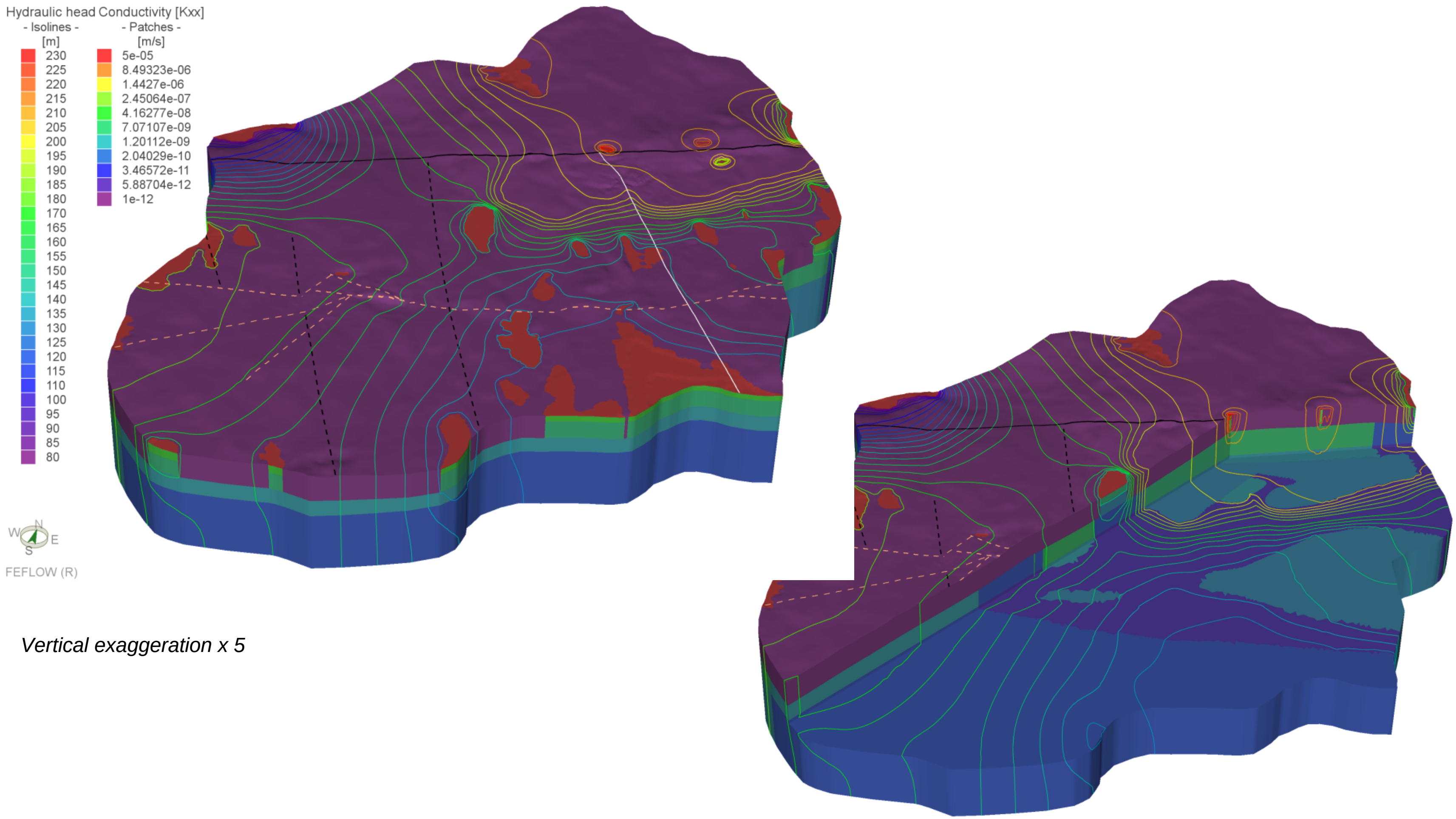

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Figure 3.3-2
3D view of calibrated steady-state head distribution

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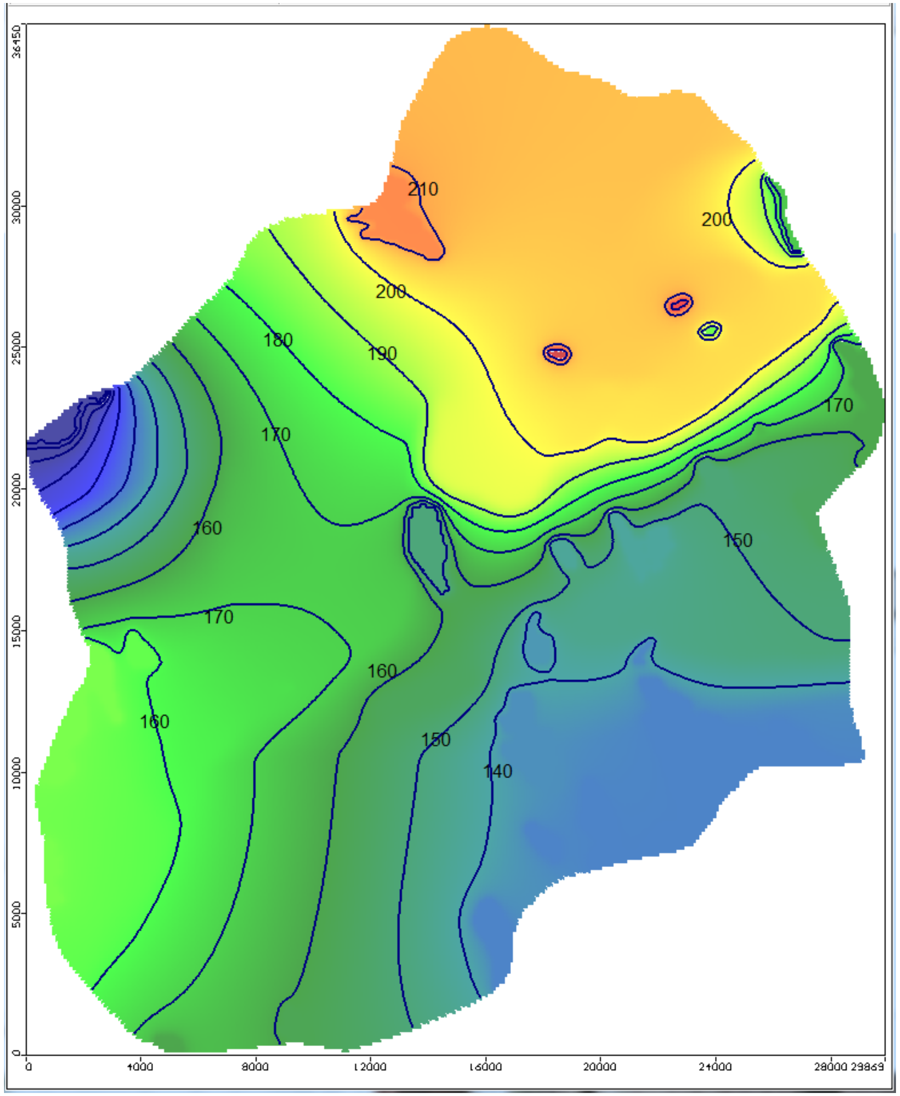

Figure 3.3-3
Modflow Calibrated steady-state head distribution

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-Areas with predicted artesian conditions occurs in blue

-Areas with predicted head below ground surface in green

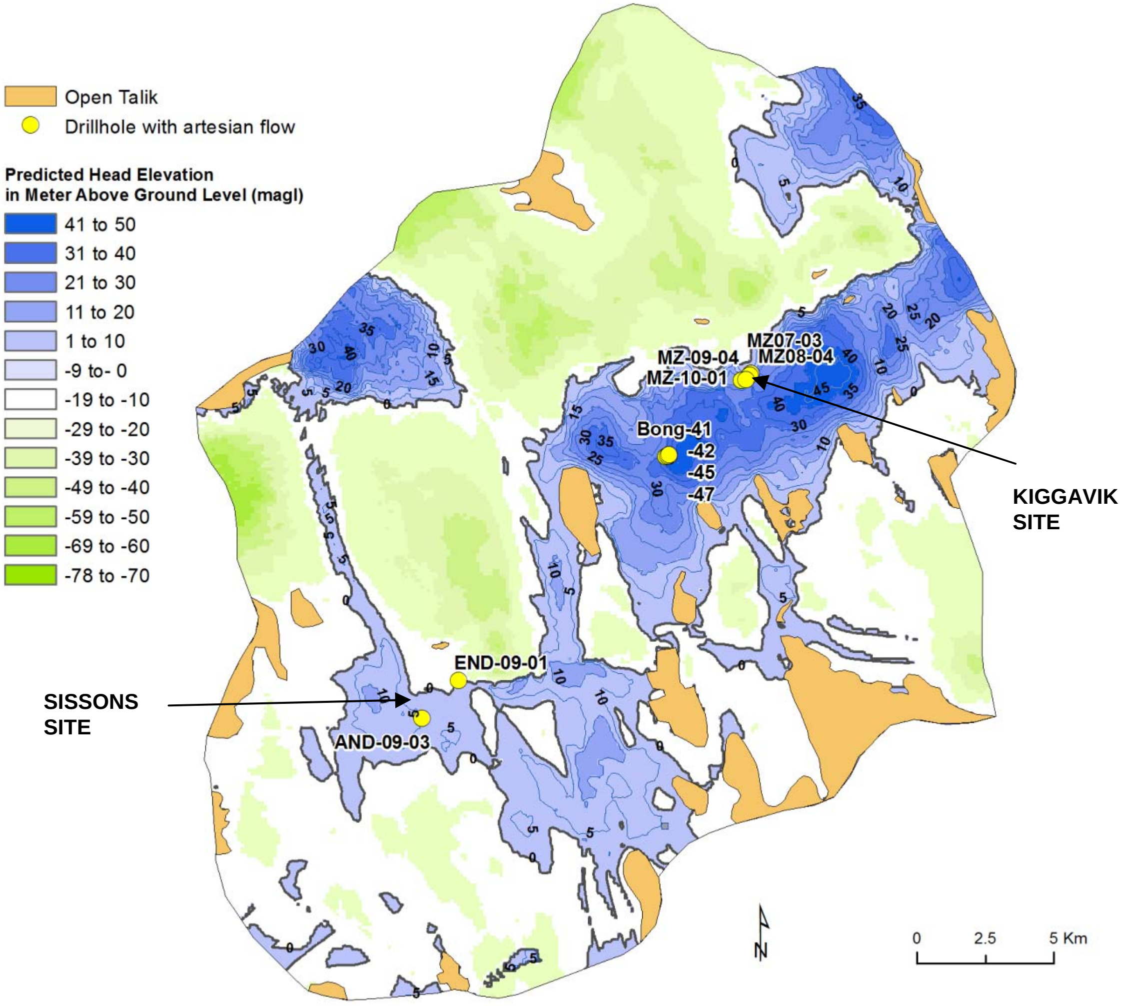

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Figure 3.3-4
Predicted artesian conditions

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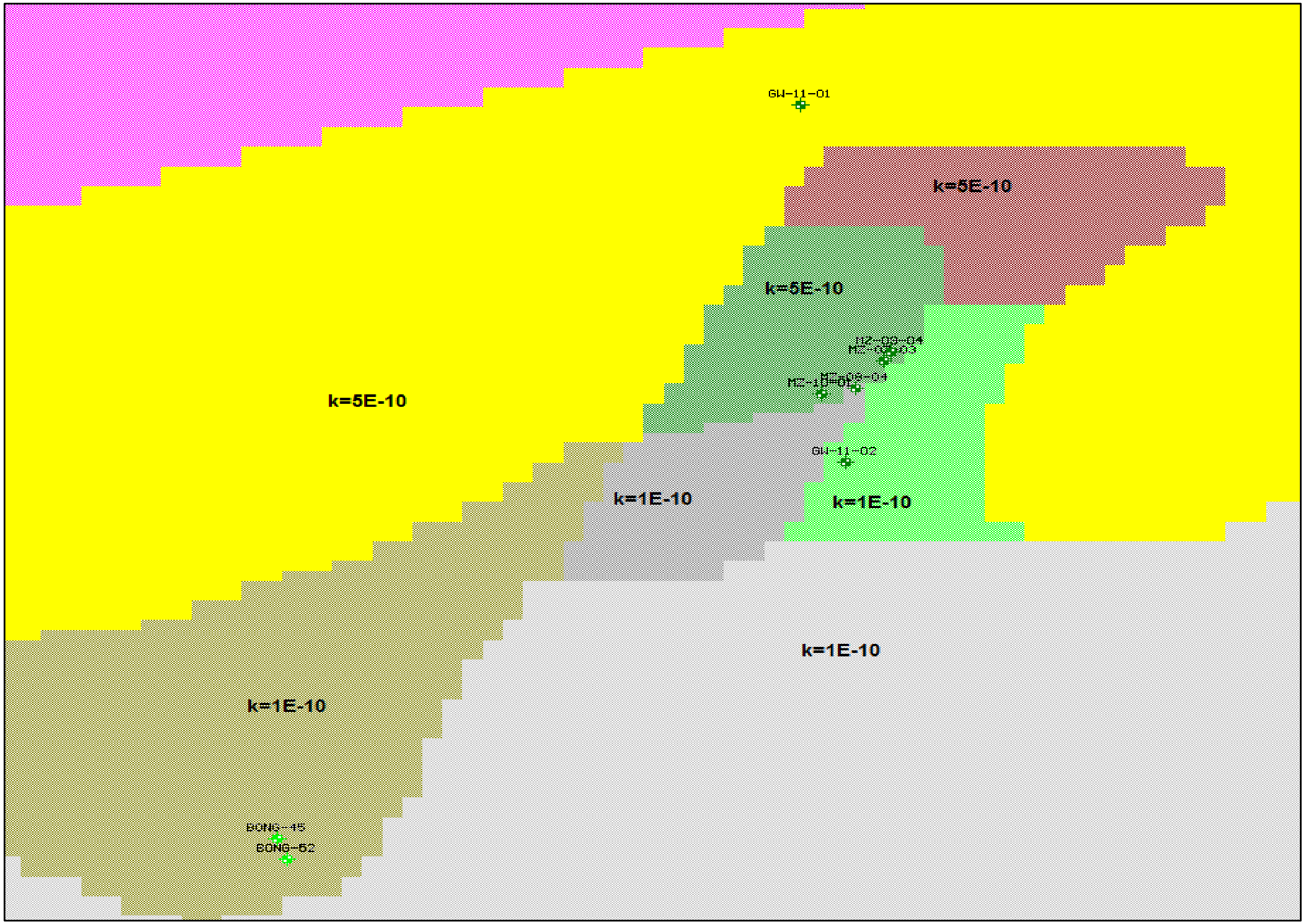

Figure 3.3-5
Additional hydraulic conductivity zones in the Kiggavik area – Modflow Model

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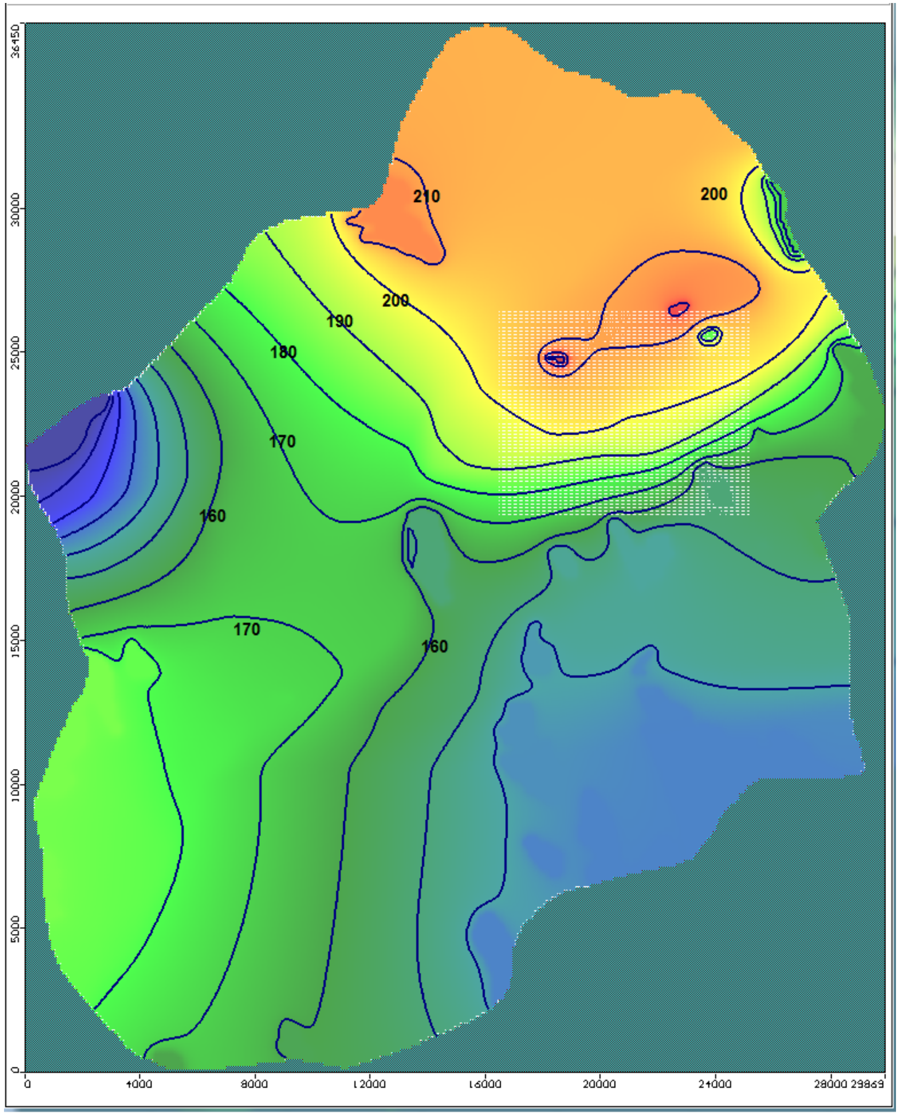

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Figure 3.3-6
Refined pre-mining steady state head distribution – Modflow Model

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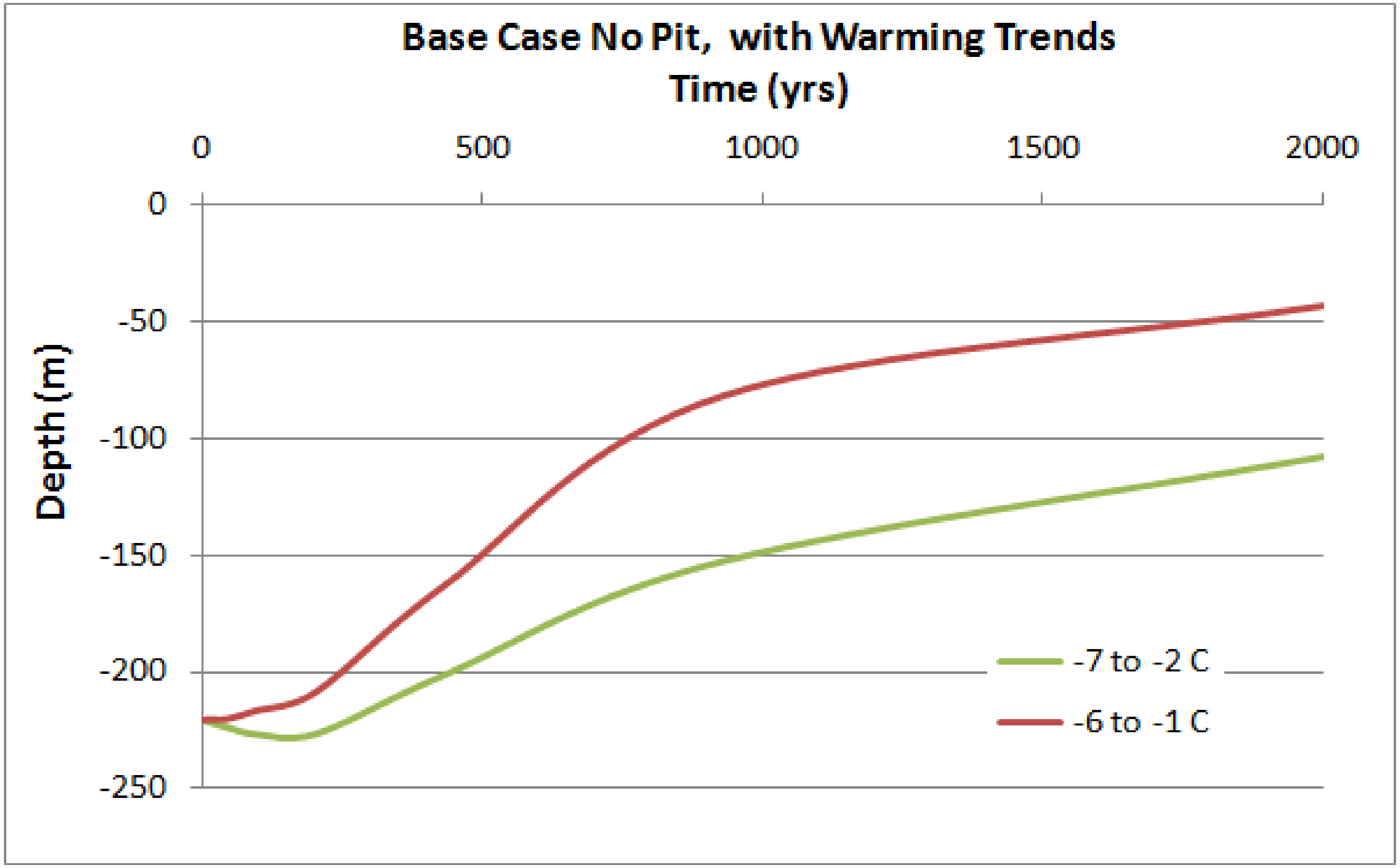

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Figure 4.1-1
Computed change in permafrost depth for two climate change scenarios

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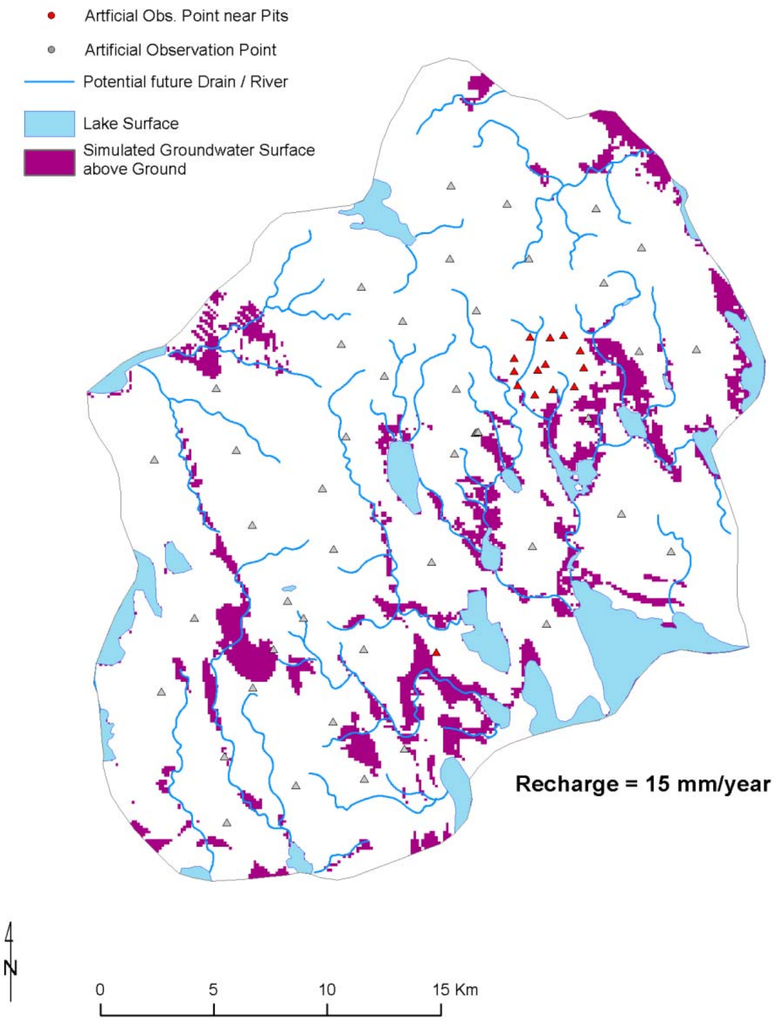

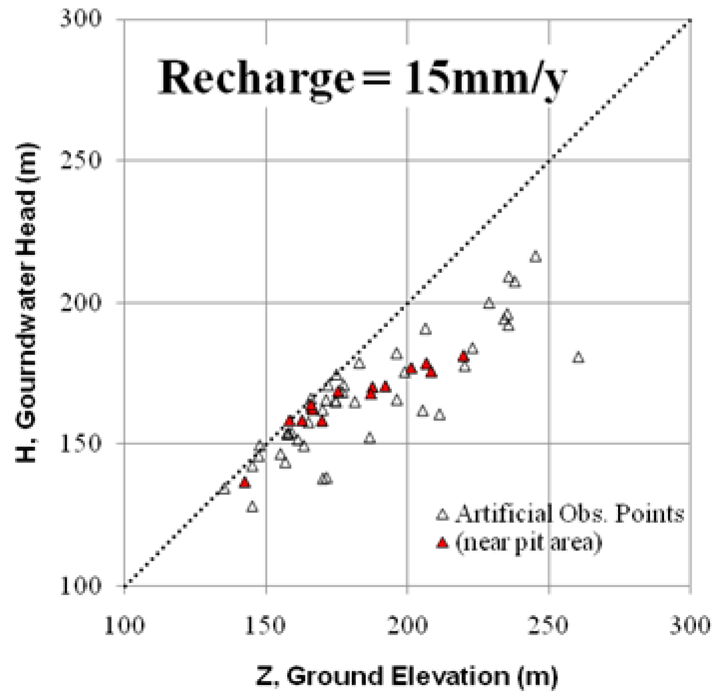

	Nb Obs. Points where H>Z	Correlation Coefficient, r
H [R=1mm/y]	1	0.71
H [R=5mm/y]	1	0.74
H [R=15mm/y]	**3**	**0.77**
H [R=40mm/y]	8	0.80

H, simulated head (m)
R, Recharge (mm/y)

Z, Ground elevation (m)
r, correlation coefficient (1)

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Figure 4.2-1
No-permafrost model – Calibration of maximum recharge rate

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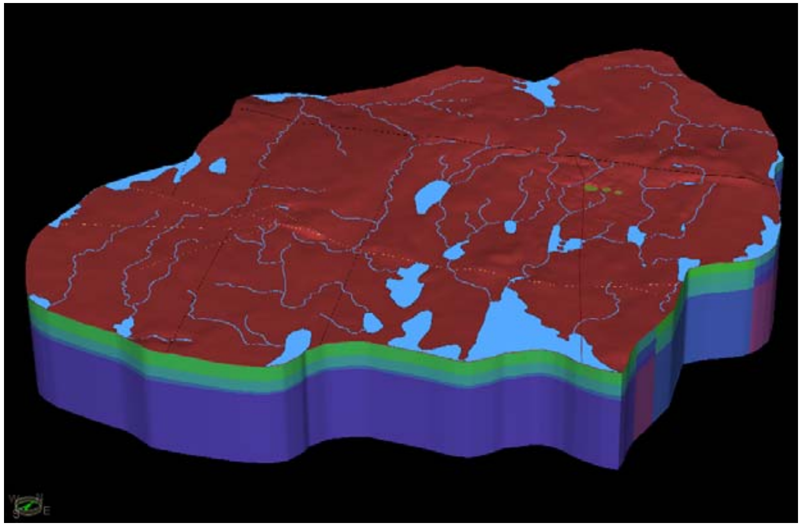

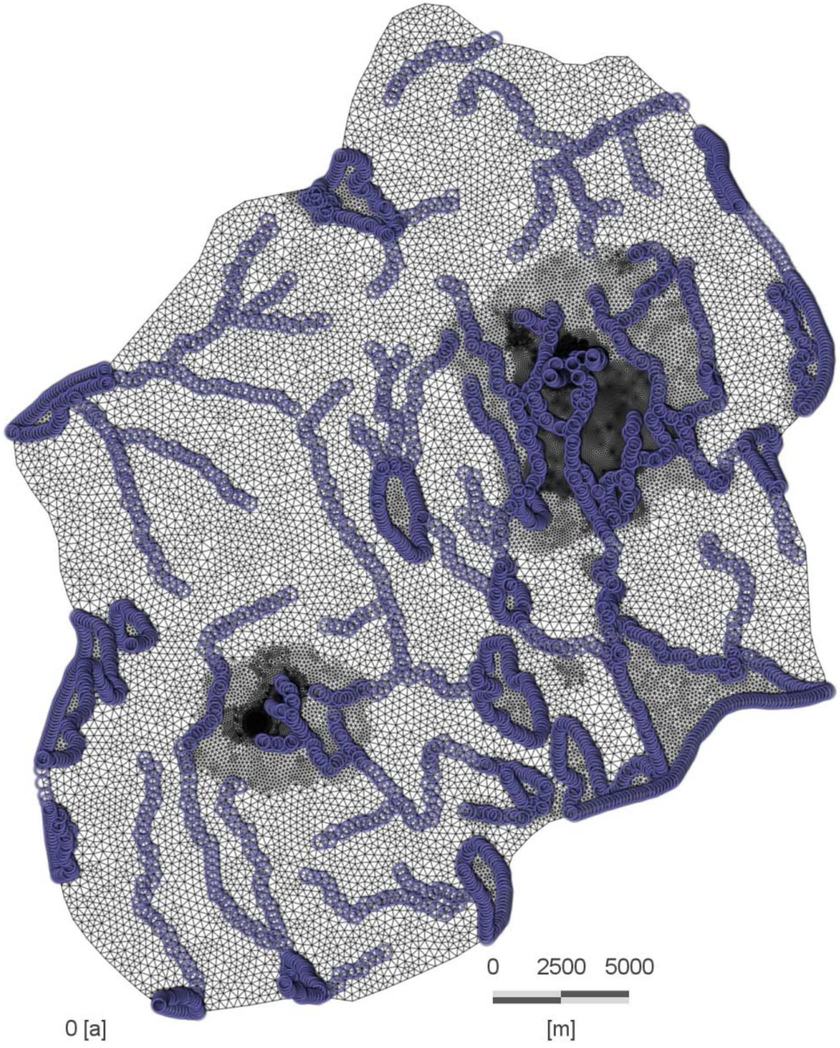

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Figure 4.2-2
No-permafrost model – Lakes and stream channels boundary conditions

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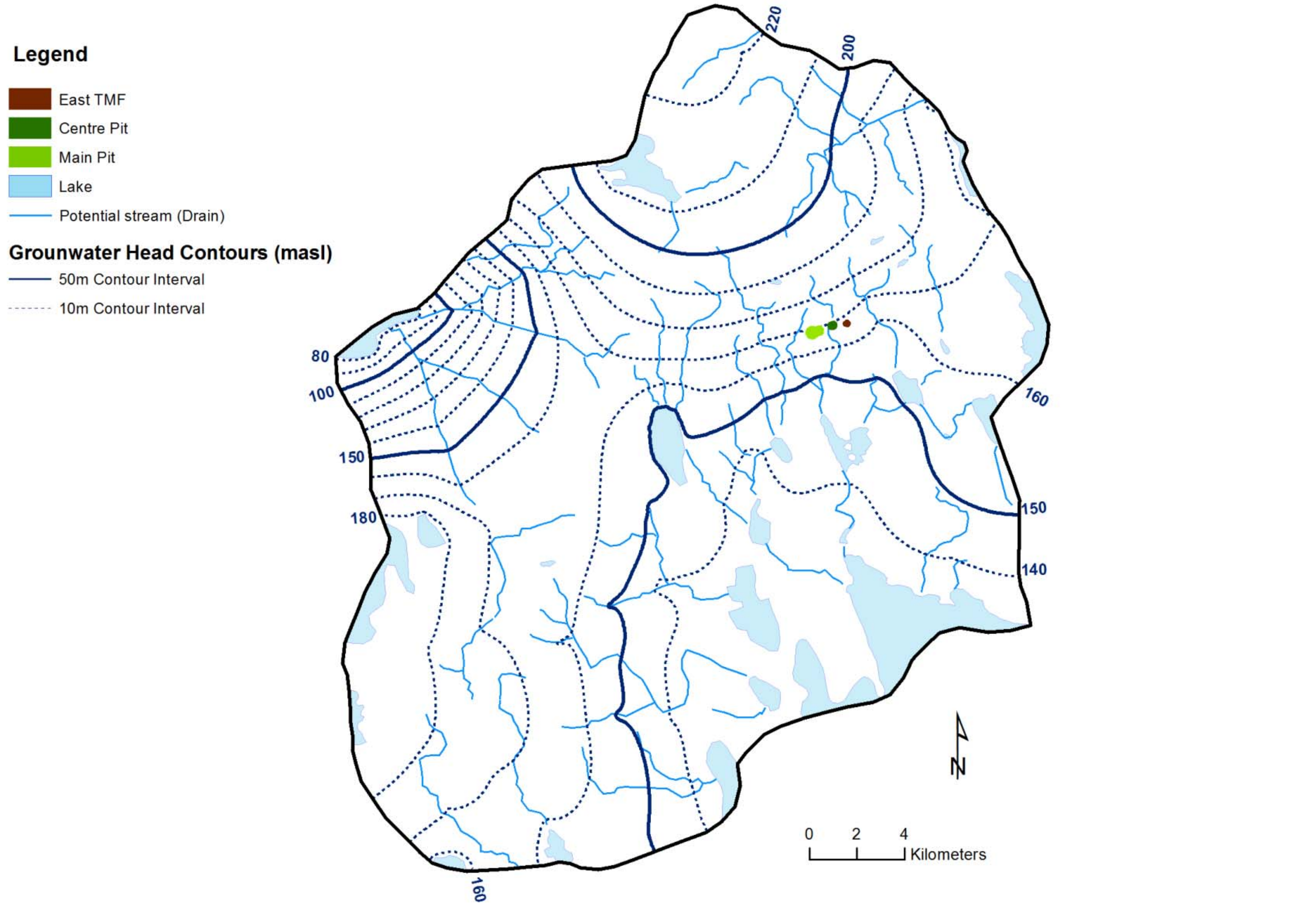

Figure 4.3-1
No-permafrost model – Steady state head distribution (Feflow)

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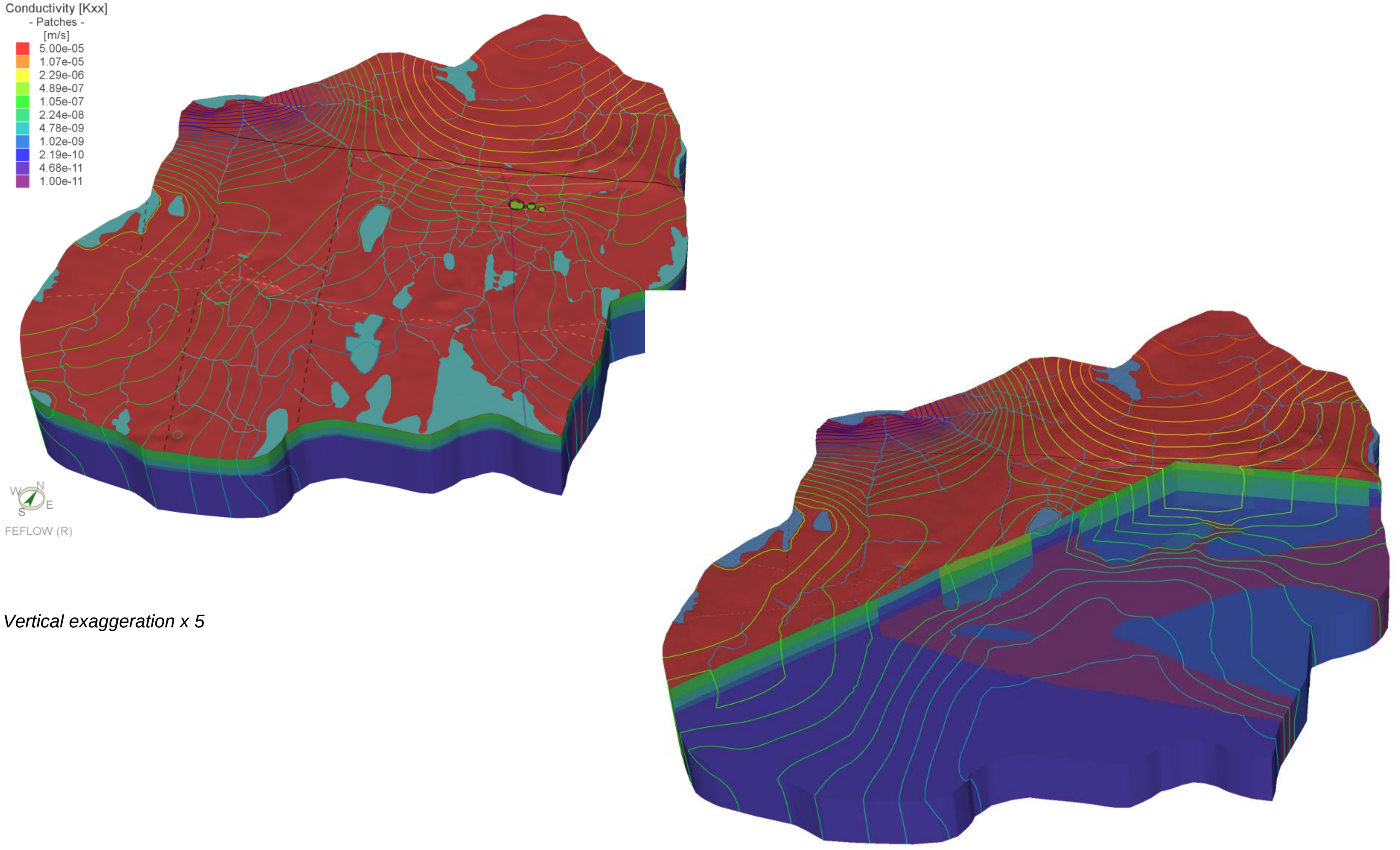

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Figure 4.3-2
No-permafrost model – 3D view of steady state head distribution (Feflow)

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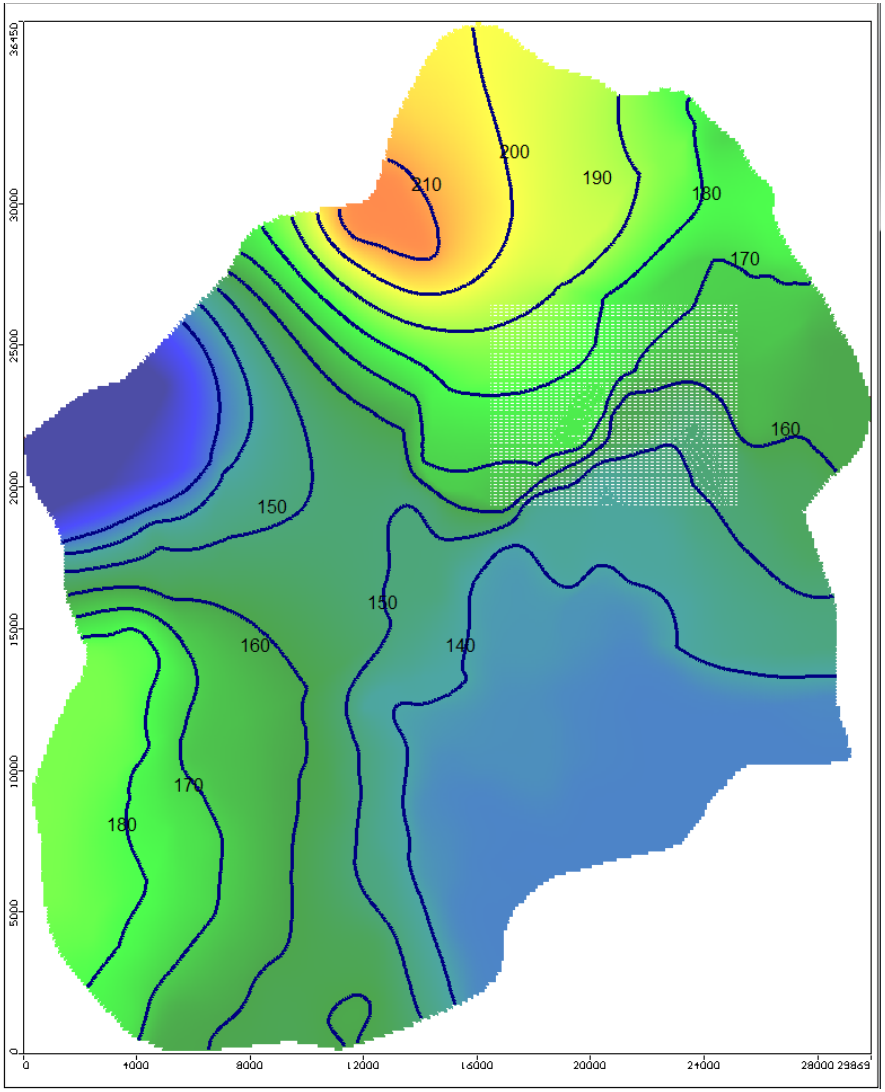

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Figure 4.3-3
No-permafrost model – Steady state head distribution, unconfined model (Modflow)

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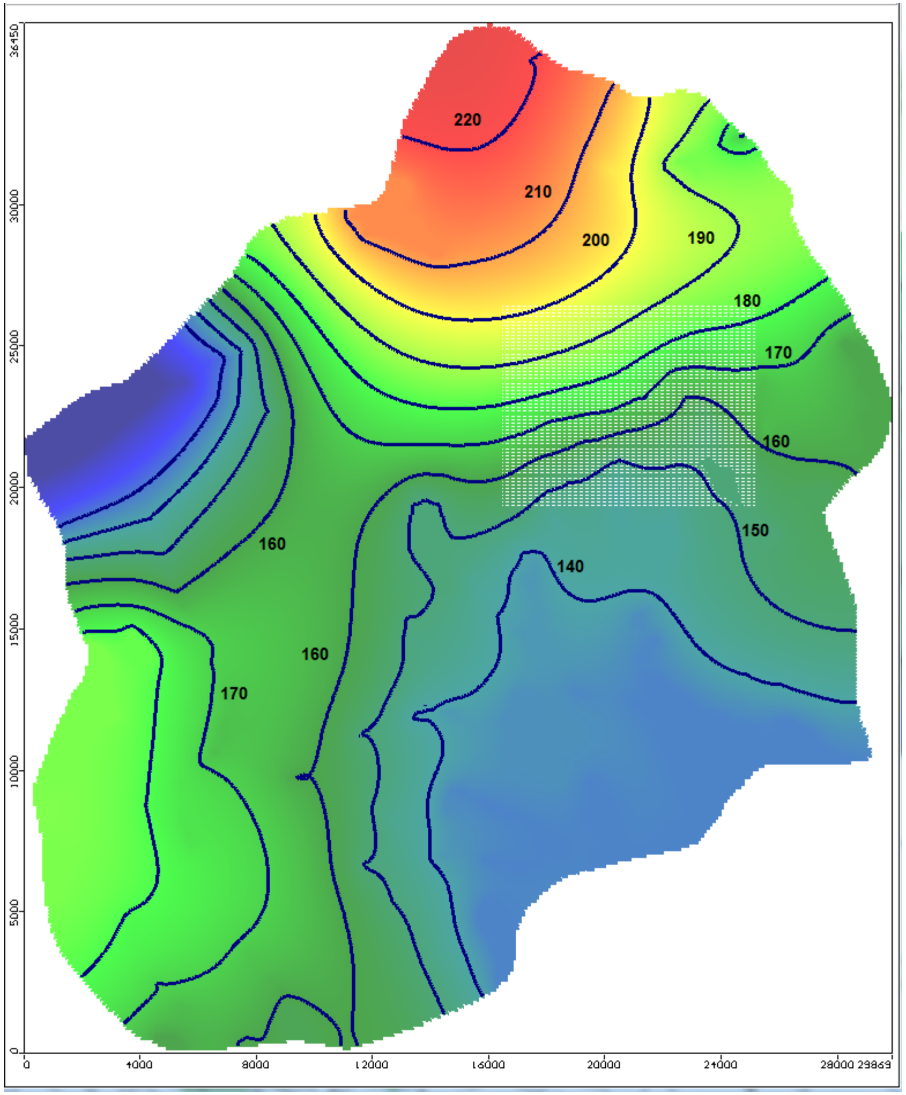

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Figure 4.3-4
No-permafrost model – Steady state head distribution, confined model (Modflow)

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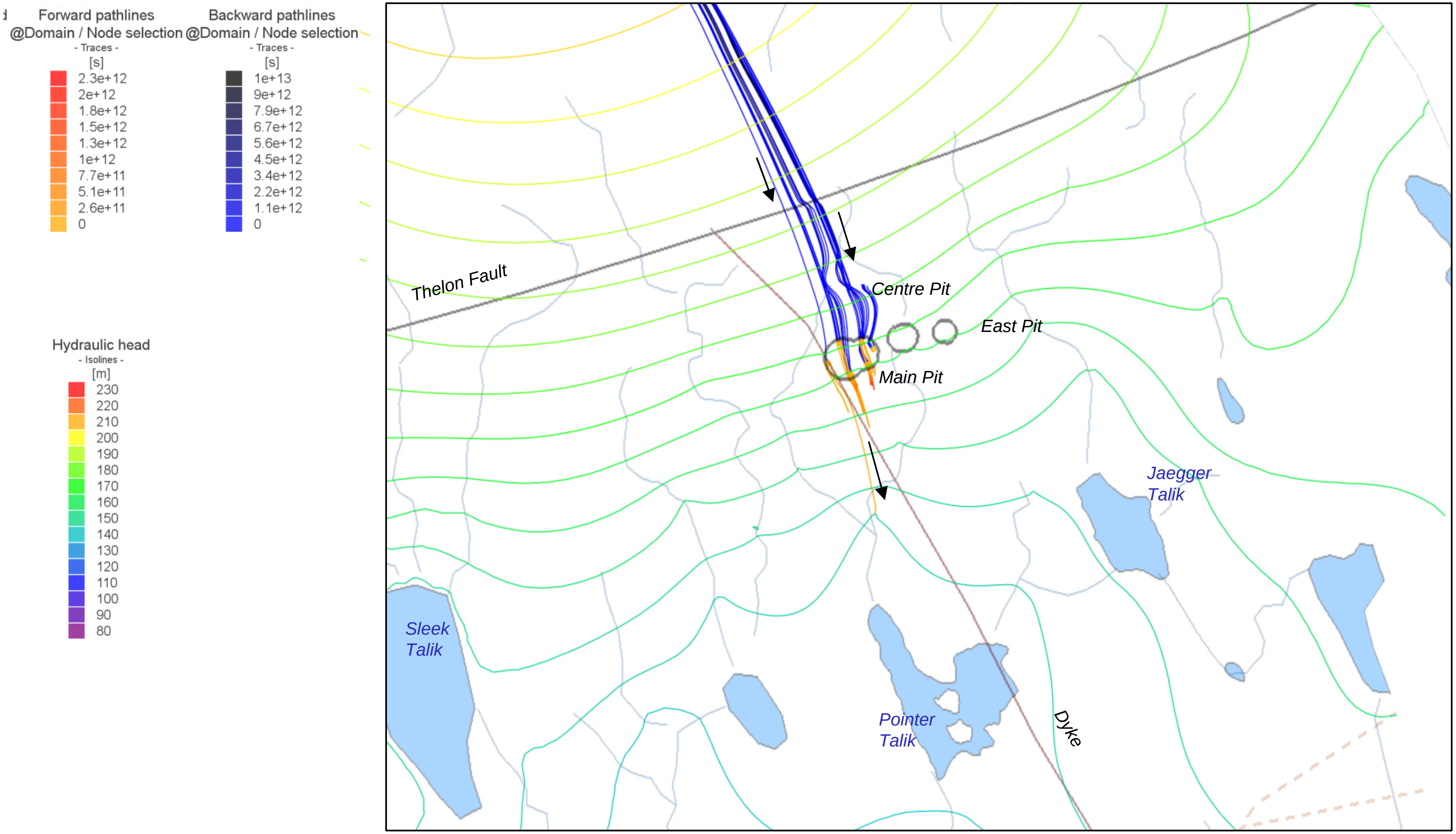

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Figure 4.3-5
No-permafrost model – Particle path analysis from the Kiggavik area (Feflow)

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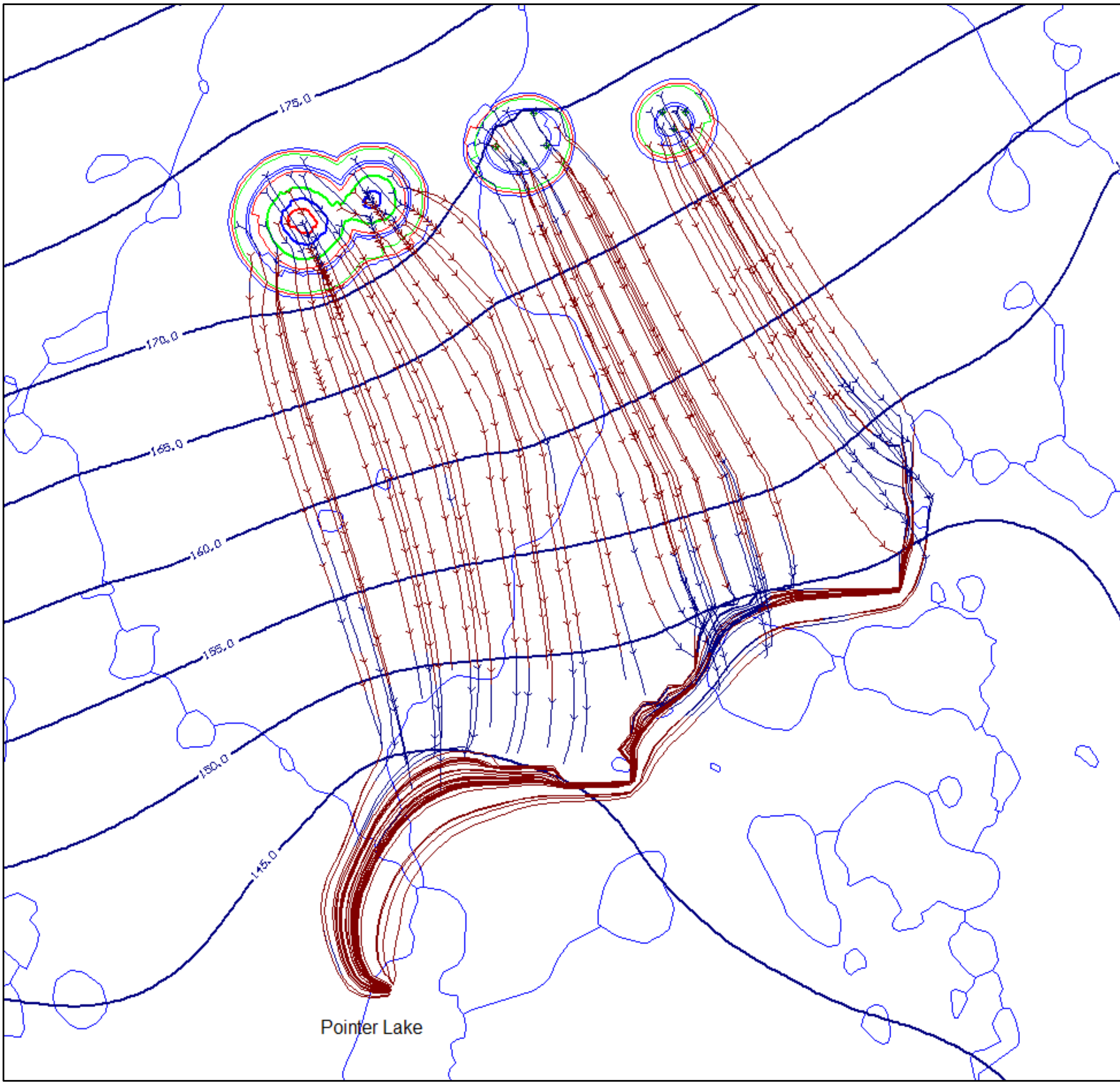

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Figure 4.3-6
Pathlines from tailings for the no permafrost scenario (pathlines for 1000 years, ticks every 100 years)

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Attachment A

Evaluation of Talik Below Pointer Lake (SRK memo 1CA015.006, April 19, 2010)

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Vancouver, B.C. V6E 3X2
Canada

vancouver@srk.com
www.srk.com

Tel: 604.681.4196
Fax: 604.687.5532

Memo

To:	File	**Date:**	April 19, 2010
cc:		**From:**	Michel Noël
Subject:	AREVA Kiggavik-Sissons Project: Evaluation of talik below Pointer Lake	**Project #:**	1CA015.006

1 INTRODUCTION

This memo presents the results of the thermal modelling that was performed to demonstrate the presence of a talik below Pointer Lake, as part of Areva's Kiggavik-Sissons Project, near Baker Lake, in Nunavut. Pointer Lake is within 2.5 km of the Main and Centre pits. The purpose of this document is to act as a technical reference for the Environmental Assessment (EA).

2 Model

Thermal modelling was carried out using the finite element model SVHEAT version 6 developed by SoilVision Systems Ltd. and FlexPDE version 6.12 developed by PDE Solutions Inc.

SVHEAT models heat transport for both steady-state and time-dependent analyses using the FlexPDE solver. It incorporates the latent heat associated with phase changes of water. The model can support geometries in 2D or 3D. SVHEAT supports multiple boundary conditions as well as transient boundary conditions. Further details are available in the User's Manual of SVHEAT (SoilVision Systems 2009).

FlexPDE is a general purpose partial differential equation (PDE) solver that is based on the finite element method. FlexPDE can solve a multitude of PDE problems in 1D, 2D and 3D spaces. More information is available in the User's Manual of FlexPDE (PDE Solutions 2010).

3 Setup

The thermal modelling was performed in steady state mode given the time scales involved with the formation of taliks under lakes. A simplified two dimensional section was used to represent the surrounding ground and Pointer Lake.

The dimensions of Pointer Lake are based on a review of the bathymetry and the minimum water column that would always remain unfrozen throughout the years. The minimum water depth was set to 1.5 m as reported by Andersland & Ladanyi (2004). The bathymetry shown in Figure 1 was provided by AREVA on February 8, 2010. Figure 2 also shows the bathymetry but is delimited by a water depth greater than 1.5 m. The water depth normal to the shoreline is wider than 200 m for most of the lake, with the exception of a small section along the southern end of the lake, where it is about 100 m. The model simulated Pointer Lake using those two widths by specifying half-widths of 50 and 100 m as the model was considered symmetrical along the middle of the lake.

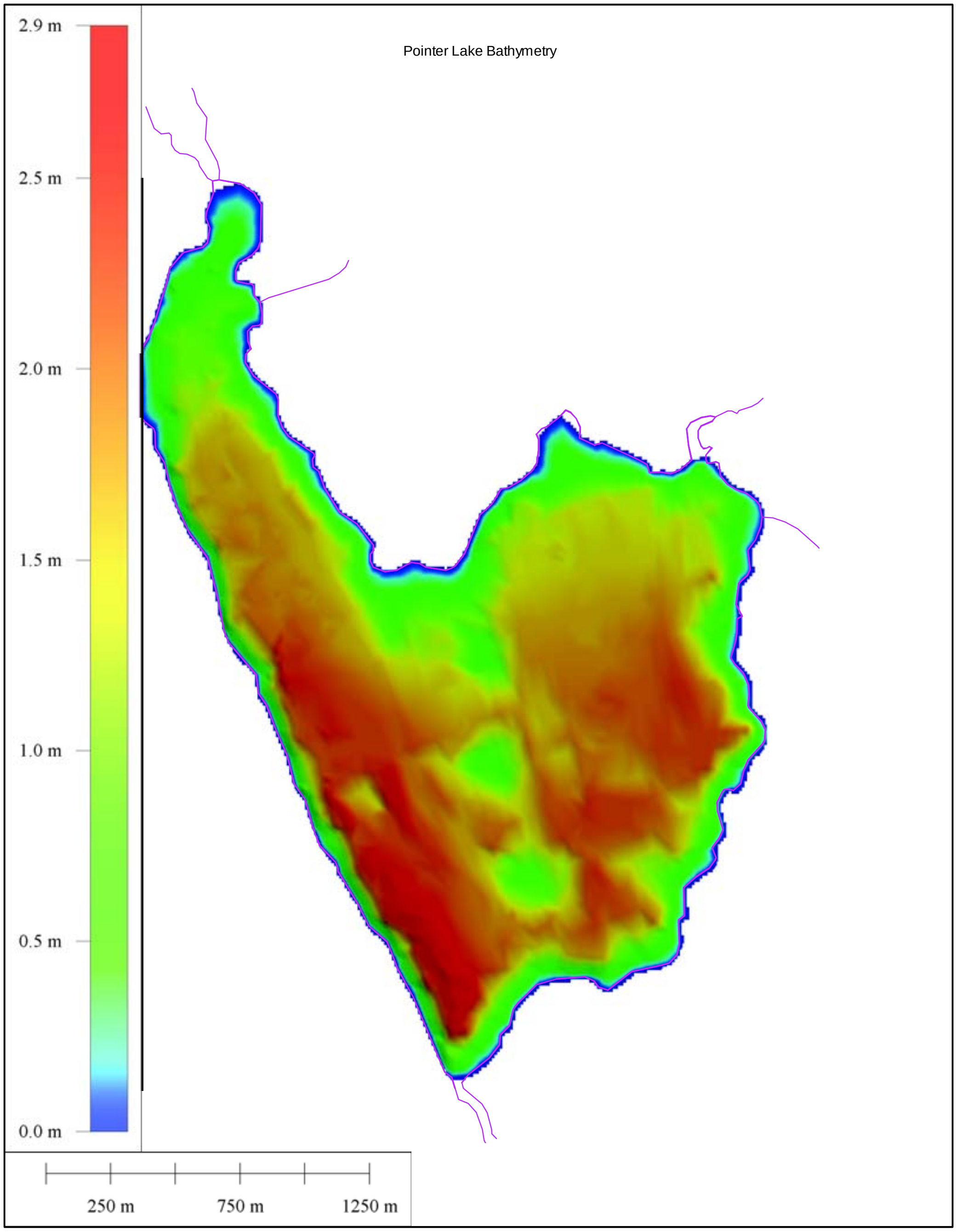

Figure 1: Pointer Lake bathymetry

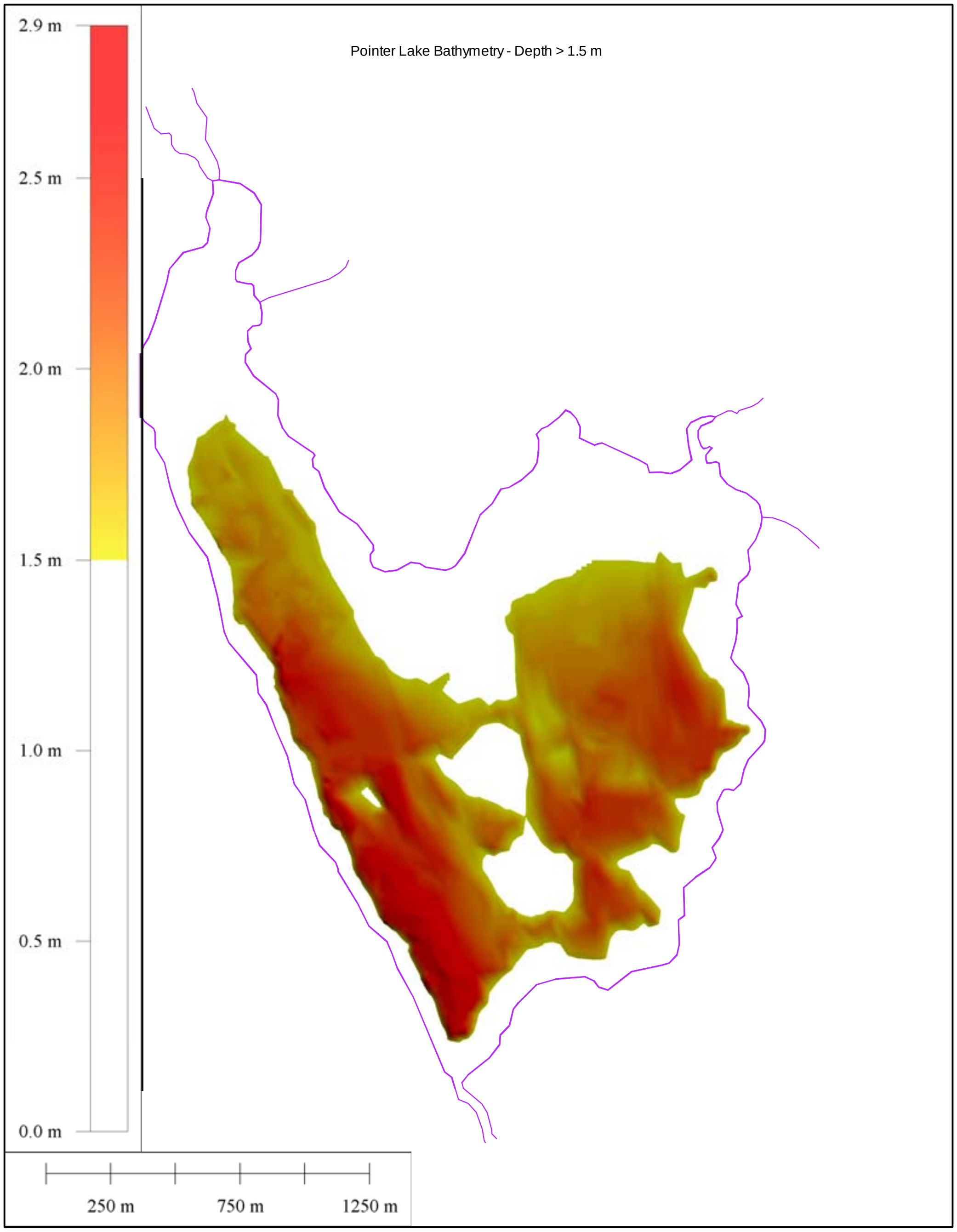

Figure 2: Pointer Lake bathymetry delimited by water depth of 1.5 m.

The ground was assigned the properties of granite that were used in SRK (2008). The bedrock was assigned a thermal conductivity of 215 kJ day^{-1} m^{-1} $°C^{-1}$. The porosity was set to 0.01 and the material was considered saturated. The volumetric heat capacity was set to 1960 (frozen) and 1980 (unfrozen) kJ m^{-3} $°C^{-1}$.

The geometry was defined as a rectangle 500 m deep and 2000m wide. The top horizontal boundary was defined as two segments to represent the lake footprint and the ground surface. The segment for the lake was either 50 or 100 m wide and the ground surface covered the remaining portion of the top boundary.

The boundary condition for the ground surface was set to a constant temperature of -7 °C, equivalent to a mean annual surface temperature (MAST). The temperature of the lake portion was approximated by assuming that the lake water would follow the ambient air temperature but would remain above a set minimum temperature. The ambient air temperature was approximated with a sinusoidal function that was based on mean annual ambient temperatures (MAAT) of -12 and -7 °C. The warmer MAAT is to represent the occurrence of warming from climate change. An amplitude of 25 °C was used for all cases. The minimum temperature of the lake bottom was set to 1 or 4 °C. The calculated mean annual lake bottom temperature (MALBT) ranged from 3.6 °C and 7.2 °C as indicated in Figure 3 below. The MALBT values were applied to the boundary segment that represented the footprint of the lake.

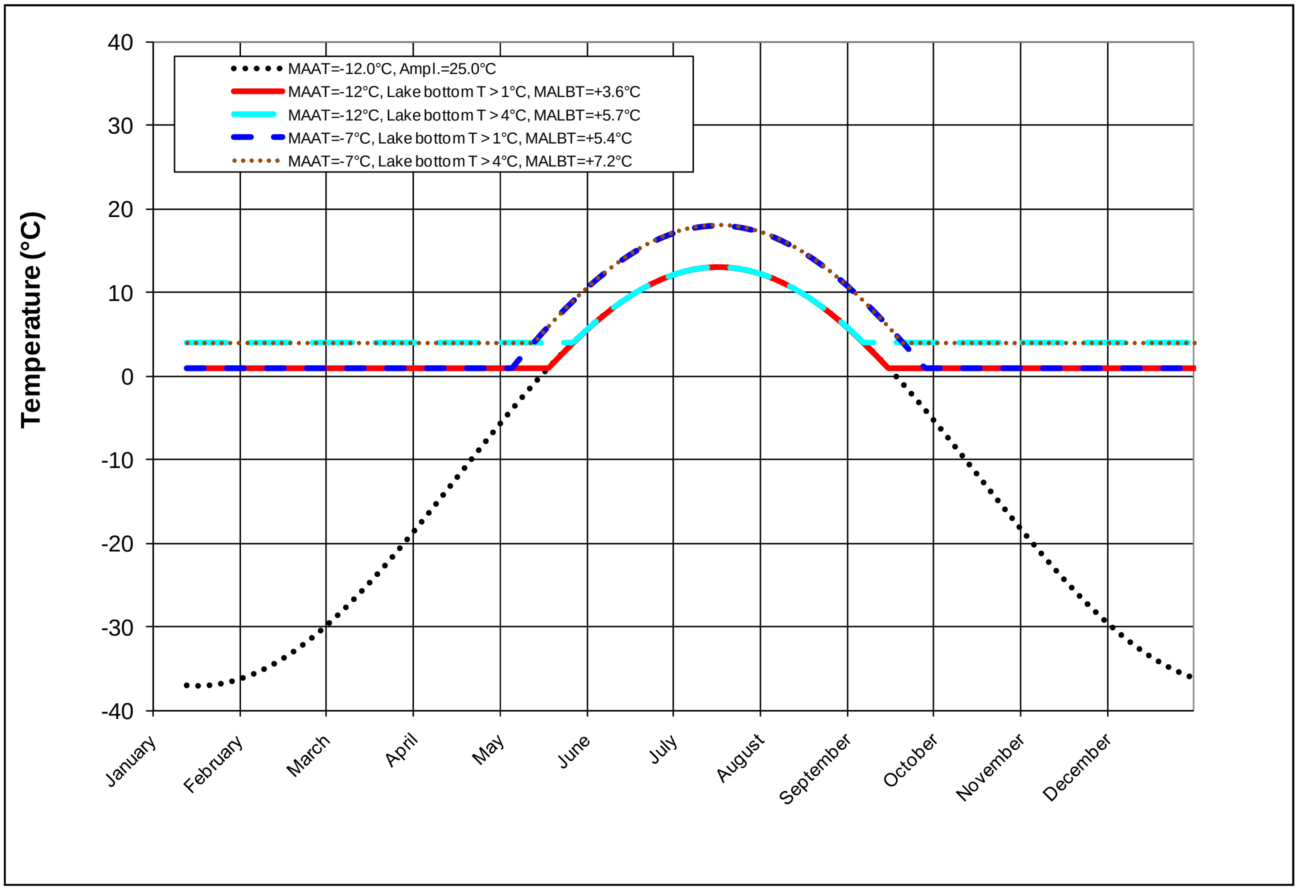

Figure 3: Estimated MALBT based on MAAT and assumed minimum lake bottom temperatures.

The bottom boundary was set to a constant heat flux of 7176 Joules day^{-1} m^{-2} which is dependent on the thermal conductivity of the bedrock and the site geothermal gradient based on a MAST of -7 °C and a permafrost depth of 210 m. The boundary conditions on both vertical sides were set as no flux boundaries, thus equivalent to having two axis of symmetry on the sides. The domain and the specified boundary conditions are shown in Figure 4.

4 Results and Discussion

The results are summarised in Figures 4 and 5 below. Figure 4 shows the contours obtained over the entire domain for the case where the MALBT was assigned a value of 5.4 °C based on a MAAT of -7 °C and a minimum lake temperature of 1 °C. The opened talik below Pointer Lake is visible and the 0 °C isotherm is consistent the specified permafrost depth of 210 m.

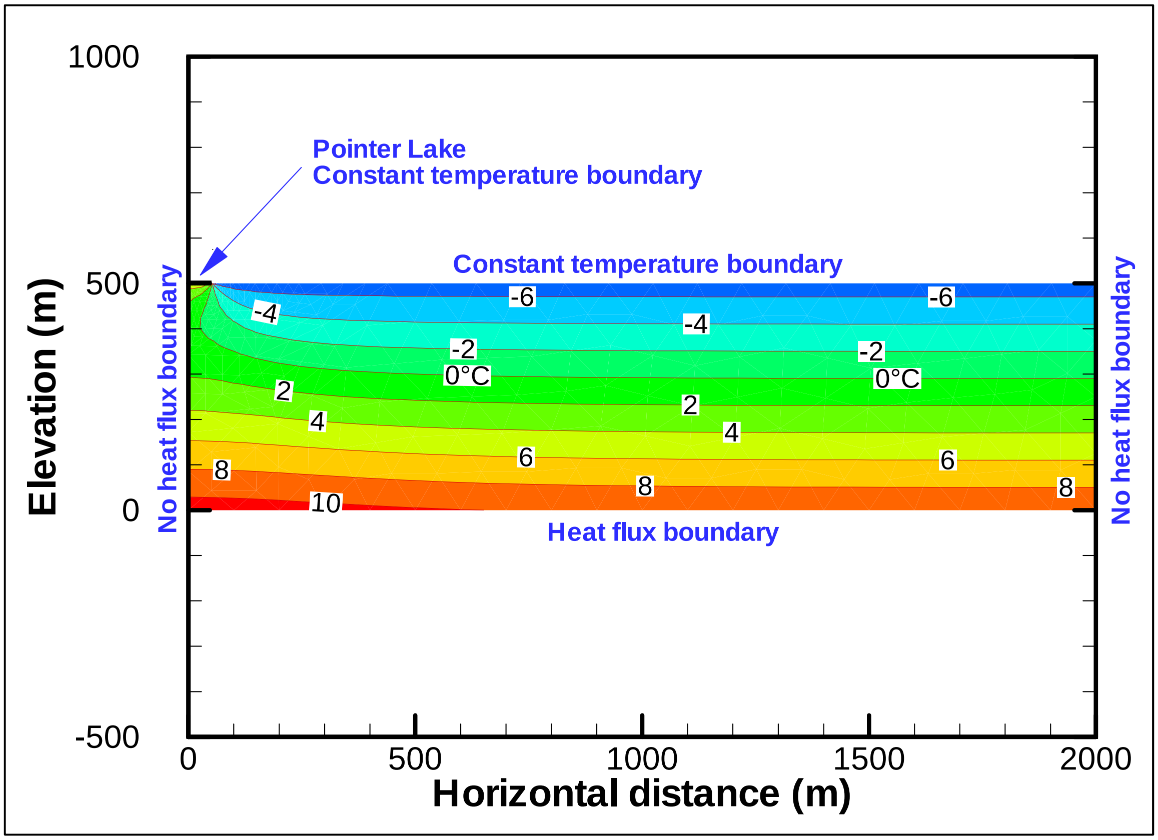

Figure 4: Specified boundary conditions and ground temperature contours with a MALBT of 5.4 °C (MAAT=-7°C and minimum lake temperature of 1 °C).

Figure 5 shows the locations of the 0 °C isotherm in the vicinity of Pointer Lake for the various MALBT values. The results show that an opened talik will be present if the MALBT is greater than about 4 °C for lake sections that are larger than 100 m (twice the modelled width as only one half was modelled). The coldest MALBT resulted in a closed talik with a very thin permafrost zone in the middle of the lake. The other cases all resulted in having opened taliks below the lake.

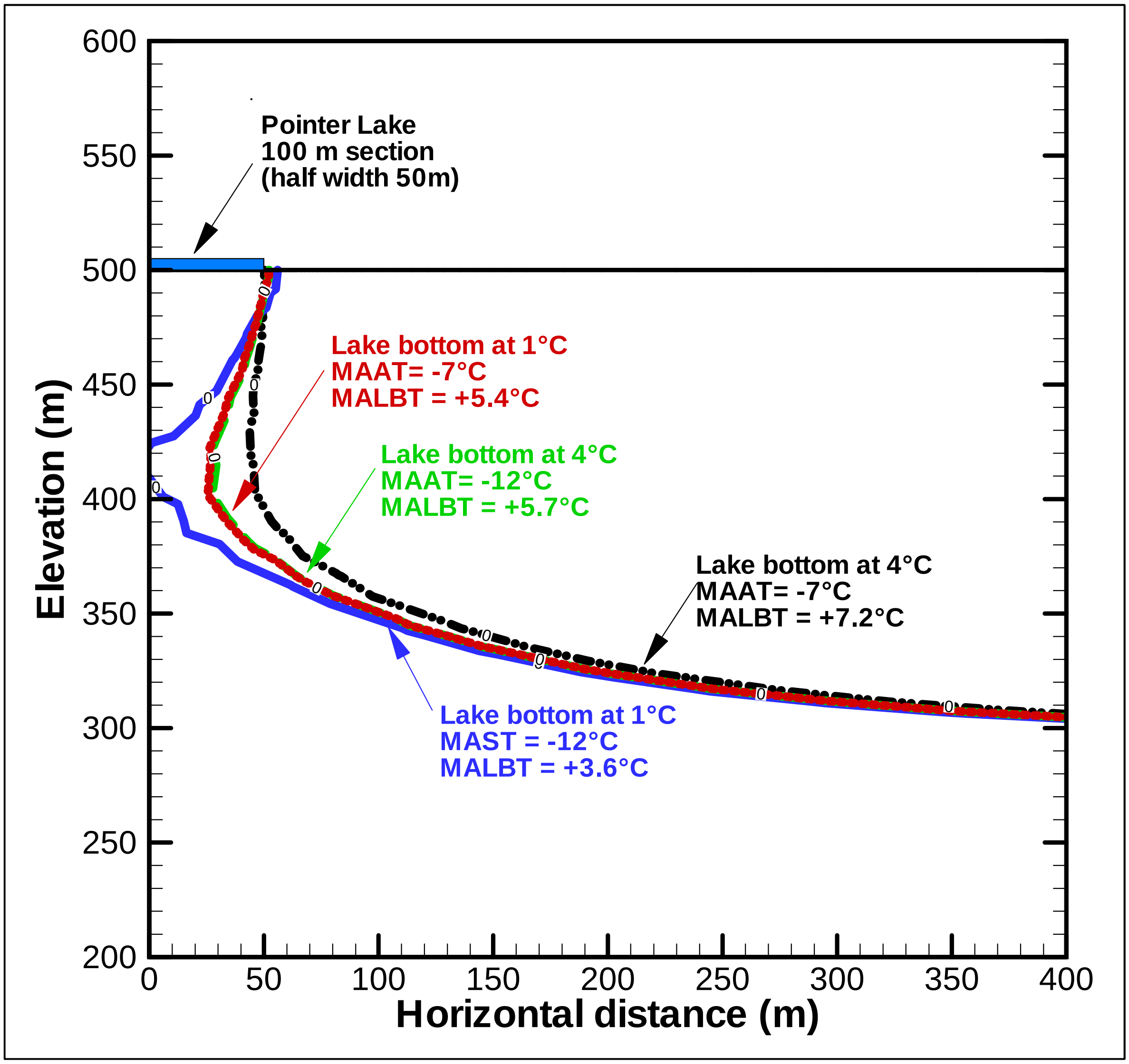

Figure 5: Location of 0 °C isotherm for various MALBT values

5 Discussion and Conclusion

The bathymetry of Pointer Lake shows that a water column greater than 1.5 m is present over about 50 percent of the lake total footprint. The bathymetry also shows that the width of water column deeper than 1.5 m is usually 200 m or more. Only a small portion over the south end of the lake is narrower, with a width of about 100 m. The thermal modelling suggests that the minimum width for having an opened talik is about 100 m (50 m half-width).

Given the geometry of Pointer Lake, the site climate, and assuming that the conditions modelled are reasonable assumptions, an opened talik will likely be present when the water column is greater than 1.5 m.

6 References

Andersland, O.B. and Ladanyi, B. 2004. Frozen ground engineering, 2nd Edition. Hoboken, NJ: John Wiley & Sons, 2004, 352 pages.

PDE Solutions Inc. 2010. flexPDE 6 User's Manual. USA

SoilVision Systems Ltd. 2009. SVHeat User's Manual. Canada

SRK Consulting (Canada) Inc. 2008. Preliminary Assessment of the Thermal Conditions at the Kiggavik-Sissons sites, Nunavut. Report presented to Areva Resources Canada Inc. June 2008.