Appendix F.5

Hydrogeologic Model Development and Application

Beaver Dam Mine Project - Revised Environmental Impact Statement Marinette, Nova Scotia

Hydrogeologic Modelling Report

Beaver Dam Mine Project
Marinette, Nova Scotia

Atlantic Gold Corporation

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1. Introduction

1.1 Background

GHD Limited (GHD) was retained by Atlantic Gold Corporation (AGC) to develop a three-dimensional (3D) groundwater flow model for the Beaver Dam Mine Site located in Marinette, Halifax County, Nova Scotia (Beaver Dam Mine Site). This Hydrogeologic Modelling Report (Report) presents the development, calibration, and application of the model to evaluate potential impacts of mining operations on the surrounding groundwater and surface water flow regimes. The Beaver Dam Mine Site is located approximately 7 kilometres (km) northeast of Highway 224. Figure 1.1 illustrates the Beaver Dam Mine Site location. The Beaver Dam Mine Site is uninhabited and the closest residences are located approximately 5 km away. The nearest regional centres are the small rural communities of Sheet Harbour and Middle Musquodoboit located approximately 23 km and 40 km away from the Beaver Dam Mine Site, respectively.

Following the discovery of gold at the Beaver Dam Mine Site in 1868, there have been several attempts to develop and mine the area. Initial development was focused on the Austen Shaft, followed by the Mill Shaft area located 1.2 km west of the Austen Shaft. The small Papke Pit approximately 400 metres (m) west of the Austen Shaft was excavated in 1926. Most of the development focused on a belt of quartz veins in greywacke and slates that were approximately 23 m wide and were intersected from the Austen Shaft. A total of 967 ounces of gold production is recorded for the Beaver Dam gold district between 1889 and 1941.

The next major period of work began in 1975 when MEX Explorations acquired claims to the Beaver Dam Mine Site. From 1978 until 1988, a number of difference companies drilled a combined total of 251 diamond holes as well as undertaking mapping and geophysical and geochemical surveys.

Between 1986 and 1989, Seabright Resources Ltd. (Seabright) explored from underground via a decline that reached a maximum depth of 100 m below ground surface (bgs). A total of 34 drillholes were drilled from underground by Seabright. In 1986, Seabright also excavated a small open pit in the Papke and Austen zones, removing 10,822 tonnes of material. In total 2,445 ounces of gold were recovered from bulk samples during this period.

In 2002, Tempus Corporation, a predecessor company to Acadian Gold Corporation and now known as Acadian Mining Corporation (Acadian), acquired the Beaver Dam Mine Site. Acadian retained Mercator Geological Services (Mercator) to manage its exploration activities until 2008, and from that date until 2013, Acadian managed all exploration activities within the Beaver Dam Mine Site. Between 2005 and 2009, Mercator and then Acadian managed several diamond drill programs with a total of 153 holes drilled.

AGC secured the Beaver Dam Mine Site in 2014 through the acquisition of Acadian. AGC undertook a drilling program from October 2014 to January 2015 and drilled 41 diamond holes and an additional 8 geotechnical holes. The October 2014 to January 2015 drillhole results were incorporated into the gold resource estimate for the Beaver Dam Mine Site (FSSI, 2015), which facilitated completing a feasibility study for developing an open pit gold mine at the Beaver Dam Mine Site (Ausenco Engineering Canada Inc., 2015). To obtain regulatory approval for an open pit mine development at the Beaver Dam Mine Site, an Environmental Impact Statement (EIS) was prepared (GHD, 2017) and submitted to the Canadian Environmental Assessment Agency (CEAA) and Nova Scotia Environment (NSE). This Report presents the 3D groundwater flow modelling conducted to support development of a revised EIS.

This Report describes the details of developing and applying a numerical 3D groundwater flow model for the Beaver Dam Mine Site. GHD applied the model as a predictive tool to evaluate impacts to groundwater quality and quantity with respect to groundwater flow and groundwater interactions with surface water at the Beaver Dam Mine Site. Groundwater quality and quantity are examined at end of mine life (EOM[1]) and post-closure (PC[2]). Specifically, the 3D groundwater flow model was developed to assess:

1. Groundwater inflow rates to the open pit mine at EOM
2. Groundwater drawdown at EOM and PC
3. Pit infilling rates following EOM
4. Change in groundwater discharge to/from surface water bodies at EOM and PC
5. Transport of constituents of concern (COCs) from mine features into the surrounding environment at EOM and PC

1.2 Purpose

This Report documents GHD's development of the numerical 3D groundwater flow model to represent the complex hydrogeologic conditions observed at the Beaver Dam Mine Site and surrounding area. The groundwater flow model was developed to provide a reasonable representation of hydrologic, geologic, and hydrogeologic conditions observed at the Beaver Dam Mine Site. The groundwater flow model was calibrated to match measured groundwater elevations and groundwater flow directions as well as estimated baseflow. GHD used the calibrated model to evaluate potential impacts of mine development on groundwater quality and quantity as well as groundwater interactions with surface water.

The objectives for developing the groundwater flow model include:

- To enhance the understanding of groundwater flow conditions at and surrounding the Beaver Dam Mine Site to facilitate developing a Hydrogeologic Conceptual Site Model (CSM) to use as the basis for developing the numerical groundwater flow model
- To construct and calibrate the numerical groundwater flow model consistent with the CSM to represent observed Beaver Dam Mine Site conditions
- To apply the calibrated groundwater flow model to evaluate potential changes in groundwater quality and quantity with respect to groundwater flow and groundwater interactions with surface water at the Beaver Dam Mine Site under EOM and PC conditions

[1] EOM is defined as the condition immediately following the cessation of mining, with the pit excavated to the maximum proposed depth and completely dewatered.

[2] PC is defined as the long-term post-reclamation condition, once the pit has filled forming the pit lake.

1.3 Scope of Work

GHD developed the groundwater flow model based on site-specific and available regional data including surface water features, topography, water well records and geologic information.

The scope of work completed by GHD to develop the groundwater flow model and apply the model to evaluate potential impacts to groundwater and surface water flow regimes included the following:

- Compiled, reviewed, and interpreted the geologic, groundwater flow, and surface water flow data available for the Beaver Dam Mine Site and surrounding area
- Developed a 3D geologic model of the Beaver Dam Mine Site and surrounding area
- Developed a CSM for the Beaver Dam Mine Site and surrounding area based on available regional and site-specific data
- Developed a 3D groundwater flow model based on the CSM to represent the existing conditions that incorporated the 3D geologic model
- Calibrated the groundwater flow model under steady-state conditions to match measured groundwater elevations and groundwater flow directions, as well as estimated baseflow
- Evaluated the sensitivity of the model calibration to model input parameters
- Applied the calibrated groundwater flow model to evaluate potential changes in groundwater quality and quantity with respect to groundwater flow and groundwater interactions with surface water at the Beaver Dam Mine Site under EOM and PC conditions
- Evaluated the sensitivity of selected model predictions to model input parameters
- Documented the groundwater flow model development and its application in this Report

1.4 Report Organization

This Report is organized as follows:

- **Section 1 – Introduction:** Presents the introduction, purpose, and scope of work of the hydrogeologic modelling conducted for the Beaver Dam Mine Site
- **Section 2 – Summary of Hydrologic, Geologic and Hydrogeologic Conditions:** Presents a summary of observed regional and site-specific hydrologic, geologic and hydrogeologic conditions at the Beaver Dam Mine Site
- **Section 3 – Conceptual Hydrogeologic Model:** Presents the CSM developed for the Beaver Dam Mine Site that forms the basis for the construction of the numerical groundwater flow model
- **Section 4 – Simulation Program Selection:** Presents a description of the simulation programs selected to conduct the hydrogeologic modelling
- **Section 5 – Base-case Groundwater Flow Model Construction:** Presents details regarding construction of the numerical groundwater flow model to represent the key components of the CSM
- **Section 6 – Base-case Groundwater Flow Model Calibration:** Presents the calibration of the numerical groundwater flow model to observed groundwater flow conditions at the Beaver Dam

Mine Site and the sensitivity analysis of model calibration to variations in model input parameters

- **Section 7 – Groundwater Flow Model Application:** Presents the application of the calibrated groundwater flow model to evaluate potential impacts to the groundwater and surface water flow regimes at the Beaver Dam Mine Site at EOM and PC and the accompanying sensitivity analysis
- **Section 8 – Summary and Conclusions:** Presents a summary of the hydrogeologic modelling conducted at the Beaver Dam Mine Site and the conclusions obtained
- **Section 9 – References:** Lists the references cited in this Report

2. Summary of Hydrologic, Geologic, and Hydrogeologic Conditions

A review of the regional and site-specific hydrologic, geologic, and hydrogeologic conditions at the Beaver Dam Mine Site was conducted to develop the CSM, followed by developing the 3D groundwater flow model. The details of the regional and site-specific hydrologic, geologic, hydrogeologic conditions are summarized below.

2.1 Hydrologic Conditions

The hydrologic conditions at the Beaver Dam Mine Site are affected by regional physiography, topography, and surface water features. The following sections provide brief overviews of the regional physiography, topography, and surface water features.

2.1.1 Physiography

The Beaver Dam Mine Site is located in the Atlantic Uplands division of the Appalachian physiographic province of Canada (Williams et al., 1972). The Atlantic Upland spans approximately 450 km from Cape Canso, past Halifax to Cape Sable and then continue northward approximately 100 km from Port Yarmouth to St. Mary bay (Goldthwait, 1924). The Atlantic Upland appears in low islands and capes along the Atlantic coast, rising inland at a rate of approximately 3 m per kilometer reaching an altitude of approximately 180 to 220 m above mean sea level (AMSL) in the centre of the Nova Scotia peninsula. The Atlantic Upland is characterized by rolling hills, drumlin fields, and smooth ridges with intervening lakes, streams and muskegs.

Physiographic sections can often be subdivided into hydrologic units (basins) of common drainage areas. The Beaver Dam Mine Site is located within East/West Sheet Harbour basin, which occupies approximately 865 square kilometers in central Nova Scotia. The East/West Sheet Harbour basin is drained by the East Branch Sheet Harbour River and the West Branch Sheet Harbour River, both of which converge on Sheet Harbour and discharge to the Atlantic Ocean. The Beaver Dam Mine Site is located in a low lying area, adjacent to Cameron Flowage. Cameron Flowage is a stillwater area on the Killag River and is the dominant physiographic feature in the vicinity of the Beaver Dam Mine Site.

2.1.2 Topography

Regionally, the topography surrounding the Beaver Dam Mine Site slopes gently from a maximum level of approximately 210 m AMSL in the central Nova Scotia peninsula northwest of the Beaver Dam Mine Site towards sea level near Sheet Harbor to the southwest of the Beaver Dam Mine Site. Locally, the Beaver Dam Mine Site is located in an area of low topographic relief at approximately 140 m AMSL with scattered drumlins reaching 165 to 175 m AMSL and Cameron Flowage channeling through a topographic low approximately of 130 m AMSL. The Beaver Dam Mine Site topography under current conditions (i.e., pre-mining) is presented on Figure 2.1.

Throughout mining operations, the local topography will be altered by the construction of major mine features including the open pit, till stockpiles, and waste stockpile. The Beaver Dam Mine Site is expected to be operated for approximately 4 years. In the final year of operation, the open pit is expected to be mined to an elevation of approximately -45 m AMSL while the waste stock pile is expected to reach an elevation of approximately 200 to 220 m AMSL.

2.1.3 Surface Water Features

Figure 2.2 presents the surface water features surrounding the Beaver Dam Mine Site. Regional surface water drainage is predominantly to the southeast along several poorly drained stream channels and shallow lakes, and there are several low-lying boggy areas across the Beaver Dam Mine Site (Peter Clifton & Associates [PCA], 2015). Most major streams in the region, including the Killag and West Branch Sheet Harbour River, follow the northwest-southeast strike of the major fault lineaments (Jacques, Whitford & Associates Ltd. [JWA], 1986a). The most significant surface water body in the Beaver Dam Mine Site area is Cameron Flowage, which is located approximately 70 m northwest of the proposed open pit mine. Cameron Flowage is a stillwater area on the Killag River (JWA, 1986a). Cameron Flowage receives the majority of surface water drainage from the Beaver Dam Mine Site with the exception of a small portion of the Beaver Dam Mine Site that drains towards Tent Lake. Cameron Flowage likely is a location of groundwater discharge.

In addition to Cameron Flowage, the most significant surface water bodies near the Beaver Dam Mine Site include Mud Lake, Crusher Lake, Tait Lake, and West Lake. The lakes are interconnected by a series of streams that drain into Cameron Flowage, which is in turn drained by Killag River.

2.2 Geologic Conditions

The geology of the Beaver Dam Mine Site generally consists of a silty sand glacial till (overburden), overlaying argillite and greywacke bedrock of the Moose River Member. The Moose River member is part of the larger greywacke dominated Goldenville Formation. The overburden deposits range in grain size from clays to boulders up to 1 m in diameter. Sections 2.2.1 and 2.2.2 provide descriptions of the overburden and bedrock geology, respectively.

The information presented below focuses on geologic conditions pertinent to the development of a 3D geologic model for the Beaver Dam Mine Site. The 3D geologic model formed the basis for the site-specific geology (i.e., hydraulic conductivity distribution) represented in the 3D groundwater flow model. Regional geologic conditions were inferred from monitoring well installation borehole records, exploratory geologic drillhole records, regional well records, and regional geology reports.

2.2.1 Overburden Geology

The overburden at the Beaver Dam Mine Site consists of glacial till deposits of varying thickness and occasional shallow peat bogs. Stea and Fowler (1979) describe the overburden as a blue-greenish-grey, loose, cobbly silt-sand till that will grade into a sandier, coarser till, sometimes with red clay inclusions. A typical composition of the glacial till matrix is 80 percent sand, 15 percent silt and 5 percent clay. Site-specific grain size analysis indicates that the till averages approximately 60 percent gravel, 25 percent sand, 15 percent silt, and 1 percent clay. In the upland regions, such as at the Beaver Dam Mine Site, the glacial till material is generally a coarse, sandy matrix with numerous quartz cobbles and boulders, exhibiting a relatively good permeability and internal drainage (JWA, 1986a). Compact silt-clay till drumlins located in the vicinity of the Beaver Dam Mine Site are expected to be less permeable due to their soil type and composition. Drumlins located in the vicinity of the Beaver Dam Mine Site are shown on Figure 2.3.

Regionally, the till deposit has an average thickness of approximately 3 m and can be up to 20 m thick in some locations such as drumlin deposits (PCA, 2015). At the Beaver Dam Mine Site, the glacial till deposits are on average approximately 3.5 m to 4.5 thick and range from 0.5 m to over 22 m in a bedrock depression associated with the Mud Lake Fault (JWA, 1986b). Figure 2.4 shows the location of the Mud Lake Fault interpreted based on the findings of JWA (1986a) combined with the estimated overburden thickness recorded in exploratory drillhole records, monitoring well installation records, and regional well records.

2.2.2 Bedrock Geology

Regional Geology

Nova Scotia is divided into two distinct geologic parts, the Avalon Terrane to the north and the Meguma Terrane to the south. The two terranes are separated by the Minus Geofracture (commonly referred to as the Cobequid-Chedabucto Fault System) (Sangster and Smith, 2007). The oldest known rocks of the Meguma Terrane are the greywackes and argillites of the Cambrian to Ordovician aged Meguma Group, which were intruded by granitic plutons during the Devonian Acadian Orogeny (Duncan, 1987; and FSS International Consultants (Australia) Pty Ltd. [FSSI], 2015).

The Paleozoic turbiditic metasedimentary sequence of the Meguma Group consists of two major stratigraphic units: the basal greywacke dominated Goldenville Formation; and the overlying, finer grained, argillite dominated Halifax Formation. The Goldenville Formation is at least 5,600 m thick, while the overlaying Halifax Formation averages approximately 4,400 m in thickness (FSSI, 2015).

The sediments of the Goldenville and Halifax Formations were deformed, uplifted, metamorphosed and intruded by granitic plutons during the Acadian Orogeny, approximately 50 to 375 million years ago. The main feature of the deformation is a series of tightly folded subparallel northeast trending upright to slightly reclined asymmetric folds (Duncan, 1987; and PCA, 2015). A group of northwest trending sinistral faults have truncated and offset the asymmetric folds by up to 6 km. Regional geologic conditions depicting the approximate locations of the Goldenville formation, Halifax formation, and granite intrusions are presented on Figure 2.5.

Local Geology

The Beaver Dam Mine Site is located within the Goldenville Formation of the Meguma Group. The series of tightly folded subparallel northeast trending anticlines and synclines have exposed the different stratigraphic members of the Goldenville Formation. After the classification proposed by Horne and Pelley (2007), the Meguma Group can be broken down into three members, consisting of the lowermost Moose River Member that is overlain by the Tangier Member, which is in turn overlain by the Taylors Head Member. Both the Beaver Dam Mine Site and the Touquoy Mine Site (located 19 km to the southwest of the Beaver Dam Mine Site) are located within the Moose River Member (FSSI, 2015).

The Moose River Member is at its widest in the Beaver Dam Mine Site vicinity and is folded into three sub-parallel anticlines. The Beaver Dam Mine Site is located on the southern limb of the overturned central anticline (commonly referred to as the Moose River-Beaver Dam Anticline), with both limbs dipping to the north.

The Beaver Dam Mine Site is centered on Moose River-Beaver Dam Anticline with gold mineralization occurring within the overturned southern limb of the anticline, which dips north at between 75 and 90 degrees. The Moose River-Beaver Dam Anticline is sinisterly offset into segments by two northwest trending faults: the Mud Lake Fault; and the Cameron Flowage Fault (shown on Figure 2.4). The Mud Lake Fault has been described as a 2 to 3 m wide zone of gouge within a 10 to 20 m wide brecciated zone (PCA, 2015). Duncan (1987) stated an average thickness of 12 m, ranging from 5 to 26 m, for the Mud Lake Fault and that the Mud Lake Fault usually can be sub-divided into three zones consisting of:

1. Hanging Wall Breccia (2-10 m) consisting of greywacke and minor argillite orthobreccia and minor parabreccia
2. Gouge Zone (2-10 m) consisting of graphitic argillite gouge and minor greywacke
3. Footwall Breccia (1-5 m) consisting of greywacke and argillite ortho-and parabreccia

The stratigraphy of the southern limb of the Moose River-Beaver Dam Anticline largely has been defined through exploratory drilling and consists of alternating interbedded argillite and greywacke units. Early efforts placed emphasis on determining the nature and extent of gold mineralization that occurs in argillite dominated units surrounded by greywacke dominated units (Duncan, 1987). The initial distinction between units was made in the late 1800s and early 1900s based on the gold bearing properties of the units, rather than their hydraulic properties. Gold bearing units at the Beaver Dam Mine Site are typically argillite dominated units surrounded by greywacke dominate units, including the Crusher Lake Greywacke as shown on Figure 2.6 (Sangster and Smith, 2007) and the Mud Lake Greywacke defined by Duncan (1987). Three argillite dominated units have been defined relative to the Beaver Dam Mine Site, consisting of the Austen, Papke, and Crouse units. The argillite and greywacke dominated units defined for the Beaver Dam Mine Site consist of:

- Crouse Argillite – approximately 7 to 22 m thick, marking the transition from overlying greywacke dominated units to lower units dominated by argillite. Composed of dark grey, moderately graphitic argillite with greywacke intercalations forming up to 40 percent of the unit.
- Hanging Wall Greywacke – approximately 6 to 18 m thick, composed of light grey, fine grained greywacke and up to 40 to 50 percent dark grey to black argillite.

- Papke Argillite – approximately 15 to 30 m thick, comprised of black, graphitic argillite with less than 20 percent greywacke.
- Millet Seed Greywacke – approximately 8 to 25 m thick, composed of light grey fine to medium grain greywacke and 20 to 30 percent argillite.
- Austen Argillite – approximately 45 to 70 m thick, composed of dark grey argillite and 20 to 30 percent greywacke.

Boreholes advanced throughout the Beaver Dam Mine Site during gold exploration identified geologic units consistent with those shown on Figure 2.6. Further boreholes advanced by GHD during monitoring well installation at the Beaver Dam Mine Site largely encountered greywacke, consistent with the Beaver Dam Mine Site being surrounding by greywacke dominated bedrock (Crusher Lake Greywacke and Mud Lake Greywacke). One GHD monitoring well borehole location, MW-02B, contacted granite bedrock, which is consistent with surficial geologic maps showing a large body of granitoids southwest of the Beaver Dam Mine Site, as shown on Figure 2.5. The borehole logs for the recent monitoring wells installed by GHD are included in GHD (2018).

The lithological dataset based on previous drillhole observations provided by AGC was combined with the lithological data from the GHD monitoring well borehole logs to develop a 3D geologic model that was used to define geologic conditions at the Beaver Dam Mine Site. The development of the 3D geologic model is described in Section 2.3.2.

2.3 Hydrogeologic Conditions

The water table at Beaver Dam Mine Site is close to ground surface (typically within 2 to 5 m bgs). The bedrock sequence forms a fractured rock aquifer system, which is overlain by a thin aquifer in the overburden (PCA, 2015). The degree of hydraulic connection amongst the smaller bedrock fracture systems is probably poor to moderate (PCA, 2015).

Local groundwater flow in the till overburden is a function of topographic relief with recharge occurring in areas of high elevation and discharge occurring to low lying streams, rivers, and bogs. Groundwater elevation contours corresponding to overburden/shallow bedrock groundwater elevations from the July 18, 2018 monitoring event are presented on Figure 2.7. The interpreted groundwater elevation contours support that overburden groundwater flow mimics topographic relief and locally discharges to low-lying surface water bodies. Cameron Flowage is likely the most significant surface water body receiving groundwater discharge at the Beaver Dam Mine Site.

Regional groundwater flow in the fractured crystalline bedrock is controlled by secondary permeability and fracturing. Bedrock groundwater flow is expected to be predominantly southeastward along the dominant fault trends, with a lesser component of groundwater flow occurring in the northeast and east directions (JWA, 1986a). Regionally, bedrock groundwater flow is from northwest to southeast, along dominant fault trends and consistent with regional topographic relief from a topographic high of over 200 m AMSL in central Nova Scotia to sea level at the southeast shore of Nova Scotia.

2.3.1 Aquifers and Hydraulic Properties

For the purposes of the hydrogeologic modelling, three major aquifer units are defined at the Beaver Dam Mine Site consisting of the overburden, shallow weathered fractured bedrock (shallow bedrock), and deeper competent less fractured bedrock (deep bedrock). The shallow and deep bedrock units are further divided into five subunits each based on rock type/structure, consisting greywacke, argillite, granite, the Cameron Flowage Fault Zone and the Mud Lake Fault Zone. The hydraulic properties (i.e., hydraulic conductivity) of each of the three major aquifer units are summarized below. The hydraulic conductivity values are based on a pumping test conducted by JWA (1986b), packer tests conducted by JWA and Stantec and summarized in PCA (2015), packer tests conducted by GHD in three deep boreholes surrounding the proposed open pit location (MW-05C, MW-07C, and MW-09C), and slug tests conducted by GHD in newly installed monitoring wells.

Overburden

The glacial till overburden deposits consist of silty sand and gravel containing cobbles and boulders up to 1 m in diameter. The median thickness of the overburden unit identified by AGC exploratory drillholes in the proposed pit area is 5.5 m, and the median thickness identified in GHD boreholes, which cover an area in and surrounding the Beaver Dam Mine Site, is 2.1 m. The hydraulic conductivity of the overburden was estimated as 2×10^{-7} metres per second (m/s) from a pumping test conducted by JWA (1986b).

GHD conducted slug testing in monitoring wells installed in the till overburden. The overburden slug test results are summarized in Table 2.1. Hydraulic conductivity values calculated from the slug tests range from 6.1×10^{-7} m/s to 3.8×10^{-4} m/s, with a geometric mean of 1.0×10^{-5} m/s. Lower conductivity values were observed in areas of increased overburden thickness (>10 m), such as in the vicinity of MW-12A and MW-14A. MW-12A is installed in a silt-clay drumlin and is expected to have a lower hydraulic conductivity value than that observed in the surrounding overburden.

Shallow Bedrock

In general, bedrock hydraulic conductivity at the Beaver Dam Mine Site has been observed to decrease with depth consistent with weathered and fractured bedrock at shallow depths grading into less fractured and more competent bedrock at depth. Consistent with JWA (1986b), shallow bedrock is defined as bedrock located from the top of bedrock to 22 m below the top of bedrock (and deep bedrock lies below this).

Table 2.2 summarizes the hydraulic conductivity results obtained for shallow bedrock from the GHD slug tests and packer tests, as well as the packer tests summarized by PCA (2015). The shallow bedrock hydraulic conductivity values range from 1.7×10^{-9} m/s to 1.6×10^{-4} m/s, with a geometric mean of 5.6×10^{-7} m/s.

Deep Bedrock

Consistent with JWA (1986b), deep bedrock is defined as bedrock located 22 m or more below the top of bedrock. Table 2.3 summarizes the hydraulic conductivity results obtained for deep bedrock from the GHD slug tests and packer tests, as well as the packer tests summarized by PCA (2015). The deep bedrock hydraulic conductivity values range from 1.0×10^{-10} m/s to 5.4×10^{-6} m/s, with a geometric mean of 2.9×10^{-8} m/s. The geometric mean hydraulic conductivity for the deep bedrock is approximately 20 times lower than that of the shallow bedrock, which is consistent with the less fractured and more competent nature of the deep bedrock.

2.3.1.1 Major Aquifer Rock Types

The most abundant rocks type located at the Beaver Dam Mine Site are the greywackes and argillites of the Goldenville Formation. As shown on Figure 2.5, granitoids are located to the west and southwest of the Beaver Dam Mine Site, and on a regional scale, bands of the Halifax Formation are located to the north and south of the Beaver Dam Mine Site. Table 2.4 presents the hydraulic conductivity values determined from the GHD and PCA (2015) packer tests sorted by lithology and structure. The geometric mean hydraulic conductivity values from packer tests completed in argillite and greywacke are 2.7×10^{-8} m/s and 3.4×10^{-8} m/s, respectively. The similar geometric mean hydraulic conductivity values for both argillite and greywacke indicate that these two bedrock types have similar hydraulic properties at the Beaver Dam Mine Site.

2.3.1.2 Fault Zones

Two major faults are located in the vicinity of the proposed Beaver Dam Mine Site. The Cameron Flowage Fault runs below Cameron Flowage and the Mud Lake Fault location passes through the proposed pit (see Figure 2.4). Hydraulic conductivity values determined from packer tests summarized by PCA (2015) for drillhole sections that intersected the Mud Lake Fault range from 1.2×10^{-9} m/s to 1.9×10^{-6} m/s, with a geometric mean of 1.4×10^{-8} m/s (see Table 2.4). The packer test results indicate that the Mud Lake Fault has a hydraulic conductivity value similar to the surrounding bedrock. Observations by JWA (1986b) that the Mud Lake Fault is filled with a clay-like gouge support the low hydraulic conductivity results obtained for the Mud Lake Fault.

2.3.2 3D Geologic Model Development

The near vertical orientation of the interbedded greywacke and argillite units, coupled with the faulting, at the Beaver Dam Mine Site does not easily lend itself to development of regionally continuous lithological units. To overcome this, GHD developed a 3D geologic model for the Beaver Dam Mine Site to facilitate a rigorous representation of the spatial variability and orientation observed in the lithology. GHD converted the 3D geologic model into a hydraulic conductivity zone distribution to apply in the 3D groundwater flow model.

GHD developed a 3D geologic model for the Beaver Dam Mine Site using the geologic indicator kriging (GIK) approach implemented in the high sophisticated modular software package Mining Visualization System (MVS) developed C Tech Development Corporation (C Tech) (C Tech, 2015). GIK is particularly well suited to interpolating systems that have complex heterogeneous geology, which do not readily lend themselves to a layered representation. GHD conducted a detailed review of the stratigraphic logs for all drillholes/monitoring well locations provided by AGC and those locations installed by GHD. Geologic units were categorized based on common lithological types. The 3D spatial distribution for each lithological unit then was interpolated throughout the Beaver Dam Mine Site using GIK.

Based on the observations documenter in the Beaver Dam Mine Site stratigraphic logs, GHD categorized the main lithological units as follows:

- Overburden
- Argillite
- Greywacke

An interpolation domain was established for the 3D geologic model that consisted of rectangular grid blocks over the horizontal and vertical extent of the available geologic data at the Beaver Dam Mine Site. GHD applied a horizontal grip block size of 10 m by 10 m and a vertical grid block size of 10 m. GIK was used to compute the probably for each lithological type category to occur in every grid block based on the observed geology at each boring. The lithological type having the highest probability (for an individual grid block) is assigned to the grid block. GIK applies an anisotropy ratio that represents the degree to which a lithological type will be interpolated horizontally in favour of vertically. For example, an anisotropy ratio of 1 represents interpolation with no direction favour, and an anisotropy ratio of 10 represents interpolation in the horizontal direction 10 times more in favour than interpolation in the vertical direction. GIK can also apply a heading (i.e., the planar direction of the formation) and a dip angle. Since the lithology at the Beaver Dam Mine Site is primarily vertical, GHD applied an anisotropy ratio of 3, a dip angle of 73 degrees, consistent with the observed dip of the interbedded argillite and greywacke units and a heading of 105 degrees, consistent with the horizontal east/west orientation of the interbedded argillite and greywacke units.

A visualization of the 3D geologic model is included electronically in Appendix A along with the visualization viewer installation, viewing, and interaction instructions.

Screen captures from the 3D geologic model are presented on Figures 2.8 and 2.9, which show the following key features.

- Lithological types identified in drillhole/borehole records
- Proposed open pit shell
- Historical Mine Features
- Approximate Mud Lake Fault Location (on Figure 2.9)

The approximate Mud Lake Fault location, based on interpretation provided by AGC, is shown on Figure 2.9.

The conversion of the 3D geologic model into the hydraulic conductivity distribution specified in the 3D groundwater flow model is described in Section 5.3.

2.3.3 Groundwater Sinks

A groundwater sink is any feature that that removes groundwater from the groundwater flow system. Within the Beaver Dam Mine Site area, the primary groundwater sinks correspond to groundwater discharge to surface water bodies. Groundwater discharge to surface water bodies is discussed in more detail in the following section.

2.3.3.1 Discharge to Surface Water Features

Locally, groundwater flow typically follows the topographic relief, moving towards surface water bodies low lying areas. The proposed open pit at the Beaver Dam Mine Site is located adjacent to Cameron Flowage, a stillwater area on the Killag River. Cameron Flowage is approximately 1.2 km long and up to 120 m wide. All surface water generated within the drainage catchment that includes the proposed open pit area flows into Cameron Flowage. Cameron Flowage also is a likely area of groundwater discharge (PCA, 2015).

The average annual groundwater discharge, or baseflow, to Cameron Flowage was estimated using the four nearest hydrometric stations and scaling the watersheds that contain those stations to the size of the Cameron Flowage watershed. The nearest four hydrometric stations are Pembroke River at Glenbervie, Musquodoboit River Near Upper Musquodoboit, Musquodoboit River Near Middle Musquodoboit, and Musquodoboit River at Crawford Falls, which have drainage areas of 7,330 hectares (ha), 14,100 ha, 33,400 ha, and 65,000 ha, respectively. A baseflow value was estimated for each drainage area using a recursive digital filter (Eckhardt, 2005) as implemented in WHAT: Web-based Hydrograph Analysis Tool (Lim et al., 2005). The estimated baseflow for each drainage area was scaled to the total drainage area of approximately 3,871 ha for Cameron Flowage, providing an estimated total average annual baseflow of approximately 23,426 cubic metres per day (m^3/d) for Cameron Flowage. The estimated average annual total flow for Cameron Flowage is 103,881 m^3/d, and the estimated baseflow of 23,426 m^3/d represents approximately 23 percent of this total flow. The estimated average annual baseflow for Cameron Flowage provides a baseline condition against which to compare predicted baseflow changes at EOM and PC.

2.3.4 Groundwater Sources

A groundwater source is any feature that contributes groundwater to the groundwater flow system. At the Beaver Dam Mine Site, the primary groundwater source is from groundwater recharge through precipitation infiltration. In some areas it is expected that groundwater will receive recharge from surface water bodies; however, surface water bodies overall are expected to receive net discharge from the groundwater flow system.

2.3.4.1 Recharge through Infiltration of Precipitation

Groundwater at and surrounding the Beaver Dam Mine Site receives precipitation at a reported average annual rate of approximately 1,357.7 millimetres per year (mm/yr) (climate normal for the 30-year period [1981-2010] at Middle Musquodoboit Climate Station). The amount of precipitation reaching the groundwater table is typically considered to range from approximately 10 to 40 percent of the average annual precipitation (Arnold et al., 2000; and Rushton and Ward, 1979).

Baseflow often is used to estimate recharge rates, with the caveats that: 1) baseflow probably represented some amount less than that which recharges the aquifer; and 2) baseflow is best applied to provide a reasonable estimate of recharge occurring over long time periods (1 year or more) (Risser et al., 2005). To estimate recharge from baseflow, the total baseflow is divided by the area of the watershed. For the Cameron Flowage watershed, the average annual estimated baseflow of 23,426 m^3/d divided by the area of the Cameron Flowage watershed of 3,871 ha gives an estimated average annual recharge rate of 221 mm/yr (approximately 16 percent of the average annual precipitation). Applying the same method to an average dry month (typically September) and an average wet month (typically April) provides an estimated range in recharge from 77 to 377 mm/yr (approximately 6 to 28 percent of the average annual precipitation). Although applying baseflow to estimate recharge has some limitations, it is suitable for the purpose of establishing a potential range of average recharge conditions at the Beaver Dam Mine Site.

The recharge estimates developed through baseflow analysis correspond well to those developed by the Nova Scotia Department of Natural Resources (NSDNR). Using a similar method, the NSDNR estimated recharge for primary watersheds across Nova Scotia (Kennedy et al., 2010). The average annual recharge rate calculated for the primary watershed within which the Beaver Dam Mine Site is located ranged from 220 to 260 mm/yr. The average annual recharge rate of 221 mm/yr estimated for the Beaver Dam Mine Site through the baseflow analysis is consistent with the range of 220 to 260 mm/yr estimated by Kennedy et al. (2010).

2.3.4.2 Recharge from Surface Water Bodies

While surface water bodies are expected with be a net groundwater sink, there will be losing reaches (i.e., sections where surface water recharges groundwater) along some surface water bodies. Surface water bodies will recharge groundwater in areas where groundwater levels fall below adjacent surface water elevations.

3. Hydrogeologic Conceptual Site Model (CSM)

The CSM forms the working basis for understanding the hydrogeologic conditions at the Beaver Dam Mine Site, including the extent, geometry, and composition of the hydrostratigraphic units, groundwater flow characters of each hydrostratigraphic unit, groundwater flow interactions between the units, and groundwater/surface water interaction. The CSM facilitates selecting model domain limits for the numerical groundwater flow model, as well as hydrostratigraphic unit representation and boundary conditions taking into consideration the observed site-specific and regional hydrogeologic conditions. The CSM then forms the basis for constructing the numerical groundwater flow model.

3.1 General Hydrogeologic Characteristics

Understanding the general hydrogeologic characteristics of the groundwater flow system for the Beaver Dam Mine Site is fundamental to developing a representative CSM and guides the development of the numerical groundwater flow model. Based on the available regional and site-specific information, the hydrogeologic characteristics are summarized as follows:

- Based on the available monitoring well installation logs, regional well records, exploratory drillhole records, and the 3D geologic model, the geologic conditions at the Beaver Dam Mine Site consist of steeply dipping interbedded argillite and greywacke overlain by a thin till overburden layer. The overburden consists of a silty sand and gravel containing cobbles and boulders up to 1 m in diameter. The interbedded argillite and greywacke bedrock sequence at the Beaver Dam Mine Site is truncated by the Mud Lake Fault towards the east end of the proposed open pit location.

- Groundwater flow at the Beaver Dam Mine Site occurs primarily in the till overburden layer and the shallow weathered fractured bedrock zone. Bedrock permeability decreases with depth indicating that groundwater flow rates also are expected to decrease with depth.
- Groundwater flow directions in the till overburden typically follow topographic relief, and the groundwater table is expected to mimic ground surface, with recharge occurring in upland areas, and discharge occurring to surface water bodies in low lying areas within the Killag River watershed.
- Groundwater flow in the bedrock is controlled by secondary permeability and fracturing, and more so in the weathered shallow bedrock than in the more competent deep bedrock. Locally, bedrock groundwater flow largely is expected to occur predominantly towards the southeast along dominant fault trends, with smaller flow components to the northeast and east. It is assumed that the secondary permeability and fracturing is well enough connected at the scale of interest that the fractured bedrock system can be treated as an equivalent porous media.
- The surface water features surrounding the Beaver Dam Mine Site may receive groundwater discharge or may recharge groundwater depending on surface water elevations and the immediately surrounding groundwater elevations.
- At depth within the deep bedrock, the permeability becomes sufficiently low such that vertical groundwater flow is negligible.

3.2 Groundwater Flow Model Domain Limits

A groundwater flow model domain should extend to where reasonably defensible boundary conditions can be established. Model domain limits, and the associated boundary conditions, should be based on regional-scale natural hydrogeologic features where possible. The model domain limits and the associated boundary conditions should be selected to minimize potentially causing an incorrect bias in model predictions over the area of interest within the interior of the model domain.

GHD selected a model domain and associated boundary conditions representative of observed conditions at the Beaver Dam Mine Site and reasonably expected conditions regionally. The selected model domain and boundary conditions assigned at the model domain limits are illustrated on Figure 3.1, and are described in general terms as follows:

- Northeast: The northeastern model domain limit is aligned with expected groundwater flow divide located between topographic highs and the surface water elevations along the centre of Como Lake and Seven Mile Stream. The northeastern boundary condition was extended beyond to the secondary watershed divide shown on Figure 3.1, to provide additional physical separation between the Beaver Dam Mine Site and northeastern boundary condition such that the northeastern boundary condition would not provide a potentially incorrect bias within the area of interest at the Beaver Dam Mine Site. A river boundary condition is specified along the location of Como Lake and Seven Mile Stream. A no-flow boundary condition is specified between topographic highs where a lake or stream/river is not present.
- Southeast: The southeastern model domain boundary was selected as corresponding to anticipated flow divides between topographic highs southeast of Cameron Flowage. Regional groundwater flow from northwest to southeast is expected to exit the model domain along the southeastern boundary to the south of Cameron Flowage, following the general topographic

relief towards the southeast. However, due to the low permeability of the bedrock, flow at depth is negligible with respect to groundwater flow conditions at the Beaver Dam Mine Site. Therefore, a no-flow boundary was assigned along the entire southeastern model domain limit.

- Southwest: The southwestern model domain limit corresponds to the tertiary water shed boundary along the centre of River Lake and the West Sheet Harbour River, as shown on Figure 3.1. A river boundary condition is specified along the southwestern model domain limit consistent the location of River Lake and the West Sheet Harbour River.
- Northwest: The northwestern boundary condition corresponds to surface water bodies along West Sheet Harbour River, Kent Lake, Cope Flowage, West Lake, and West Brook. Between West Brook to north of McNeil Brook, the northwestern boundary corresponds to an inferred flow divide between topographic highs. River boundary conditions are specified where surface water bodies are present, and a no-flow boundary condition is specified where a flow divide is inferred between topographic highs.

As presented on Figure 3.1, the model domain extends approximately 8.5 km in the north-south direction and 9 km in the east-west direction. Details on implementing the boundary conditions described above at the model domain limits are provided in Section 5.2. Additional river boundary conditions on the interior of the model domain corresponding to surface water bodies are shown on Figure 3.1. Section 5.2 describes the basis for these interior boundary conditions.

Vertically, the model domain extends from ground surface, where a recharge boundary condition is applied, to approximately 250 m bgs where a vertical no-flow boundary is inferred. At this depth, the permeability the deep bedrock becomes sufficiently low such that active groundwater flow, and vertical groundwater flow in particular, is considered negligible. Ground surface is at approximately 130 m AMSL in the vicinity of the Beaver Dam Mine Site making the bottom of the model domain correspond to -120 m AMSL. The bottom of the proposed open pit is to extend to an elevation of -45 m AMSL, 75 m above the bottom of the model domain.

3.3 Hydrostratigraphic Unit Representation

The steeply dipping and interbedded nature of the argillite and greywacke units at the Beaver Dam Mine Site, combined with the truncation of these units caused by the Mud Lake Fault, precludes using horizontal layers specific to each hydrostratigraphic unit. The 3D geologic model that GHD developed for the Beaver Dam Mine Site using MVS accounted for the dip angle and heading of the steeply dipping interbedded argillite and greywacke units, as well as the Mud Lake Fault. GHD imported the 3D geologic model into the numerical groundwater flow model as a 3D hydraulic conductivity distribution that specifically honoured the location of argillite and greywacke.

The Cameron Flowage Fault is located beyond the area investigated by the exploratory drillholes, and thus its location and orientation are not represented in the 3D geologic model. As a result, the Cameron Flowage Fault is assumed to have a vertical orientation, and its location is assigned based on the interpreted regional orientation presented in JWA (1986a).

Within the model domain, the Halifax Formation and location of granitoids are incorporated based on the regional extents presented on Figure 2.5.

For each bedrock and fault zone, it is assumed there is a shallow more permeable zone, caused by weathering and fracturing, and a deeper less permeable zone where weathered and fracturing are diminished.

The specific hydrostratigraphic units considered in the CSM for the Beaver Dam Mine Site are as follows:

- Overburden
- Shallow Greywacke
- Deep Greywacke
- Shallow Granite
- Deep Granite
- Shallow Argillite
- Deep Argillite
- Shallow Mud Lake Fault Zone
- Deep Mud Lake Fault Zone
- Shallow Cameron Flowage Fault Zone
- Deep Cameron Flowage Fault Zone

The shallow units listed above are considered more permeable due to weathering and fracturing, while the deep units are considered less permeable due to reduced weathering and fracturing.

4. Simulation Program Selection

The simulation program selection to develop the numerical groundwater flow model for the Beaver Dam Mine Site was based on the following considerations:

- The ability of the program to represent the key components of the CSM
- The demonstrated verification that the program correctly represents the hydrogeologic processes being considered
- The proven acceptance of the program by regulatory agencies and the scientific/engineering community
- The ability of the program to represent the proposed mine design
- The ability of the program to provide a reasonable numerical solution in consideration of the complexity of the hydrogeological conditions at the Beaver Dam Mine Site

4.1 Groundwater Flow Model

MODFLOW-NWT (Niswonger et al., 2011), developed by the United States Geological Survey (USGS), is capable of simulating steady-state or transient groundwater flow in two or three dimensions. MODFLOW-NWT uses a finite-difference method leading to a numerical approximation that allows for a description of and solution to complex groundwater flow problems. A rectangular grid is superimposed over the study area to horizontally subdivide the region of interest into a number of rectangular cells, and then the study area is subdivided vertically using layers. Hydraulic properties are assigned to the model cells consistent with the hydrogeologic unit that falls within each cell. Groundwater flow is formulated as a differential water balance for every model cell and hydraulic head is solved at the center of every model cell. MODFLOW-NWT allows for the specification of flows associated with wells, areal groundwater recharge, rivers, drains, streams, and other groundwater sources/sinks.

MODFLOW-NWT was selected to simulated groundwater flow for this modelling study due to its ability to efficiently solve complex groundwater flow simulations characterized by drying and rewetting of model cells such as that encountered in the simulation of dewatering scenarios. MODFLOW-NWT is a standalone version of MODFLOW-2005 (Harbaugh, 2005), which is an update to the original MODFLOW (McDonald and Harbaugh, 1988) and MODFLOW-2000 (Harbaugh et al., 2000). MODFLOW has been extensively verified and is readily accepted by many regulatory agencies throughout North America and Europe. MODFLOW-NWT is capable of representing the hydrogeologic components of the CSM for the Beaver Dam Mine Site. The Newton Solver (NWT) and the Upstream Weighting (UPW) package included in MODFLOW-NWT was employed to solve the groundwater flow equation. For convergence, the solution technique required the satisfaction of both hydraulic head and flow residual criteria providing a rigorous and reliable simulated water balance throughout the model domain.

4.2 Parameter Estimation

The calibration of the groundwater flow model was aided through the use of the parameter estimation program PEST, which is an acronym for Parameter Estimation (Watermark Numerical Computing, 2016). PEST is a model-independent parameter estimator that has become a groundwater industry standard for groundwater flow model calibration. It has a powerful inversion engine, which provides the ability to set bounds on model input parameters such as hydraulic conductivity and groundwater recharge. PEST was used in conjunction with pilot points (Doherty et al., 2010). Pilot points are a spatial parameterization device that can be used to estimate an initial hydraulic conductivity distribution. PEST conveys to MODFLOW-NWT input parameter values that vary within their specified bounds with the objective of establishing optimal input parameter values that minimize the error between observed and simulated calibration targets. For each run of input parameters, PEST calculates objective function values (OFVs) at each model calibration target location. OFVs represent the error between calculated versus measured values at each calibration target location. PEST automatically makes changes to the input parameter values (within their specified bounds) to reduce OFVs, selecting the run that exhibits the lowest overall OFVs as the optimal solution.

4.3 Contaminant Transport Model

Contaminant transport was simulated using MT3DMS (Zheng and Wang, 1999). MT3DMS is a reactive transport model that, when integrated with MODFLOW-NWT, can simulate multispecies transport in one, two, or three dimensions, and is able to simulate transport processes that are applicable to the Beaver Dam Mine Site, including advection, biodegradation (or decay), adsorption and dispersion in groundwater flow systems. MT3DMS is commonly used by the industry and accepted by regulatory agencies throughout North America and Europe.

4.4 Graphical User Interface

The graphical user interface (GUI) Groundwater Vistas (Rumbaugh, 2017) was used as the interface between the assembled hydrogeologic data and the required MODFLOW-NWT and MT3DMS input files. The GUI facilitates pre- and post-processing of MODFLOW-NWT and MT3DMS input/output files.

5. Groundwater Flow Model Construction

Groundwater flow model construction is the process of developing the horizontal and vertical discretization of the selected model domain, specifying hydraulic properties consistent with the hydrostratigraphic units, and implementing boundary conditions consistent with the CSM. The groundwater flow model construction relative to these aspects is presented in the following sections.

5.1 Groundwater Flow Model Spatial Domain and Discretization

Horizontally, the model domain is discretized into rows and columns using a rectangular finite-difference grid. The finite-difference grid is extended over the model domain described in Section 3.2. The finite-difference grid is presented on Figure 5.1. A minimum finite-difference grid spacing of 10 m was applied over the area of interest as defined by the preliminary mine layout. Beyond the area of interest, the grid spacing progressively increases to a maximum of 100 m at the edge of the model domain. The model domain is discretized horizontally into 272 rows and 290 columns.

Vertically, the model domain extends from ground surface to approximately 250 m bgs where a vertical no-flow boundary is inferred, as described in Section 3.2. The vertical discretization of the model domain consists of 13 model layers to capture major changes in lithology as represented by the 3D geologic model. With the exception of model layer 1, the model layers have a uniform thickness. For model layer 1, a variable layer thickness is assigned, consistent with the estimated overburden thickness presented on Figure 2.4. Ground surface elevations over the model domain were generated using a combination of Digital Elevation Model (DEM) data for the Beaver Dam Mine Site, LiDAR imagery data for the Beaver Dam Mine Site, and surveyed ground surface elevations at monitoring well, drillhole, and surface water gauge locations. Model layer 2 has a uniform thickness of 22 m, corresponding the depth of the shallow bedrock zone. Model layers 3 through 13 have a uniform thickness of 20 m.

5.2 Flow Model Boundary Conditions

As described in Section 3.2 and shown on Figure 3.1, the boundary conditions for the groundwater flow model consist of:

- River boundary conditions to represent surface water features that potentially could receive groundwater discharge or potentially could recharge groundwater (e.g., Cameron Flowage, Como Lake, Crusher Lake, Mud Lake, etc.)

- No-flow boundary conditions to represented anticipated flow divides located between topographic highs along the model domain limits
- Recharge over the top of the model domain due to precipitation infiltration
- Vertical no-flow boundary condition at depth corresponding to the inferred base of the active groundwater flow system within deep bedrock

With respect to the predictive simulations of the open pit mine, pit filling, and proposed surface water management ditches, the following additional boundary condition types are used:

- A drain boundary condition is specified to represent surface water features that are considered to represent a point of groundwater discharge only. This includes surface water management ditches, which are assumed to rapidly convey groundwater discharge to Cameron Flowage, and the seepage face of the open pit mine above the specified pike lake elevation.
- A general head boundary condition is applied to represent groundwater in-flow/out-flow. A general head boundary is specified to simulate pit lake elevations at PC, and to estimate groundwater inflow into the open pit at specific pit lake stage elevations occurring as the pit fills.

The implementation of these boundary conditions in the model is described in further detail below.

5.2.1 River Boundary Condition

A river boundary can simulate the interaction between surface water and groundwater. It can represent both groundwater discharge to surface water (i.e., a gaining stream) and groundwater recharge from surface water (i.e., a losing stream). If a specified river stage elevation is lower than the simulated groundwater elevation, the river boundary receives discharge from groundwater. If the specified river stage elevation is higher than the simulated groundwater elevation, the river boundary serves as a recharge to groundwater. The quantity of surface and groundwater exchange is equal to the difference between the simulated groundwater elevation within the river cell and the specified head within the river cell multiplied by a conductance term. The conductance term reflects the relative ease of groundwater flow through sediments or bedding material that form the base of the surface water body.

As shown on Figure 3.1, river boundary conditions were assigned to represent natural surface water features located within the active model domain. The river cell stage elevations were assigned based on ground surface elevations minus the depth to water interpolated between surface water gauge locations. The conductance term for the river cells was estimated using:

$$C_{River} = \frac{KA}{M}$$

Where:

C_{River}	=	river cell conductance (square metres per day [m^2/d])
K	=	hydraulic conductivity of streambed sediments (m/d)
A	=	area of the river cell (square metres [m^2])
M	=	thickness of the river bed material (m)

For larger surface water bodies (i.e., lakes and wider water bodies like Cameron Flowage) that encompass multiple model cells, the river cell area was calculated as the model cell area or the portion of the surface water body contained by the river cell. For narrow surface water bodies (i.e., streams), the river cell area was calculated as the length of the stream within the river cell multiplied by stream width estimated from satellite imagery. The streambed sediment thickness was assumed to be 0.1 m. The hydraulic conductivity of the streambed sediments was adjusted during model calibration.

5.2.2 No-Flow Boundary Condition

No-flow boundary conditions were applied where negligible groundwater flow across a model boundary reasonably can be expected. No-flow boundary conditions are specified between adjacent topographic highs where groundwater is expected to flow downslope creating a groundwater flow divide with negligible groundwater flow across the divide (the divide is assumed to correspond to a line drawn between the two adjacent topographic highs). At the bottom of the model domain (at approximately 250 m bgs), it is assumed that the permeability of the deep bedrock becomes sufficiently low such that active groundwater flow, and vertical groundwater flow in particular, is considered negligible. As a result, a no-flow boundary condition is specified across the bottom of the model domain. A no-flow boundary condition also is applied along the southeastern model domain boundary where, due to the low permeability of the bedrock, flow across this boundary is negligible with respect to groundwater flow conditions at the Beaver Dam Mine Site.

5.2.3 Recharge

Recharge from precipitation infiltration was applied as the top model domain boundary condition. Based on the 30-year annual average normal precipitation values from 1981 to 2010 for Middle Musquodoboit, Nova Scotia (Stantec, 2018), the average annual precipitation is 1,357.7 mm/yr. The total precipitation in June 2018 (one month prior to the July 18, 2018 monitoring event selected as the base case calibration target dataset, as described in Section 6.1) was 178.1 mm, which is the equivalent of a total annualized precipitation of 2,137.2 mm (about 1.6 times high than the 30-year average annual precipitation). The average monthly precipitation for June (from 1981 to 2010 for Middle Musquodoboit) is 99.8 mm, and the total precipitation for June 2018 is approximately 1.8 times this average.

The amount of precipitation reaching the groundwater table as recharge depends on topography, shallow soil types, ground cover and land use (vegetation or building/pavement coverage), season, weather conditions, etc. Through the baseflow analysis described in Section 2.3.4.1, recharge for the Beaver Dam Mine Site was estimated to range from 77 to 377 mm/yr. Recharge was adjusted within this range during model calibration as described in Section 6.

The ground cover and land use is consistent throughout the Beaver Dam Mine Site; therefore, a single uniform recharge rate was applied over the entire model domain.

5.2.4 Drain Boundary Condition

A drain boundary condition simulates groundwater/surface water interaction in terms of groundwater discharge only. Unlike a river boundary condition, a drain boundary condition cannot represent a losing stream condition where surface water recharges groundwater. The drain boundary condition is active if the specified drain stage elevation is lower than the simulated groundwater elevation, and inactive when the specified drain stage elevation is higher than the simulation groundwater elevation. Similar to river cells, the quantity of groundwater discharge to the drain boundary is equal to the difference between the simulated groundwater elevation within the drain cell and the specified drain stage elevation multiplied by a conductance term.

A drain boundary condition was applied along the open pit wall to simulate the open pit above specified pit lake stage elevations. The drain stage elevation above the specified pit lake stage was set based on the elevation of the proposed pit walls. The drain conductance was set to a high value of 1,000 m^2/d to ensure that any groundwater entering a drain cell along the open pit wall would discharge to the open pit without resistance (when the groundwater elevation is above the drain stage elevation).

A drain boundary condition was also applied to simulate the surface water management ditches planned throughout the Beaver Dam Mine Site. The ditches are designed to efficiently convey collected surface water runoff to the settling pond prior to discharge into Cameron Flowage, and are expected to function as a groundwater discharge location as well. The conductance term for drain cells assigned to represent the surface water management ditches was calculated using the same approach as applied for the river cells. The area of the drain cell was calculated based on the length of the surface water management ditch specified within the drain cell multiplied by the designed width of the surface water management ditch. The hydraulic conductivity used to calculate the conductance term is the same as that used for the river cell streambed sediments since the surface water management ditches are designed to be naturally lined.

5.2.5 General Head Boundary Condition

A general head boundary (GHB) condition was assigned to represent the open pit below the simulated pit lake stage elevation. The GHB condition requires specifying a hydraulic head value and a conductance term for each model cell where the boundary is applied. The hydraulic head values were set equal to the simulated pit lake stage elevation, and the conductance term was set to a high value of 1,000 m^2/d to ensure that any groundwater entering a GHB cell along the open pit wall would discharge to the open pit without resistance (when the groundwater elevation is above the hydraulic head value).

5.3 Hydraulic Conductivity Distribution

The hydraulic conductivity zones were assigned in the model to represent each of the major hydrogeologic units identified in the CSM and represented in the 3D geologic model. A variable hydraulic conductivity distribution was assigned in model layer one to represented the overburden, which ranges from less permeable silty-clay to more permeable cobbled silty-sand. A single hydraulic conductivity value was assigned to each of the shallow and deep bedrock and fault zones where these hydrogeologic units are intersected by model layers 2 to 13. The hydraulic conductivity zones specified in model layers 2 to 13 are presented on Figures 5.2 through 5.14, respectively. Specifying hydraulic zones per hydrogeologic unit permits parameter estimation for each unit implemented through PEST using pilot points. The hydraulic conductivity value for each unit was adjusted during model calibration within reasonable bounds based on the results of the hydraulic conductivity testing conducted within each hydrogeologic unit (see Tables 2.1, 2.2, and 2.3), as well as values available in published literature consistent with the geological materials that make up each unit.

6. Groundwater Flow Model Calibration

Groundwater flow model calibration is the process of adjusting model input parameter and boundary conditions such that simulated results provide a reasonable representation of observed groundwater flow conditions at the Beaver Dam Mine Site. The object is to determine a unique combination of input parameters to produce a numerical solution that best matches the observed groundwater elevations, observed groundwater flow directions, and estimated baseflow at the Beaver Dam Mine Site.

6.1 Calibration Targets

Selection of steady-state model calibration target datasets normally considers whether the available groundwater elevation monitoring captures the following:

- Represents the range in groundwater flow conditions (i.e., seasonal variations) observed at the Beaver Dam Mine Site, typically consisting of a base case (i.e., average) condition, and wet and dry conditions
- Groundwater stresses/boundary conditions represent the range of conditions affecting groundwater elevations and flow directions
- Provides spatial coverage of the model domain with measurements at the majority of the available monitoring well locations
- Includes the key area of interest within the model domain

The monitoring network includes monitoring well/surface water gauge locations both within and surrounding the area of interest where mining operations are proposed. Groundwater/surface water elevations have been measured at the monitoring well/surface water gauge network at the Beaver Dam Mine Site since the network was installed in May 2018. Site-wide synoptic groundwater/surface water elevation measurement events available for model calibration were collected on July 18, August 1, August 22, and September 5, 2018. Scheduling constraints precluded the collection of an entire year of groundwater/surface water elevation data to assess seasonal variations prior to completing model calibration. As a result, using the groundwater/surface water monitoring results for the Beaver Dam Mine Site alone does not permit evaluation of potential seasonal variations. However, continuous groundwater/surface water elevation monitoring data (over several years) are available for the Touquoy Mine Site and were evaluated for applicability in estimating the range of potential seasonal variation in groundwater flow conditions at the Beaver Dam Mine Site, as described below.

Transducers are installed at groundwater monitoring wells to continuously monitor groundwater elevations at the Touquoy and Beaver Dam Mine Sites. Transducer data collection at both sites overlaps from May 28 to August 26, 2018. These data were used to evaluate whether groundwater elevation fluctuations occurring during this time period were correlated to one another between the two sites. If so, seasonal variations observed in the Touquoy Mine Site groundwater elevation measurements would be reasonably applicable to the Beaver Dam Mine Site. The Pearson product-moment correlation coefficient (correlation coefficient) was calculated to determine the degree of correlation between the May 28 to August 26, 2018 groundwater elevations measured via transducers at both the Touquoy and Beaver Dam Mine Sites. The correlation coefficient value can range from -1 to 1. A correlation coefficient value of -1 would indicate a strong negative relationship between two variables (i.e., when observed groundwater elevations increase at the Touquoy Mine Site, they are observed to decrease at the Beaver Dam Mine Site). A correlation coefficient value of 1 would indicate a strong positive relationship (i.e., when observed groundwater elevations increase at the Touquoy Mine Site, they are also observed to increase at the Beaver Dam Mine Site). A correlation coefficient value of 0 would indicate no relationship, or correlation, between the two datasets (i.e., observed groundwater elevation fluctuations at the Touquoy Mine Site are not related to observed groundwater elevation fluctuations at the Beaver Dam Mine Site).

For each monitoring well at the Beaver Dam Mine Site, a correlation coefficient was calculated corresponding to each monitoring well at the Touquoy Mine Site. This process identified which monitoring wells at the Touquoy Mine Site correlated best (i.e., had the highest correlation coefficient) to the monitoring wells at the Beaver Dam Mine Site. Table 6.1 presents the calculated correlation coefficients. The right most column (with the heading 'Maximum Correlation') indicates the correlation coefficient corresponding to the well at the Touquoy Mine Site that best correlates to a given Beaver Dam Mine Site well. In general, it was found that each well at the Beaver Dam Mine Site achieved good correlation to at least one well at the Touquoy Mine Site. Calculated correlation coefficients for the best matching monitoring wells between the Touquoy and Beaver Dam Mine Sites range from 0.43 to 0.99, with the majority the maximum correlation coefficients being above 0.8. These results indicate a strong positive relationship between groundwater elevations measured at the Touquoy and Beaver Dam Mine Sites. This is expected given that the Touquoy Mine Site is only 19 km to the southwest of the Beaver Dam Mine Site, and the two sites are located within the same geologic formation and have very similar hydrologic settings. Therefore, the groundwater elevation measurements collected at the Touquoy Mine Site can be reasonably applied to infer the potential range of seasonal variations in groundwater elevations, and thus groundwater flow conditions, at the Beaver Dam Mine Site.

Groundwater elevation data collected at the Touquoy Mine Site indicate that dry conditions are generally observed in August through September. Therefore, the September 5, 2018 synoptic round of groundwater elevation measurements at the Beaver Dam Mine Site, corresponding to the lowest average observed groundwater elevations, was selected as the dry condition calibration target dataset. The July 18, 2018 synoptic round of groundwater elevations was selected as the base case calibration target dataset. While typically more representative of dryer conditions, the July 18, 2018 groundwater elevations represent the highest average groundwater elevations measured to date at the Beaver Dam Mine Site.

High groundwater elevations, representative of wet conditions, are typically observed around the time of spring freshets that usually occur in April at the Touquoy Mine Site. Currently, groundwater elevation measurements for wet conditions at the Beaver Dam Mine Site are not available. Groundwater elevation data collected at the Touquoy Mine Site were applied to develop a wet condition calibration target dataset for the Beaver Dam Mine Site. The average observed groundwater elevation at the Touquoy Mine Site in April 2018, corresponding to wet conditions, is 113.46 m AMSL. The average observed groundwater elevation at the Touquoy Mine Site on July 18, 2018 was 112.62 m AMSL. The difference between the April 2018 and July 18, 2018 average observed groundwater elevations at the Touquoy Mine Site is 0.84 m. To develop a wet condition calibration target dataset for the Beaver Dam Mine Site, 0.84 m was added uniformly to the July 18, 2018 base case calibration target data set.

In addition to the base case, and dry and wet condition groundwater elevations, the model calibration was also compared against estimated baseflow throughout the model domain. Estimated baseflow rates for Cameron Flowage described in Section 2.3.3.1 were scaled up to the model domain size of 7,816 ha. The total estimated baseflow for the entire model domain is 47,299 m^3/d.

Model calibration is evaluated against the base case, and dry and wet condition groundwater elevations, as well as estimated baseflow, as presented in Section 6.3. The model calibration methodology is described in Section 6.2.

6.2 Calibration Methodology

The groundwater flow field throughout the model domain was simulated under steady-state conditions for each calibration target dataset. The solution to the groundwater flow equation was obtained using a numerical solver with specified convergence criteria. As described in Section 4.1, the NWT solver and the UPW package implemented in MODFLOW-NWT was used. The convergence criteria between successive solver iterations was specified as 0.0001 m for the maximum hydraulic head change, and 100 m^3/d for the maximum flow residual throughout the model domain.

Model calibration was performed in an iterative manner by adjusting the hydraulic conductivity values per geologic unit, recharge rate, and the hydraulic conductivity of the streambed sediments for river cell boundary conditions. PEST was applied to aid the model calibration process as an automated means to optimize model input parameter values within reasonable or expected ranges.

The model calibration was evaluated both qualitatively and quantitatively. Qualitative evaluations included visually comparing the simulated versus observed groundwater elevations and groundwater flow directions, as well as the spatial distribution of calibration residuals, or error in matching the calibration targets. Calibration residuals are calculated as the observed groundwater elevation minus the simulated groundwater elevation at each calibration target location. A negative residual value indicates that the observed groundwater elevation is over-predicted, and a positive residual value indicates that the observed groundwater elevation is under-predicted. Focused areas of largely over- or under-predicted groundwater elevations would indicate spatial bias in the calibration results, and adjustments to model input parameters are made to minimize this bias.

The quantitative assessment of the calibration was conducted by examining the calibration residual statistics. Statistics such as the mean residual, absolute mean residual, sum of the residual values squared (referred to as the 'residual sum of squares'), and residual standard deviation, were calculated to quantify an overall measure of the discrepancy between observed and simulated groundwater elevations provided by the calibrated model. The objective of the model calibration is to minimize these residual statistics.

Another quantitative assessment of the calibration was conducted by comparing the difference between observed and simulated total baseflow for the model domain, with the goal of minimizing this difference.

A further quantitative measure of the calibration was provide by the simulated volumetric water budget report by MODFLOW-NWT, indicating the quantities of flow into and out of the model domain via groundwater flow components specified on the model. The volumetric budget was reviewed to ensure that the total inflows and outflows were consistent with the CSM, and to ensure that the discrepancy between simulated inflows and outflows is less than 1 percent, indicating that a satisfactory numerical convergence was obtained for the solution of the groundwater flow equation.

6.3 Groundwater Flow Model Calibration Results

The locations of all calibration targets are presented on Figure 2.4. The base case, dry condition, and wet condition calibration targets are listed in Tables 6.2, 6.3, and 6.4, respectively. Figures 6.1, 6.2, and 6.3 present simulated versus observed groundwater elevation contours in the overburden/shallow bedrock for the base case, dry condition, and wet condition, respectively. Figures 6.1, 6.2, and 6.3 provide a qualitative evaluation of the model calibration and demonstrate that there is reasonably good agreement between the simulated and observed groundwater elevations and groundwater flow directions in the overburden.

Tables 6.2, 6.3, and 6.4 present the calibration residual at each target location for the base case, dry condition, and wet condition, respectively. Scatter plots of observed versus simulated groundwater elevations are presented on Figures 6.4, 6.5, and 6.6 for the base case, dry condition, and wet condition, respectively. Figures 6.4, 6.5, and 6.6 all show there is a reasonable distribution of plotted points above and below the line of exact match. This indicates that there is limited spatial bias in areas of over- and under-predicted groundwater elevations throughout the monitoring well network for all three calibration cases. The residual values at each target location are presented on Figures 6.1, 6.2, and 6.3 and demonstrate that the over- and under-predictions of observed groundwater elevations have a reasonably random distribution throughout the Beaver Dam Mine Site and surrounding area. This further supports that there is limited spatial bias in areas of over- or under-predicted groundwater elevations, and particularly so when considering that the range in observed groundwater elevations is approximately 34 m for all three calibration conditions.

The residual statistics for the base case calibrated model are summarized on Figure 6.4. The calibrated model provides a residual mean of -0.51 m, an absolute residual mean of 0.71 m, a residual sum of squares of 91.73 m^2, and residual standard deviation of 1.27 m. These residual statistics were minimized during the model calibration process while maintaining a reasonable representation of observed groundwater flow directions. The residual statistics for the base case calibrated model are considered reasonably small. There are a limited number of target locations that are distant from the primary area of interest surrounding the proposed open pit mine that have relatively larger residual values (i.e., MW-21B and MW-21C). MW-21B and MW-21C are far removed from the area of interest, are located in an area of coarsening model cell discretization, and exhibit significant downward gradients relative to other monitoring locations because they are located in an area of steep topographic relief. Improving the match to MW-21B and MW-21C is not possible without deteriorating the overall match to observed groundwater elevations. Since these locations are distant from the primary area of interest (i.e., the proposed open pit mine) improving the match to observed groundwater elevations at these locations is not warranted.

The residual standard deviation for the base case calibrated model is only 4.0 percent of the range in the July 18, 2018 measured groundwater elevations, as indicated on Figure 6.4. Spitz and Moreno (1996) suggest that the residual standard deviation should be less than about 10 percent of the range in measured groundwater elevations used as calibration targets. The residual standard deviation for the calibrated model lies well below this metric. This result, combined with the residual mean and the absolute mean being less than 1.0 m, indicates that the base case calibrated model provides a reasonably good match to the measured groundwater elevations.

The residual statistics for the model calibration to dry and wet conditions are summarized on Figures 6.5 and 6.6, respectively. The model calibration to dry and wet conditions was achieved through a combination of adjusting hydraulic conductivity values during simultaneous calibration to the base case, dry, and wet conditions, independently reducing the recharge rate for the calibration to dry conditions, and increasing the recharge rate for the calibration to wet conditions. The recharge rate was decreased for the model calibration to dry conditions to reflect the lower volume of groundwater recharge that occurred in September relative to the July base case condition. The recharge rate was increased for the model calibration to wet conditions to reflect the increase in groundwater recharge that occurs during spring freshets relative to the July base case condition. Dry condition groundwater elevations were approximately 0.38 m lower than the base case groundwater elevations, and wet condition groundwater elevation were 0.84 m higher than the base case groundwater elevations. The river boundary conditions within the model domain were held constant between the base case, dry, and wet conditions as average observed surface water levels at the Beaver Dam Mine Site showed less than 6 centimetres (cm) variation over the four synoptic rounds of groundwater/surface water monitoring conducted at the Beaver Dam Mine Site from July 18 through September 5, 2018. In general, the dry and wet condition residual statistics are similar to the base case calibration.

The simulated baseflow for the base case condition is 46,814 m^3/d which is within approximately 1 percent of the estimated baseflow of 47,299 m^3/d for the model domain. This indicates that a good match was obtained to the estimated baseflow, which further supports that a reasonable model calibration was obtained.

The volumetric water budget for the calibrated model was examined for the model calibration to the base case, dry and wet conditions. A discrepancy of close to zero occurs in the water budget between the simulated inflow and outflows for all three cases, which demonstrates that good numerical convergence was achieved throughout the model domain.

Table 6.5 presents the calibrated parameter values and the corresponding bounds applied during model calibration. In general, the bounds for hydraulic conductivity values were determined from the hydraulic conductivity values obtained from the slug tests and packer tests conducted at the Beaver Dam Mine Site (see Tables 2.1, 2.2, and 2.3). The recharge bounds were set based on the baseflow analysis presented in Section 2.3.4.1.

The overburden hydraulic conductivity assigned to the calibrated model in the vicinity of MW-12A is approximately one order of magnitude below the minimum observed overburden hydraulic conductivity of 6.1×10^{-7} m/s. The measured overburden hydraulic conductivity at MW-12A of 8.8×10^{-7} m/s is near the minimum measured overburden hydraulic conductivity, and is located in a silt-clay drumlin that is expected to have a lower hydraulic conductivity value relative to the surrounding quartzite till overburden. The reduced overburden hydraulic conductivity in the vicinity of MW-12A better reflects the groundwater mounding in the overburden observed at MW-12A. As shown in Table 6.5, the calibrated variable hydraulic conductivity distribution assigned to the overburden has an average value of 1.4×10^{-4} m/s, which is within the range of measured overburden hydraulic conductivity values.

As shown in Table 6.5, the calibrated hydraulic conductivity for the shallow bedrock ranges from 3.7×10^{-7} to 4.3×10^{-7} m/s across the different shallow bedrock hydraulic conductivity zones (i.e., argillite, greywacke, granite, Cameron Flowage Fault, and Mud Lake Fault). The calibrated hydraulic conductivity for all zones in the deep bedrock is 3.3×10^{-9} m/s (i.e., deep argillite, greywacke, granite, Cameron Flowage Fault, and Mud Lake Fault).

A horizontal to vertical hydraulic conductivity anisotropy ratio of 5:1 was applied in the overburden to represent horizontal stratification of the different soil types (clay, silty, sand and gravel/cobbles) that make up the overburden. A horizontal to vertical hydraulic conductivity anisotropy ratio of 1:1 was applied in bedrock to represent the relatively uniform vertical to horizontal hydraulic characteristics of the folded and fractured bedrock.

The calibrated hydraulic conductivity values are generally consistent with the measured hydraulic conductivity values obtained from slug tests and packer tests conducted at the Beaver Dam Mine Site. The calibrated hydraulic conductivity for the shallow bedrock tended towards a higher value (3.7×10^{-7} to 4.3×10^{-7} m/s), while the calibrated hydraulic conductivity for the deep bedrock tended towards a lower value (3.3×10^{-9} m/s), which is consistent with the CSM of reduced permeability with depth in the bedrock, as presented in Section 3. The calibrated hydraulic conductivity values in the shallow and deep bedrock do not vary significantly with rock type, which is consistent with packer test results that showed similar hydraulic conductivity values in argillite and greywacke, as well as within the Mud Lake Fault Zone.

For the base case, dry, and wet conditions, the calibrated recharge rates are 209, 219, and 250 mm/yr, respectively. The range in calibrated recharge rates for the base case, dry, and wet conditions is within the range of 77 to 377 mm/yr identified through the baseflow analysis presented in Section 2.3.4.1. The range in calibrated recharge rates also is consistent with regional recharge estimates of 220 to 260 mm/yr for the primary watershed containing the Beaver Dam Mine Site (Kennedy et al., 2010).

6.4 Calibrated Model Sensitivity Analysis

GHD conducted a sensitivity analysis of the calibrated model to evaluate the potential impact of parameter changes on the calibrated model results and to address uncertainties associated with the model input parameters. A total of 15 model input parameters were considered in the sensitivity analysis, including all of the model input parameters (i.e., boundary conditions and hydraulic properties) that were adjusted during model calibration.

A series of sensitivity simulations for base case, dry, and wet condition target sets were conducted for each model input parameter. Each input parameter value was adjusted while holding all other input parameter values constant with those specified in the calibrated model. The value of each parameter was adjusted by three gradations above and below the value specified in the calibrated model. In general, the input parameter values adjusted were based upon the range of parameter values specified during PEST calibration simulations. For the overburden, the variable hydraulic conductivity distribution was adjusted uniformly by a specified hydraulic conductivity value such that the average hydraulic conductivity value varied within the specified range in overburden hydraulic conductivity values.

A total of 90 sensitivity simulations were conducted; six for each of the 15 model input parameters. For each sensitivity simulation, the residual sum of squares between the observed and simulated groundwater elevations was determined for the base case, dry, and wet conditions. The percent difference between the residual sum of squares for each sensitivity simulation and that of the calibrated model was calculated. Table 6.5 presents the adjustments that were made to each input parameter value in the sensitivity simulations. The resulting change in the residual sum of squares also is shown in Table 6.5. Of the 90 sensitivity simulations, only two (both corresponding to a decrease in hydraulic conductivity for the deep greywacke unit) provided an improvement in the residual sum of squares of greater than 1 percent across the base case, dry, and wet condition calibration target datasets. This change was not incorporated into the calibrated model since a decrease in the hydraulic conductivity for the deep greywacke unit would approach its lower bound and doing so would not be conservative with respect to predictive scenarios (i.e., reducing the hydraulic conductivity of the deep greywacke unit would reduce the lateral extent of groundwater drawdown, reduce changes in baseflow, and reduce COC mobility). Therefore, the sensitivity analysis results demonstrate that the input parameter values applied in the calibrated model are at or near optimal to match all three calibration target datasets and/or provide a conservative bias with respect to conducting the predictive simulations.

7. Groundwater Flow Model Application

As described in Section 1.1, the primary objectives of this modelling effort include simulating the predictive scenarios to estimate the following:

1. Groundwater inflow rates into the open pit mine at EOM
2. Groundwater drawdown at EOM and PC
3. Pit infilling rates following EOM
4. Change in groundwater discharge to/from surface water bodies at EOM and PC
5. Transport of COCs from mine features into the surrounding environment at EOM and PC

GHD implemented the EOM and PC scenarios in the calibrated model to simulate potential impacts of the Beaver Dam Mine Site development. Where appropriate, predictive simulation results are compared against spatial boundaries and regulatory guidelines to assess the extent and significance of potential impacts. The implementation of the EOM and PC scenarios in the calibrated groundwater flow model is described in Section 7.1. Sections 7.2 and 7.3 present the definition of spatial boundaries and applied regulatory criteria, respectively, to assess the potential impacts of the EOM and PC scenarios. The predictive simulation results are summarized in Section 7.4.

7.1 Scenario Implementation

7.1.1 Estimation of Groundwater Inflow Rates at EOM

EOM was simulated through incorporating the proposed open pit mine and surface water management ditches into the calibrated models for the base case, dry, and wet conditions. The surface water management ditches were incorporated by specifying drain boundary conditions corresponding to the proposed ditch locations and dimensions, as discussed in Section 5.2.4. The open pit mine was represented by specifying drain cells along the perimeter of the proposed open pit mine. Internal model cells within the proposed open pit mine are set to no-flow boundaries. The stage elevation of the drain cells was set based on the proposed pit floor elevations provided by AGC. As discussed in Section 5.2.4, a high conductance value of 1,000 m^2/d was assigned to the drain cells such that water entering a drain cell would discharge to the open pit without resistance (when the groundwater elevation is above the drain stage elevation). The simulated volumetric flow of water entering the pit drain cells was summed over the entire pit to estimate the total groundwater inflow rate into the pit at EOM under the base case, dry, and wet conditions.

7.1.2 Estimation of Drawdown at EOM and PC

Simulated drawdown was estimated through comparing simulated groundwater elevation contours under the calibrated base case, dry, and wet conditions against those simulated under each condition at EOM and PC. To estimate drawdown for each condition, simulated groundwater elevation contours at EOM or PC were subtracted from simulated groundwater elevation contours for the calibrated model (i.e., to estimate drawdown under dry conditions, EOM groundwater elevation contours under dry conditions were subtracted from groundwater elevation contours for the dry condition calibrated model). The extent of drawdown was compared against the project area (PA), local assessment area (LAA), and regional assessment area (RAA) boundaries shown on Figure 1.1.

7.1.3 Pit Infilling Rate

The pit infilling rate was developed by calculating the groundwater inflow rate at specific stage elevations as the proposed open pit mine fills with water following EOM and fills towards the PC pit lake level. The groundwater inflow rate was calculated in a 10 m increment from an initial stage elevation of -30 m AMSL (approximately 15 m above the proposed open pit mine floor) to a final pit lake elevation of 127 m AMSL (GHD, 2019a). As pit infilling progressed, drain cells with stage elevations below a specified pit lake stage elevation were converted to GHB cells to allow either groundwater discharge to the pit or groundwater recharge from the pit. Drain cells located above a specified pit lake stage elevation remained unchanged from the EOM condition so that simulation of only groundwater discharge to the pit would continue at these drain cells. The stage elevation of the GHB cells was set to the specified pit lake stage elevation. As discussed in Section 5.2.5, the conductance of the GHB cells was set to a high value of 1,000 m^2/d to ensure that any groundwater entering the GHB cells would interact freely (i.e., without resistance) with the pit lake.

To calculate the pit infilling rate at each stage, GHD added the simulated groundwater inflow rate to the inflow from direct precipitation minus lake evaporation, the average annual inflow from the surface water management ditches that is rerouted into the pit at EOM, and to the inflow from overland surface water runoff. Inflow from direct precipitation is calculated through multiplying the average annual precipitation of 1,357.7 mm/yr minus the average annual lake evaporation rate of 515.1 mm/yr by the pit lake area at a given stage elevation. The applied average annual precipitation rate and lake evaporation rate were provided by Stantec (2018). The average annual inflow rate from the surface water management ditches was calculated from the average monthly inflow rate presented in GHD (2019b). GHD calculated surface runoff volumes through multiplying the drainage area of the pit minus the lake area by the average annual precipitation multiplied by a runoff coefficient of 0.85. The total time to fill each stage was calculated through dividing the volume of the stage by the pit infilling rate at that stage. The time to infill for each stage was summed over all stage elevations from -30 to 127 m AMSL to estimate the total time to fill the pit.

7.1.4 Simulated Change in Baseflow

GHD applied the numerical groundwater flow model to evaluate potential changes in baseflow that may occur at the Beaver Dam Mine Site under EOM and PC conditions. The simulated baseflow was calculated through a mass balance of river boundary conditions within the model domain (i.e., baseflow is equal to the simulated groundwater recharge from surface water bodies minus groundwater discharge to surface water bodies). The simulated baseflow at EOM is subtracted from the simulated baseflow for the calibrated model to estimate the potential change in baseflow. The potential change in baseflow is also estimated at PC. The change in baseflow is calculated under base case, dry, and wet conditions to estimate a potential range in baseflow changes moving from the current conditions (i.e., the calibrated model), to EOM conditions, and then to PC conditions. The potential change in baseflow is compared to the estimated total flow and baseflow in Cameron Flowage.

7.1.5 COC Transport

The development of the Beaver Dam Mine Site has the potential to degrade groundwater and surface water quality within and surrounding the PA. Water released from the open pit lake, or water that migrates through the waste rock and low grade ore stockpiles shown on Figure 7.1, may have associated COC concentrations that could migrate into the surrounding environment. Therefore, GHD developed a contaminant transport model to simulate the potential migration of COCs at the Beaver Dam Mine Site at EOM and PC.

Three naturally occurring transport mechanism zones were specified, including the overburden, shallow bedrock, and deep bedrock. The transport mechanism zones reflect the difference in transport processes that occur within each zone, such as different effective porosities within each zone. Effective porosity values of 0.15, 0.1, and 0.02 were assigned to the overburden, shallow bedrock, and deep bedrock, respectively.

The COCs are treated as a conservative tracer using a constant unit concentration specified within each source zone. Sorption/retardation and reactions along the groundwater flow path, which may reduce COC concentrations, are assumed to be negligible and therefore were not simulated. This is conservative with respect to simulating potential COC migration. The COC transport mechanisms implemented in each zone include advection and dispersion only, which are discussed in Sections 7.1.5.1 and 7.1.5.2, respectively.

COC migration was simulated using MT3DMS. For each potential source zone that may have a unique source concentration (i.e., full pit lake, waste rock piles, and low grade ore [LGO] stockpiles), an independent transport simulation was conducted. Contaminant transport was simulated for 500 years to approximate steady-state conditions and provide a conservative estimate of maximum concentrations at potential receptors (i.e., the nearby surface water bodies of concern). The concentration simulated at each receptor was multiplied by the source concentrations for each source zone provided by Lorax Environmental (2018a), and using the principle of superposition[3], summed across each transport simulation (i.e., full pit lake, waste rock piles, and LGO stockpiles) to estimate the total COC concentrations at potential receptors. Source concentrations are presented in Table 7.1. It is assumed that the transition from EOM to onset of slightly acidic drainage and corresponding PC source terms would take approximately 20 to 30 years (Lorax Environmental, 2018b). PC source concentrations generally are higher than for EOM. Therefore, to be conservative, PC source conditions are applied at a full pit lake condition occurring approximately 28 years from EOM.

7.1.5.1 Advection

Advection, the bulk movement of a fluid through a geologic medium, is the primary transport mechanism at the Beaver Dam Mine Site. The advection mechanism is governed by Darcy's Law, which determines the groundwater flow velocity, accounting for the hydrogeologic characteristics (hydraulic gradients, hydraulic conductivity, and porosity), of the aquifer. Groundwater flow conditions simulated by MODFLOW-NWT represent advection throughout the entire model domain. MT3DMS uses the groundwater flow field simulated by MODFLOW-NWT as input for solving the advection-dispersion transport equation.

7.1.5.2 Dispersion

Dispersion is a transport mechanism by which a solute spreads along the groundwater flow path. Dispersion results from two basic processes: molecular diffusion; and mechanical mixing. Molecular diffusion is a process where solutes move from zones of higher concentrations to zones of lower concentrations. The driving force of this movement is kinetic activity at the molecular level. Mechanical dispersion occurs due to the variability (i.e., heterogeneity) in pore-space groundwater velocities that act to spread or mix a solute in an aquifer. The primary aquifer characteristics that cause this mixing are variable frictional forces in pore channels, variations in pore channel geometry, and pore channel branching.

Dispersion/spreading of solutes during groundwater flow results in dilution of solute pulses and attenuation of concentration peaks. This dilution/attention affect is accounted for in the transport equation by applying longitudinal, transverse, and vertical dispersivity coefficients in a 3D domain.

Obtaining field measurements of the dispersivity is impracticable. However, simple estimate techniques, based on the length of plume or distance to the measured point (″scale″), are available by compiling field data. It is noted that researchers indicate dispersivity values can range over two to three orders of magnitude for a given value of plume length or distance to a measurement point (Gelhar et al., 1992). Empirical relationships of dispersivity versus plume length (L_P) are provided by Al-Suwaiyan (1996) and Xu and Eckstein (1995), as follows:

3 The principle of superposition states that for a linear problem (i.e., the 3D contaminant transport equation), the net response cause by two or more stimuli (e.g., contaminant sources) is the sum of the responses that are caused by each stimuli individually. Therefore, each source zone can be simulated independently and summed together to estimate the total combined impact of all sources at a given receptor.

$$\alpha_L = 0.82(\log_{10}(L_P))^{2.446}$$

Where:

α_L = is the longitudinal dispersivity in m

L_P = is the estimated plume length (m)

The plume length or scale is assumed to be 900 m, roughly corresponding to the maximum distance from a potential source zone (i.e., the waste rock piles) to a potential groundwater receptor (i.e., Mud Lake). Using an assumed plume length of 900 m, an estimated longitudinal dispersivity value of 11.6 m was calculated. The horizontal transverse dispersivity was specified to be 1/10 of the longitudinal dispersivity and the vertical transverse dispersivity was assumed to be 1/100 of the longitudinal dispersivity, as suggested by Gelhar et al. (1992) and Spitz and Moreno (1996).

7.2 Spatial Boundaries

The spatial boundaries considered in the evaluation of potential groundwater impacts resulting from the Beaver Dam Mine Site development are the PA, LAA and RAA. The PA, LAA and RAA boundaries are presented on Figure 1.1. The PA encompasses the proposed Beaver Dam Mine Site features including the open pit, waste rock piles, LGO stockpiles and Haul Road. The LAA encompasses an 800 m buffer from the PA, as required by the Province of Nova Scotia with respect to blasting for mining and construction projects. The RAA aims to account for the maximum extent of potential groundwater quality and quantity impacts and roughly corresponds to the extent of the groundwater flow model domain.

7.3 Regulatory Guidelines

Potential groundwater quality impacts should be compared against appropriate groundwater quality guidelines. There are no potable groundwater uses at the Beaver Dam Mine Site, therefore, simulated COC concentrations are compared against the Nova Scotia Environment (NSE) Tier 1 Environmental Quality Standards (EQS) for non-potable course grained soil for agricultural/residential use. The NSE Tier 1 EQS guidelines do not specify concentration limits for the potential COCs at the Beaver Dam Mine Site, therefore there will be no significant groundwater impacts above applicable groundwater guidelines. However, the NSE Tier 1 EQS guidelines state that where groundwater discharges to surface water, the Tier 2 Pathway Specific Standards (PSS) should be applied. Therefore, where groundwater discharges to surface water, the estimated groundwater COC concentrations are compared against the Tier 2 PSS guidelines for groundwater discharge to surface water. Certain COCs, including aluminum, arsenic, cadmium, and iron are naturally elevated relative to Tier 2 PSS guidelines. Therefore, estimated COC concentrations are also compared against observed background concentrations in groundwater.

7.4 Scenario Simulation Results

7.4.1 Simulated Groundwater Inflow Rates at EOM

Groundwater inflow rates into the open pit were simulated under base case, dry and wet conditions at EOM. The simulated volumetric flow from the pit drain cells was summed over the entire open pit to estimate the range of potential groundwater inflow rates into the open pit (presented in Table 7.2). The simulated pit groundwater inflow rates range from 631 m^3/d under dry conditions to 676 m^3/d under wet conditions. The simulated pit groundwater inflow range is consistent with the range of estimated groundwater inflow rates from 550 to 1,450 m^3/d presented in PCA (2015).

7.4.2 Simulated Drawdown

Figures 7.1a/b, 7.2a/b, and 7.3a/b show simulated drawdown for EOM/PC under base case conditions, dry conditions, and wet conditions, respectively. As shown on Figure 7.2a, the greatest extent of drawdown is simulated under dry conditions at EOM. A maximum drawdown of approximately 0.5 m is simulated adjacent to Cameron Flowage, within the PA, as shown on Figure 7.2a. Maximum simulated drawdown at EOM is generally less than 10 cm outside of the PA, and is negligible beyond the LAA. Figures 7.1b, 7.2b, and 7.3b show that simulated drawdown decreases at PC relative to EOM for all conditions.

7.4.3 Estimated Pit Infilling Rate

The pit infilling rate at each stage and the time to infill each stage is presented on Table 7.3. The time to infill each stage is summed across all stages from -30 to 127 m AMSL which results in a total estimated pill infilling time of 13.8 years.

7.4.4 Simulated Change in Baseflow

GHD applied the numerical groundwater flow model to simulate potential changes in baseflow that may occur at the Beaver Dam Mine Site under EOM and PC conditions. The simulated change in baseflow in the Cameron Flowage watershed is presented in Table 7.4. The simulated baseflow reduction ranges from 1,414 to 1,634 m^3/d at EOM and from 1,287 to 1,508 m^3/d at PC. The range in baseflow reduction represents 5 to 7 percent of the total baseflow in Cameron Flowage, and is under 2 percent of the total estimated average annual flow in Cameron Flowage presented in Section 2.3.3.1. During mine operations, all groundwater discharge to the open pit mine and to the surface water management ditches will be managed and ultimately discharged to Cameron Flowage. Once the pit lake has reached 127 m AMSL the pit will naturally discharge to Cameron Flowage. Therefore, no reduction in total flow is expected during mine operation or once the pit has filled. Approximately 85 percent of the total baseflow reduction is simulated to occur within the PA, and the remaining 15 percent of total baseflow reduction is simulated to occur between the PA and the LAA indicating that mine operations will not impact the baseflow beyond LAA.

7.4.5 Simulated COC Transport

GHD conducted COC transport simulations to estimate the location and significance of potential COC impacts to surface water bodies. Simulated unit concentration contours presented on Figures 7.4 through 7.15 under base case, dry and wet conditions for EOM and PC show that the maximum unit concentration simulated to discharge to a natural surface water body occurs at the east end of Crusher Lake within the PA. Simulated unit concentrations also migrate towards Mud Lake from the waste rock stockpiles and towards Cameron Flowage from the LGO stockpiles. At EOM and PC, the pit acts as a groundwater sink and unit concentrations are simulated to migrate towards the pit from the LGO and Waste Rock Stockpiles. COC concentrations at surface water body locations are estimated through multiplying simulated unit concentrations by source concentrations as described in Section 7.1.5. Simulated COC concentrations are compared against Tier 2 PSS guidelines and observed background groundwater concentrations to evaluate if the simulated impact is potentially significant. The location of potentially significant simulated impacts is compared against the PA, LAA and RAA boundaries.

Table 7.5a presents the maximum simulated COC concentrations that discharge to surface water under the base case, dry and wet conditions for EOM, for both the Base Case and Upper Case source concentrations provided by Lorax Environmental (2018a). The Upper Case source concentrations correspond to the 90th percentile of estimated source concentrations while Base Case source concentrations correspond to the median of estimated source concentrations. The mining plan includes the removal of the LGO stockpile at EOM; however, the LGO stockpile is included as a potential source zone in the Upper Case source term scenarios for the purpose of a conservative evaluation. Table 7.5a shows that at EOM all simulated COC concentrations are below Tier 2 PSS guidelines for Base Case and Upper Case source concentrations, with the exception of arsenic that exceeds its Tier 2 PSS guideline, but is within the range of background concentrations observed in groundwater. Therefore, COC concentrations are not predicted to have a significant impact to groundwater discharge at EOM.

Table 7.5b presents maximum simulated COC concentrations which discharges to surface water under PC conditions for the Base Case and Upper Case source concentrations. Applying the Base Case source concentrations at PC, aluminum, arsenic, and cadmium are simulated to exceed the Tier 2 PSS guidelines, but remain within the range of the observed background groundwater concentrations. Silver and copper concentrations exceed both the observed background groundwater concentrations and the Tier 2 PSS guidelines. For the Base Case source concentrations under PC conditions, the simulated COC exceedances in groundwater discharge only occur at the east end of Crusher Lake within the PA.

Applying Upper Case source concentrations under PC conditions, aluminum, silver, arsenic, cadmium, and copper are simulated to exceed both the Tier 2 PSS guidelines and the observed background groundwater concentrations. Again, the simulated COC exceedances occur primarily at the east end of Crusher Lake within the PA. Two exceptions to this occur for aluminum and copper which have simulated exceedances of the Tier 2 PSS guidelines in groundwater discharge towards the west end of Mud Lake, to the tributary immediately adjacent to the west waste rock pile and to Cameron Flowage from the LGO stockpile.

As shown on Figure 7.4 through 7.15 maximum concentrations that potentially exceed the Tier 2 PSS guidelines are generally simulated at the east end of Crusher Lake within the PA. The simulated concentrations discharging to surface water bodies are below the Tier 2 PSS guidelines beyond the LAA, supporting that any potential significant impact to groundwater quality is confined to within the LAA. No impacts to groundwater quality are predicted near the RAA boundary.

7.5 Scenario Simulation Sensitivity Analysis

7.5.1 Pit Inflow Rate Sensitivity Analysis

GHD conducted a sensitivity analysis on simulated pit inflow rates under wet conditions to assess the sensitivity of the simulated pit inflow rates to changes in calibrated parameter values. The pit inflow sensitivity analysis results are presented in Table 7.6 and include the following parameters:

- Pit Conductance
- Mud Lake Fault Hydraulic Conductivity
- Cameron Flowage Fault Hydraulic Conductivity
- Deep Argillite Hydraulic Conductivity
- Deep Greywacke Hydraulic Conductivity
- Shallow Argillite Hydraulic Conductivity
- Shallow Greywacke Hydraulic Conductivity

As shown in Table 7.6, the simulated pit inflow rates for the sensitivity analysis range from 677 to 1,628 m^3/d. However, the maximum inflow rate of 1,628 m^3/d corresponds to a 3,700 percent increase in the RSS compared to the calibrated wet conditions and is therefore not supported by observed groundwater elevations. Thus, the expected range in simulated pit inflow rates obtained through sensitivity analysis is from 677 to 854 m^3/d, which again compares well with the range estimate pit inflow rates of 550 to 1,450 m^3/d presented in PCA (2015).

7.5.2 COC Transport Sensitivity Analysis

The sensitivity analysis of the simulated COC concentrations was conducted in accordance with British Columbia Ministry of the Environment Guidelines (Wels et al., 2012). As described by Wels et al. (2012), there are four types of uncertainty/sensitivity:

- Type 1: Modification of this parameter within a reasonable bound has an insignificant impact on both model calibration residuals and predictive simulation results
- Type 2: Modification of this parameter within a reasonable bound has a significant impact on model calibration residuals, but has an insignificant impact on predictive simulations results
- Type 3: Modification of this parameter within a reasonable bound has a significant impact on model calibration residuals and predictive simulation results
- Type 4: Modification of this parameter within a reasonable bound has an insignificant impact on model calibration residuals, but a significant impact on predictive simulations results

Type 1 and 2 sensitivities are not of concern for predictive simulations as their impact on the predictive simulation results are insignificant. Type 3 is only of concern for an uncalibrated model and while important has been addressed through model calibration and model calibration sensitivity analysis. Type 4 is of potential cause for concern because a non-uniqueness in a model input might allow a range of valid calibrations which could have significant impact on model predictions. A non-unique model calibration can occur when model calibration residuals are insensitive to changes in a given parameter value. Therefore, in addition to testing an increase in hydraulic conductivity values for the Mud Lake Fault Zone and Cameron Flowage Fault Zone, where the model calibration sensitivity analysis identified parameters which did not significantly impact model calibration residuals, changes to those parameters were further evaluated through COC transport sensitivity analysis. The parameter changes and the subsequent change in the maximum simulated concentration for each surface water reach (i.e., grouping of surface water bodies) are presented in Tables 7.7a through 7.7u. Surface water reach locations are shown on Figure 7.16.

The COC transport sensitivity analysis shows that the maximum concentration simulated to discharge to a surface water body does not increase above Tier 2 PSS guidelines for all transport sensitivity scenarios in the instances where the initial COC transport simulations did not provide an exceedance under the base case, dry, or wet condition[4]. Where an exceedance was simulated for the initial COC transport simulations[5], the maximum concentrations discharging to a surface water body under the transport sensitivity scenarios do not increase beyond the maximum values initially simulated under the base case, dry or wet condition. Therefore, the sensitivity analysis of the simulated COC concentrations discharging to surface water does not identify any additional significant impact within the PA, LAA, or RAA.

8. Summary and Conclusions

GHD developed a 3D numerical groundwater flow model to represent the geologic and hydrogeologic conditions within the overburden and bedrock observed at the Beaver Dam Mine Site and surrounding area. The 3D groundwater flow model is based on a 3D geologic model that GHD developed for the Beaver Dam Mine Site to facilitate a rigorous representation of the observed geology. GHD directly converted the 3D geologic model into a hydraulic conductivity zone distribution to apply in the 3D groundwater flow model. The groundwater flow model was developed using the USGS's MODFLOW-NWT groundwater flow computer program. GHD calibrated the groundwater flow model to provide a reasonable representation of the groundwater elevations and groundwater flow directions demonstrated in the base case (July 18, 2018), dry (September 5, 2018) and wet (estimated wet conditions using season variations observed at the Touquoy Mine Site) calibration target datasets. Model calibration was compared against and provides a reasonable match to estimated baseflow conditions within the model domain. The model input parameters (e.g., hydraulic conductivity and recharge) applied in the calibrated model are consistent with observed Beaver Dam Mine Site conditions.

GHD conducted a sensitivity analysis of the calibrated model which demonstrated that model parameter input values were at or near their optimal values or were selected to provide a conservative bias with respect to predictive simulations. As a result, the calibrated model input parameters are considered reasonable and appropriate for providing a calibrated groundwater flow model suitable for use as a predictive tool to evaluate potential impacts of the Beaver Dam Mine Site development.

4 For the initial COC transport simulations, the following metals did not exceed both Tier 2 PSS guidelines and background concentrations in any transport simulation: antimony, calcium, chromium, cobalt, iron, lead, magnesium, manganese, mercury, molybdenum, nickel, selenium, sulphate, thallium, uranium and zinc.

5 For the initial COC transport simulations, the follow metals exceeded Tier 2 PSS guidelines and background concentrations in at least one transport simulation: aluminum, arsenic, cadmium, copper, and silver.

Using the calibrated model, GHD estimated that pit inflow rates could range from 631 to 854 m^3/d. It is further estimated that it will take approximately 13.8 years for the open pit to naturally fill to a pit lake elevation of 127 m AMSL following EOM.

GHD applied the calibrated model to estimate potential groundwater quantity impacts at EOM and PC. A maximum drawdown of 0.5 m was simulated adjacent to Cameron Flowage and simulated drawdown was generally less than 0.1 m outside of the PA, and negligible beyond the LAA. The simulated reduction in baseflow for the Cameron Flowage watershed represents approximately 5 to 7 percent of the total baseflow, and under 2 percent of the total estimated average annual flow in Cameron Flowage. Approximately 85 percent of the simulated baseflow reduction occurs within the PA, with the remaining 15 percent occurring within the LAA, supporting that Beaver Dam Mine Site development will not impact groundwater quantity beyond the LAA. Furthermore, all groundwater discharge to mine features will be managed and discharged to Cameron Flowage following treatment. Therefore, the total flow average annual flow in Cameron Flowage should not be impacted by the Beaver Dam Mine Site development during operation and once the pit lake has been filled and discharges naturally to Cameron Flowage.

GHD also applied the calibrated groundwater model to simulate potential COC impacts to surface water bodies surrounding the Beaver Dam Mine Site. No significant simulated COC impacts to surface water bodies were predicted at EOM. At PC, using the Base Case (i.e., median) source concentrations, aluminum, arsenic and cadmium are simulated to discharge to Crusher Lake, within the PA, above the Tier 2 PSS guidelines, but within the range of the observed background concentrations in groundwater. Silver and copper concentrations simulated to discharge to Crusher Lake exceed both the Tier 2 PSS guidelines and the background levels. Using the Upper Case (i.e., 90th percentile) source concentrations, aluminum, silver, arsenic, cadmium, and copper are simulated to exceed both the Tier 2 PSS guidelines and the background levels in groundwater discharge to Crusher Lake within the PA. Aluminum and copper also discharge to surface water above the Tier 2 PSS guidelines and the background levels towards the west end of Mud Lake, to the tributary immediately adjacent to the west waste rock pile and to Cameron Flowage, within the LAA. No significant impacts to groundwater quality is simulated beyond the LAA; and no impacts, significant or insignificant are simulated towards the RAA boundary.

Model development and predictive scenario analysis is based on data available at the time of model development. As additional data is collected during the development of the Beaver Dam Mine Site, it is recommended that the calibrated model and predictive scenario results be updated, as warranted.

All of Which is Respectfully Submitted,

GHD

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Project Manager:

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Peter Oram, P.Geo.

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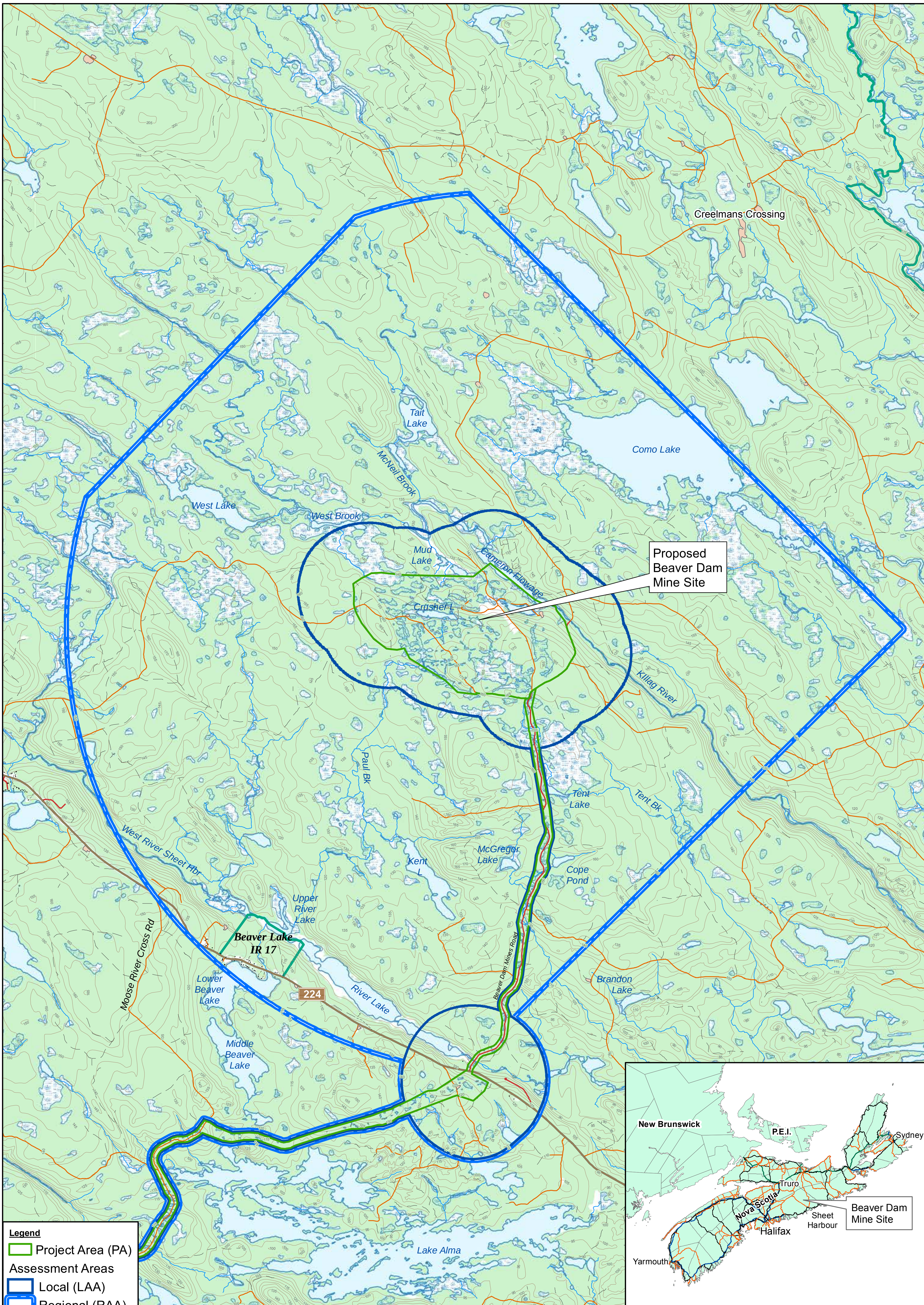
Figures



Source: Service Nova Scotia, Atlantic Mining NS, GHD, McCallum Environmental

0 500 1,000 1,500
Meters

Coordinate System:
NAD 1983 CSRS UTM Zone 20N

GHD

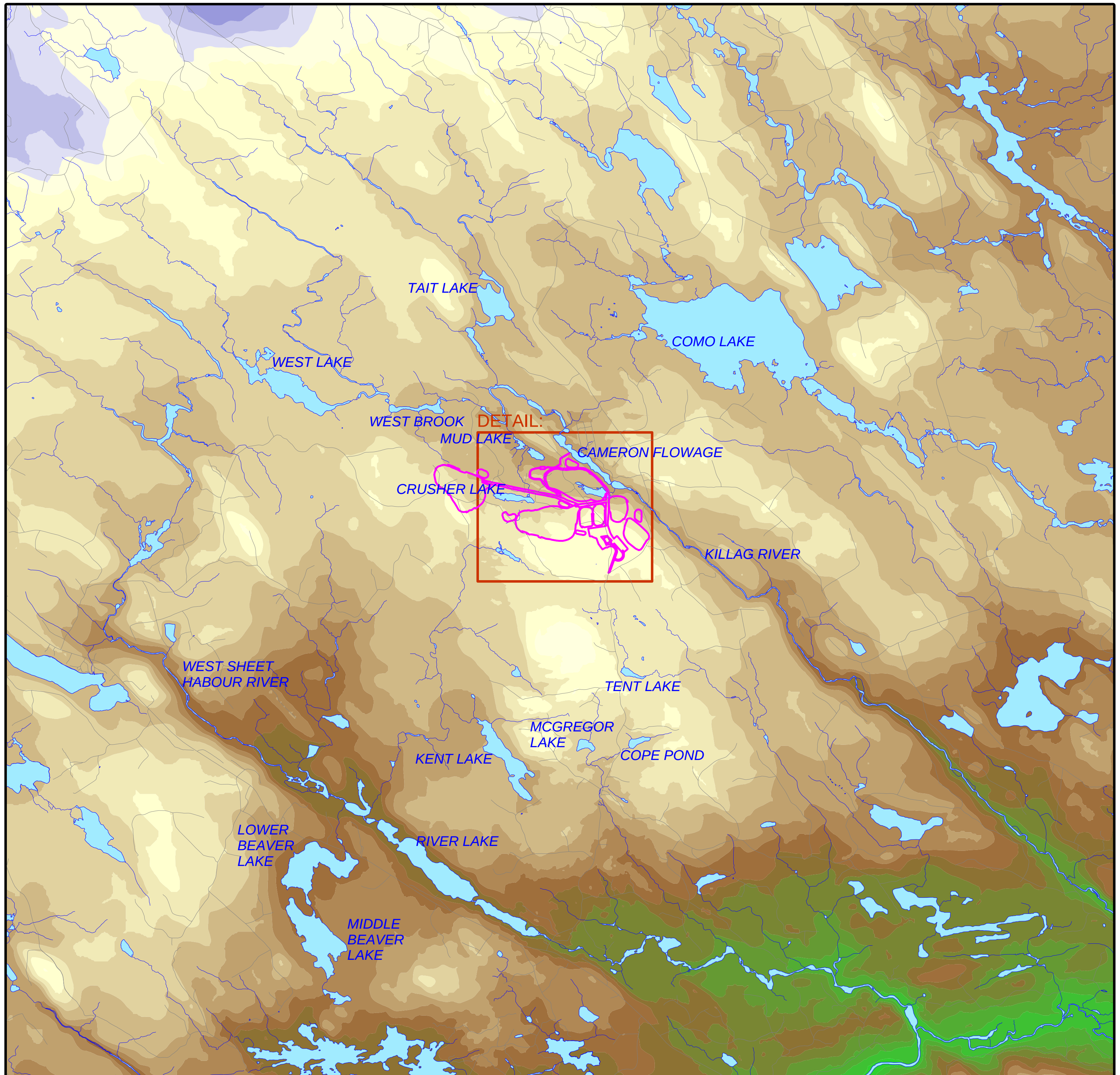
ATLANTIC GOLD CORPORATION
MARINETTE, NOVA SCOTIA
BEAVER DAM MINE

088664 (009)
Dec 18, 2018

BEAVER DAM MINE SITE LOCATION

FIGURE 1.1

GIS File: I:\GIS_DATA\Projects\6-chars\08----\088---\088664 Atlantic BD\088664(009)\088664-20(009)_GIS-DA002.mxd



LEGEND

SURFACE WATER BODY

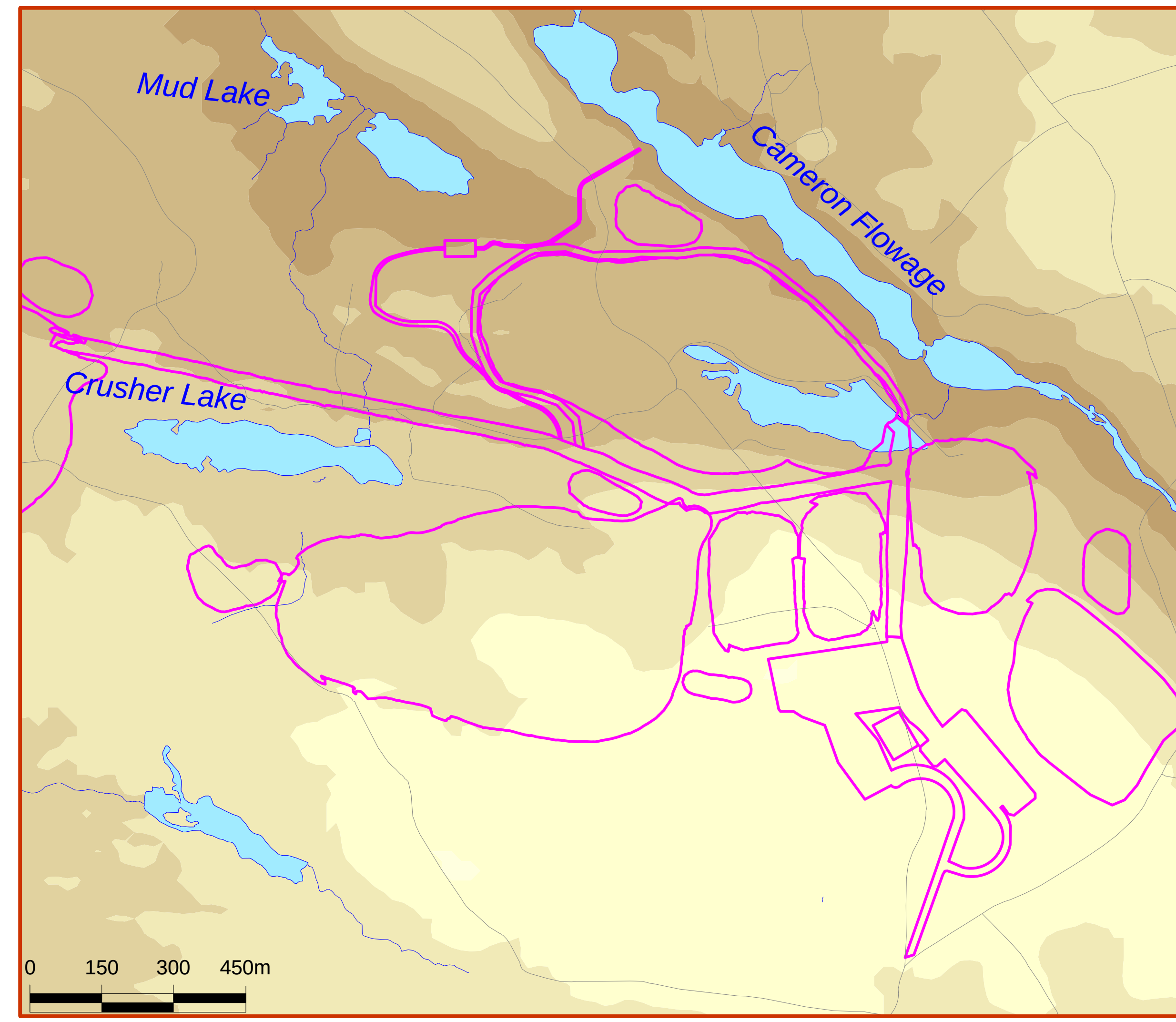
MINE FEATURES

ROAD

GROUND SURFACE ELEVATION (m AMSL)

0 20 40 60 80 100 120 140 160 180 200

DETAIL:



0 700 1,400 2,100m

N

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BEAVER DAM MINE

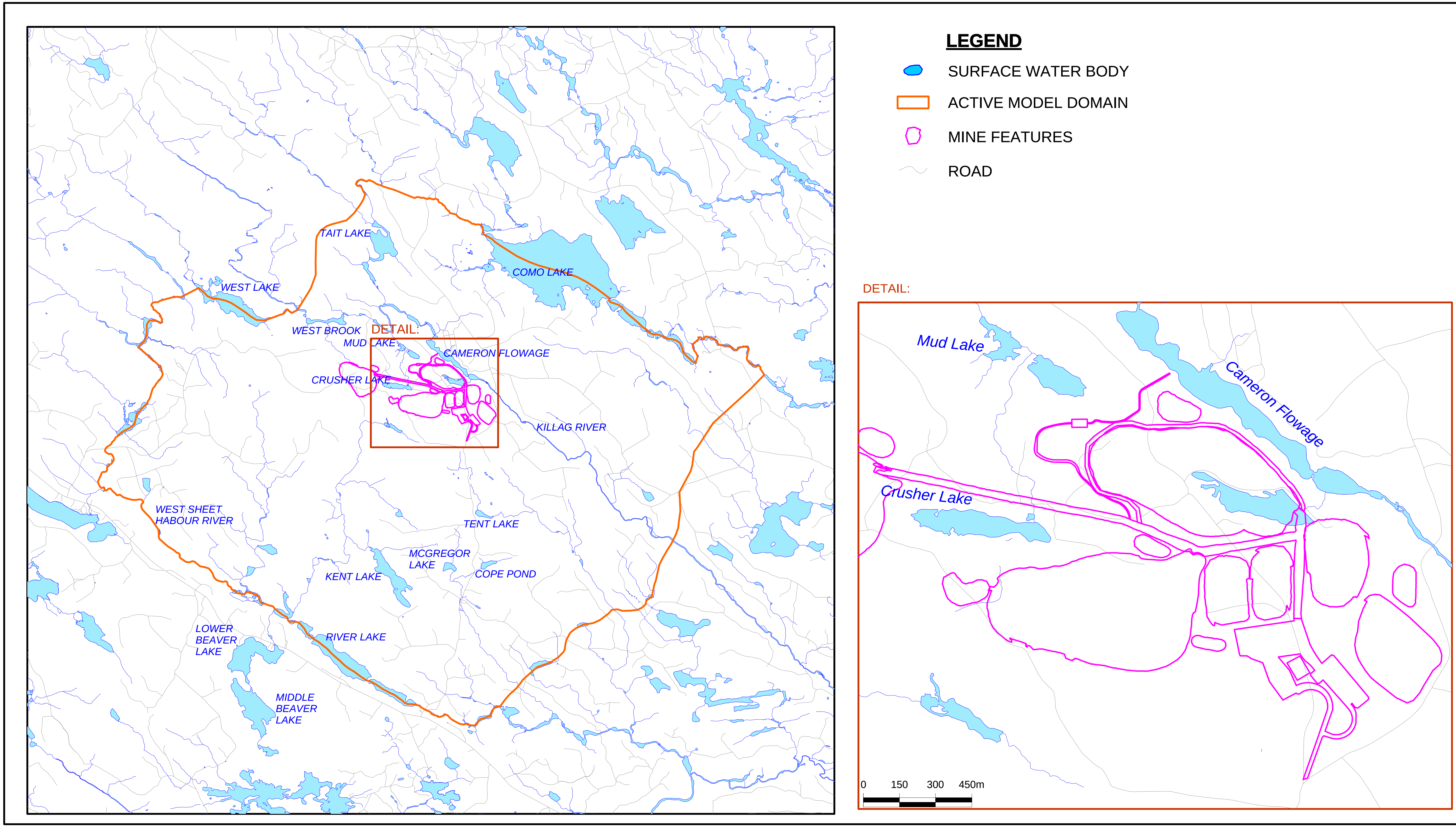
PRE-MINING TOPOGRAPHY

088664-020

February 20, 2019

FIGURE 2.1

HEG file: Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\Figure 2.1 - Pre-Mining Topography.srf



0 700 1,400 2,100m

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BEAVER DAM MINE

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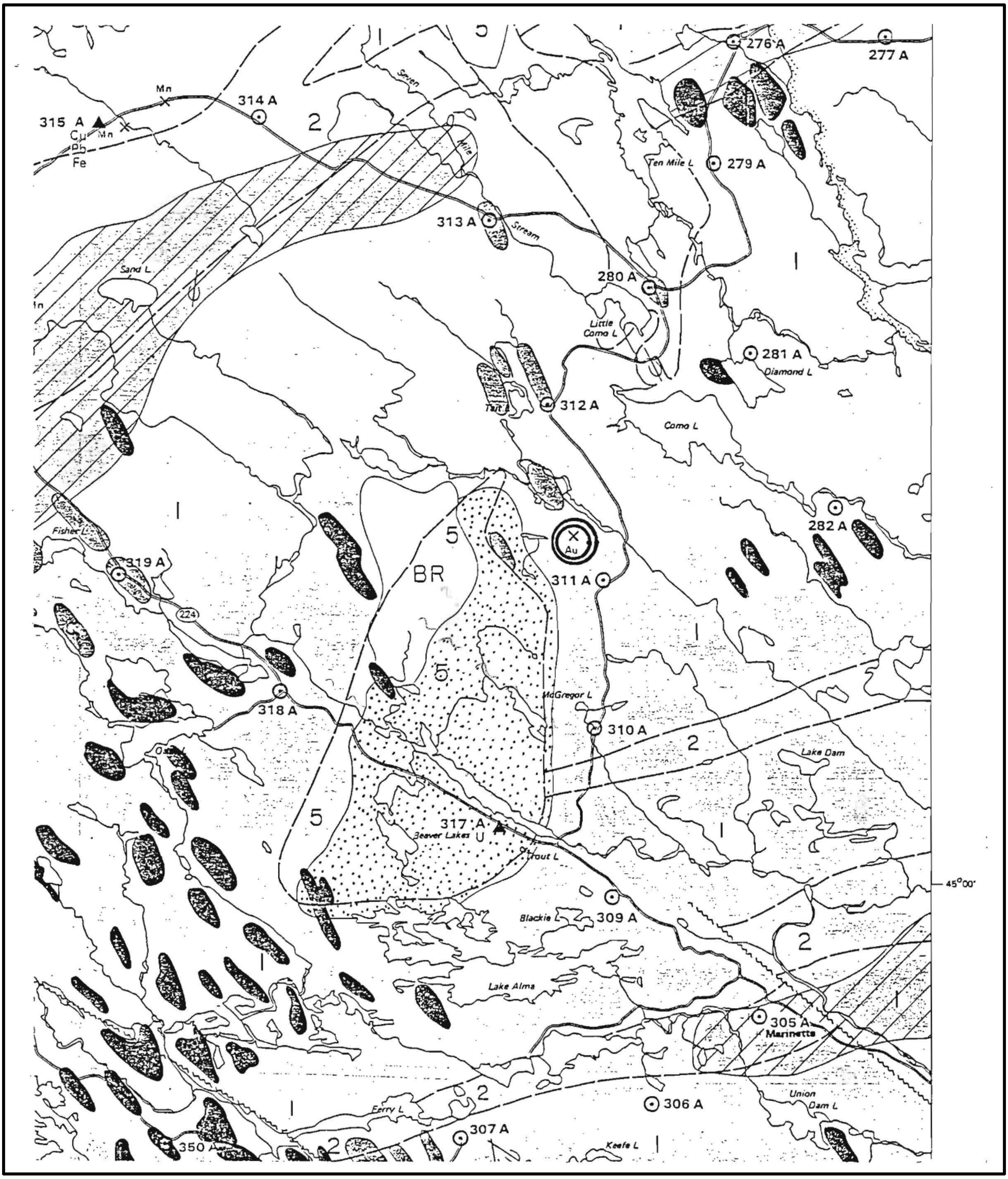
SURFACE WATER FEATURES

FIGURE 2.2

HEG file: Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\RPTFigures\Figure 2.2- Surface Water Features.srf



SOURCE:
NOVA SCOTIA DEPARTMENT OF MINES & ENERGY ON ENVIRONMENTAL ASSESSMENT OF GOLD MINING EXPLORATION, BEAVER DAM, NOVA SCOTIA. REPORT 86-005, 1965.
PRODUCED BY JACQUES, WHIRFORD AND ACCOCIATES LIMITED AND P. LANE AND ASSOCIATES LLIMITED. (1986)

LEGEND

- SLATE TILL
- QUARTZITE TILL
- GRANITE TILL
- SILT-CLAY TILL DRUMLIN
- LOCATION OF BEAVERDAM MINE

Bedrock Geology

12	Basalt, sandstone, shale	6	Mixed sedimentary and volcanic rocks
11	Sedimentary rocks	5	Granite: mainly granite
10	Marginal basin sedimentary rocks	4	Torbrook formation
9	Marginal basin sedimentary rocks	3	White rock
8	Continential and marginal basin sedimentary rocks	2	Halifax formation
7	Undifferentiated sedimentary and volcanic rocks	1	Goldenville formation

0 70 140 210km

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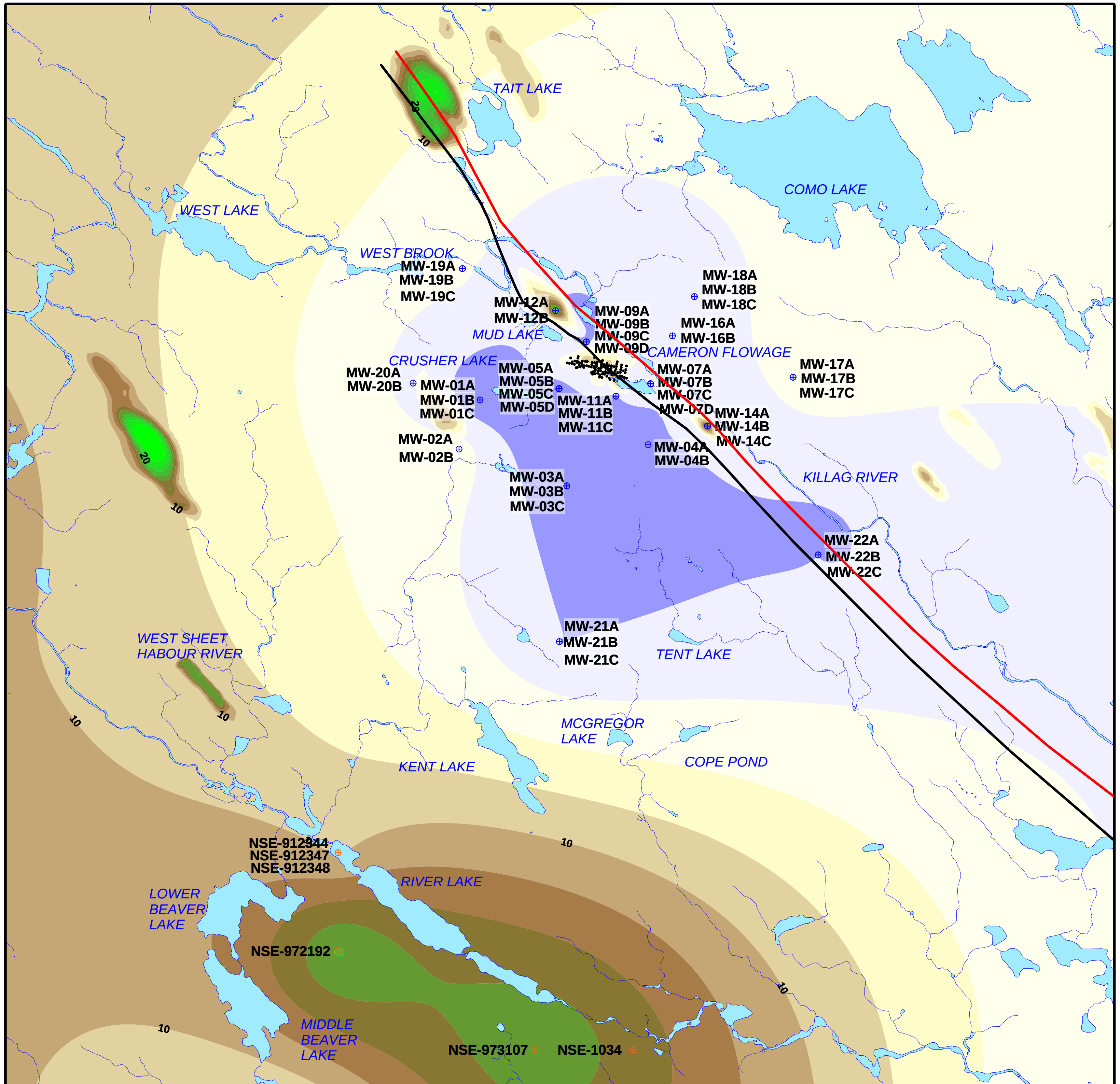
BEAVER DAM MINE

LOCATION OF DRUMLINS

088664-020
Nov 9, 2018

FIGURE 2.3

Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\RPTFigures\Figure2.3 - Location of Drumlins.srf



LEGEND

SURFACE WATER BODY

MUD LAKE FAULT

CAMERON FLOWAGE FAULT

MW-17A GROUNDWATER MONITORING LOCATIONS

EXPLORATORY DRILLHOLE LOCATIONS

NSE-1034 REGIONAL WELL RECORD LOCATIONS

OVERBURDEN THICKNESS (m)

0 2 4 6 8 10 12 14 16 18 20 22 24

0 700 1,400 2,100m

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BEAVER DAM MINE

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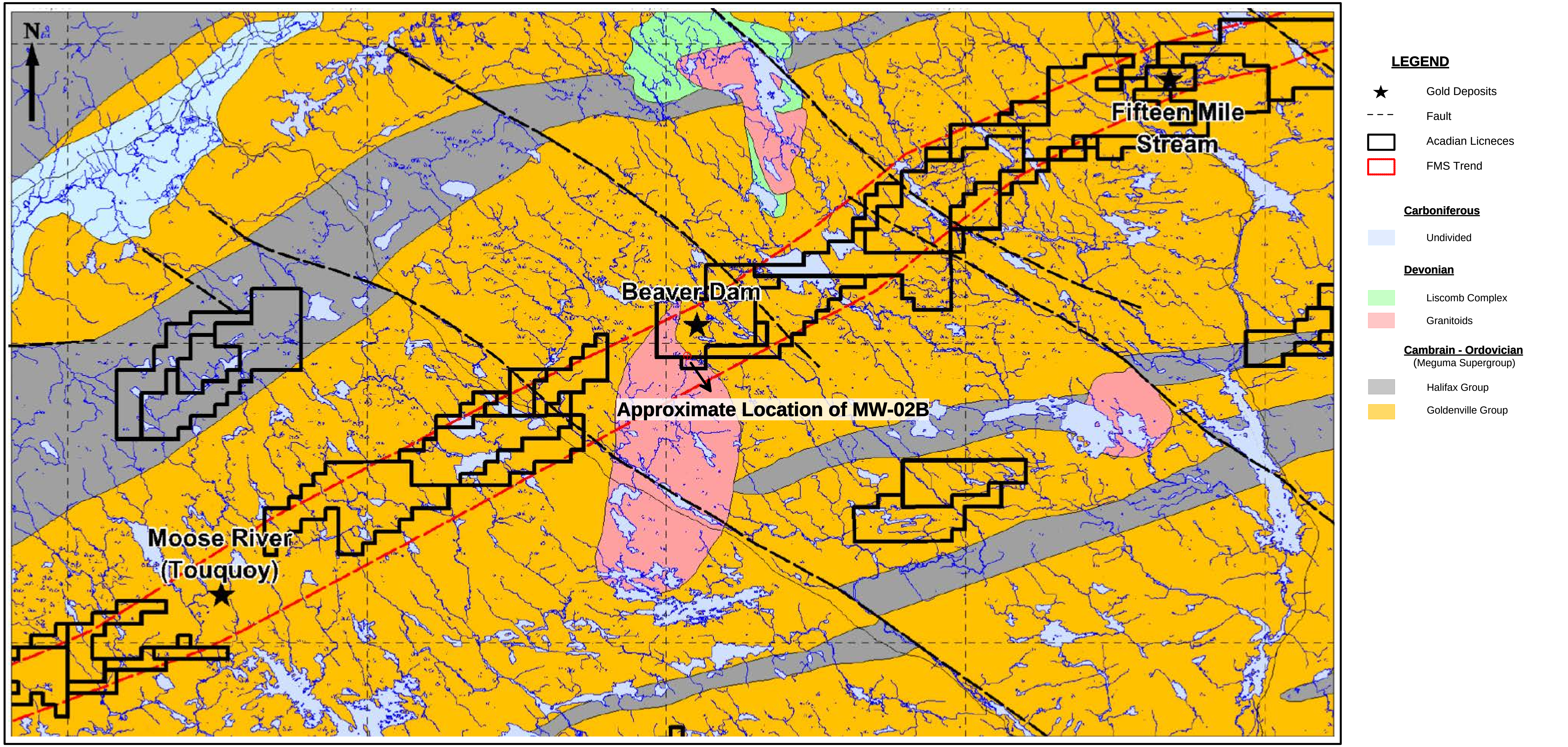
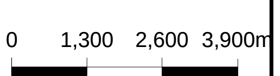
ESTIMATED OVERBURDEN THICKNESS

FIGURE 2.4

Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\RPTFigures\Figure 2.4 - Estimated Overburden Thickness.srf



SOURCE:
ANNUAL QUALIFIED PERSONS REPORT FOR BEAVER DAM GOLD PROJECT, HALIFAX, NOVA SCOTIA - YEAR ENDED 31 MARCH 2014 - LIONGOLD CORPORATION LIMITED, SINGAPORE PREPARED IN ACCORDANCE WITH THE REQUIREMENTS OF SINGAPORE EXCHANGE PRACTICE NOTE 6.3. PRODUCED BY DR SIMON DOMINY AND MR RICHARD HORNE



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REGIONAL GEOLOGY

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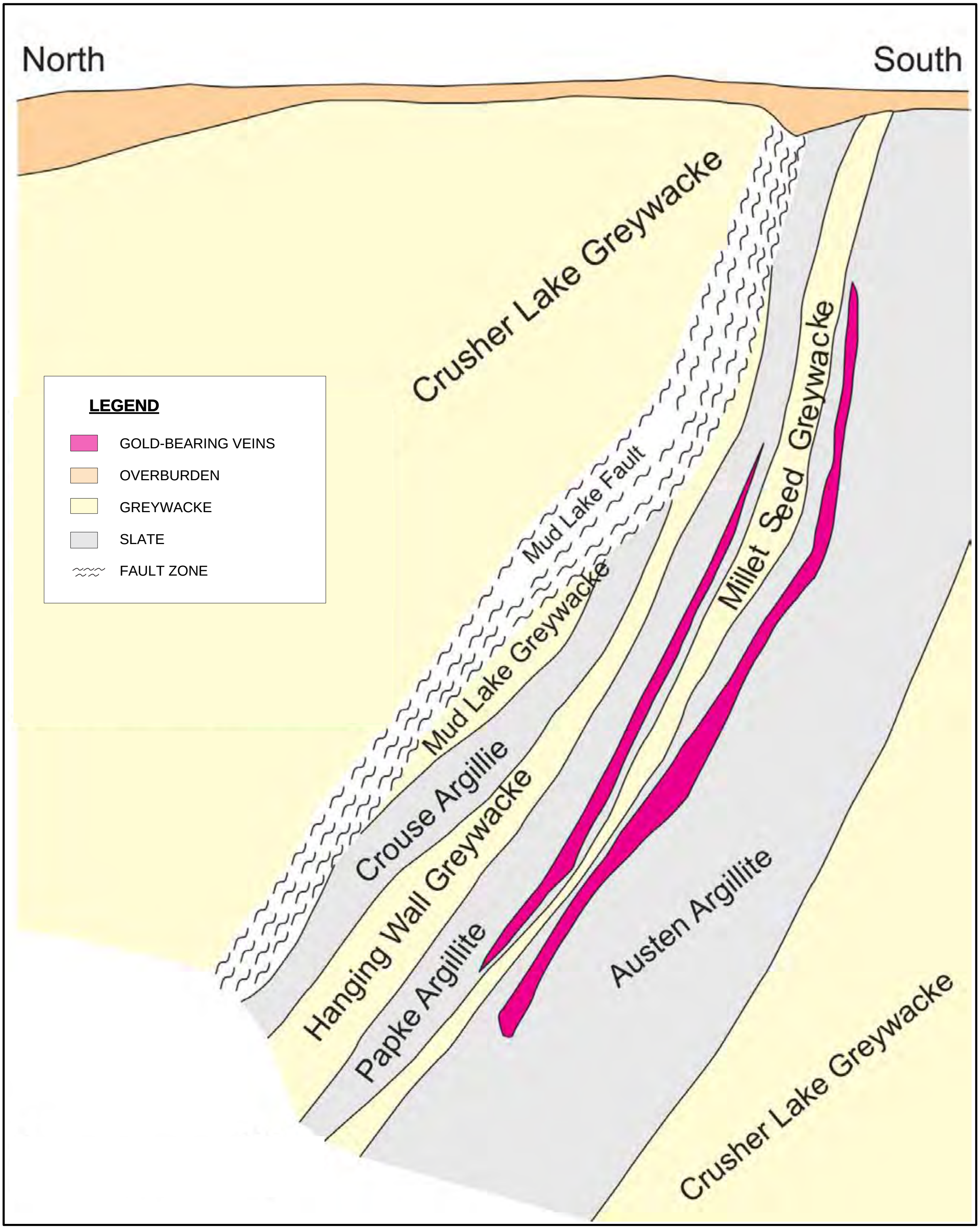
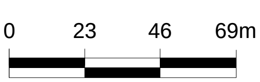
February 20, 2019

FIGURE 2.5



SOURCE: SANGSTER, A.L.,AND SMITH, P.K., 2007, METALLOGENIC SUMMARY OF THE MEGUMA GOLD DEPOSITS, NOVA SCOTIA, IN GOODFELLOW, W.D., ED., MINERAL DEPOSITS OF CANADA: A SYNTHESIS OF MAJOR DEPOSIT-TYPES, DISTRICT METALLOGENY, THE EVOLUTION OF GEOLOGICAL PROVINCES



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BEAVER DAM MINE

SECTION THROUGH BEAVER DAM DEPOSIT

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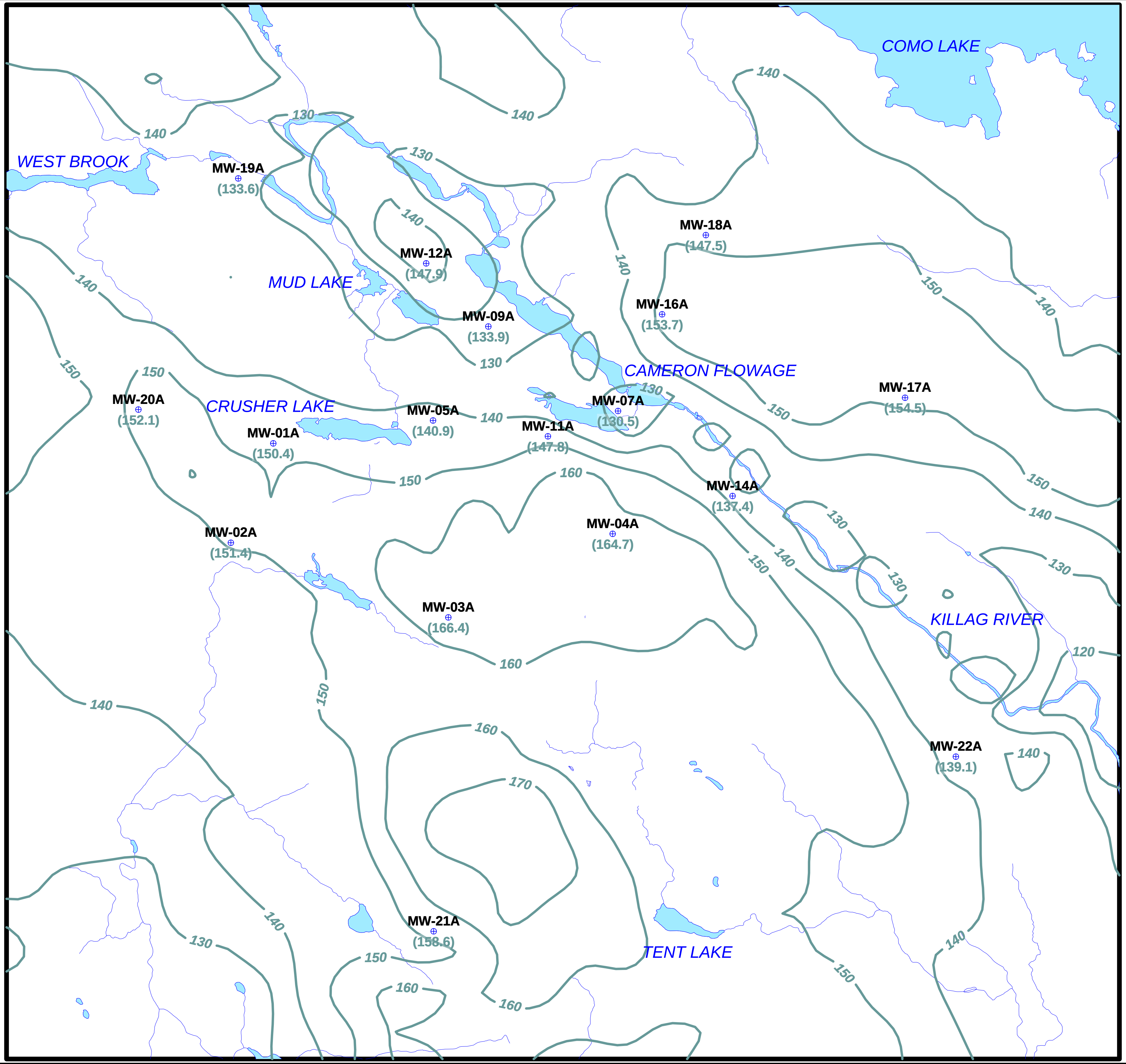
FIGURE 2.6



LEGEND

SURFACE WATER BODY

MW-17A — WATER LEVEL MONITORING LOCATION

(154.5) — OVERBURDEN GROUNDWATER ELEVATION MEASURED ON JULY 18, 2018 (m AMSL)

140 — OBSERVED OVERBURDEN GROUNDWATER ELEVATION CONTOURS - JULY 18, 2018 (m AMSL)

0 600 1,200 1,800m

N

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MARINETTE, NOVA SCOTIA
BEAVER DAM MINE

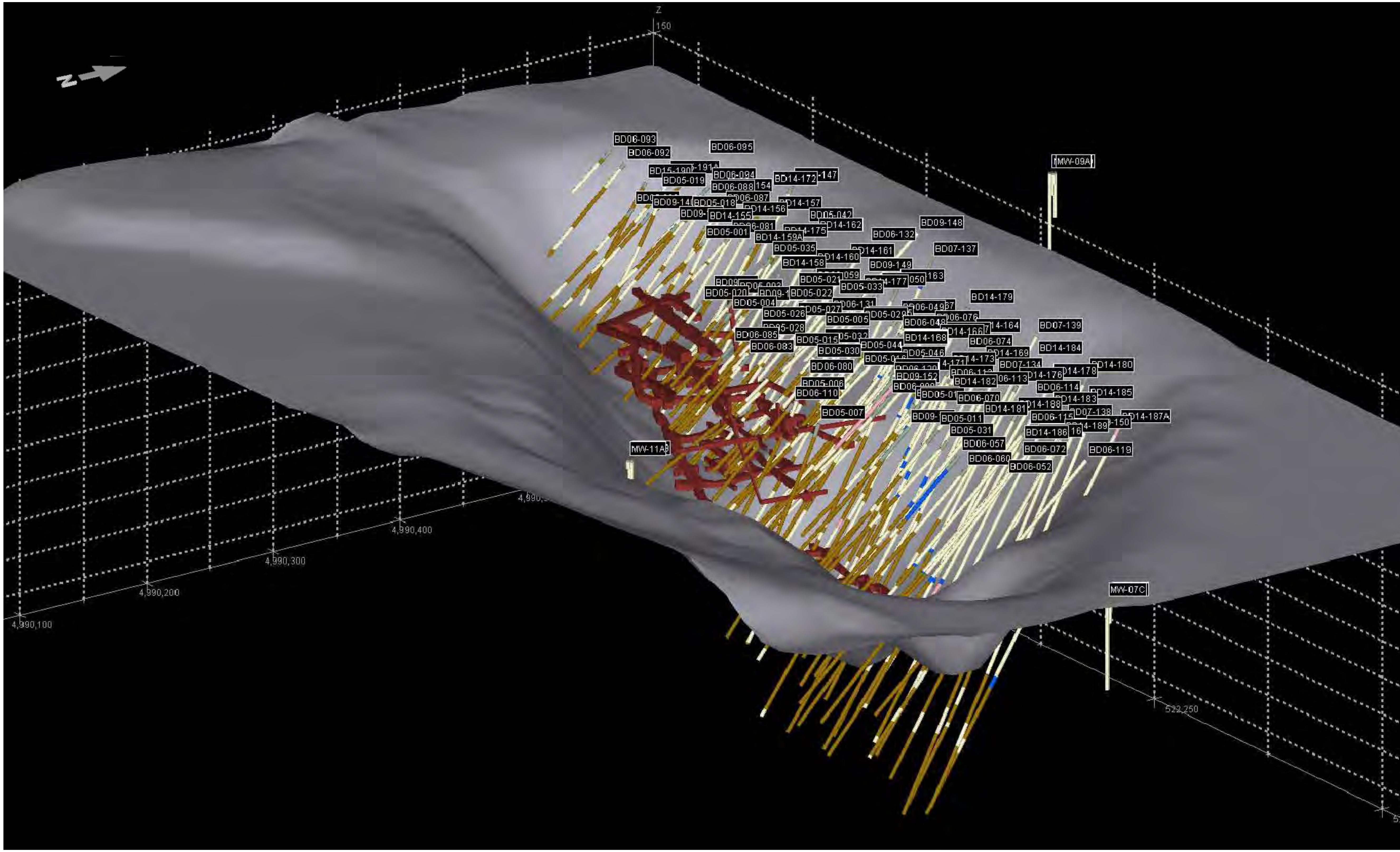
OBSERVED OVERBURDEN GROUNDWATER ELEVATION CONTOURS - JULY 18, 2018

088664-020

February 20, 2019

FIGURE 2.7

HEG file: Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\RPTFigures\Figure 2.7 - Observed Overburden Groundwater Elevation Contours - July 18, 2018.srf



LEGEND

HISTORICAL MINE WORKINGS
PROPOSED MINE EXCAVATION

OVERBURDEN
ARGILLITE
GREYWACKE
MUD LAKE FAULT
UNDEFINED

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MARINETTE, NOVA SCOTIA
BEAVER DAM MINE

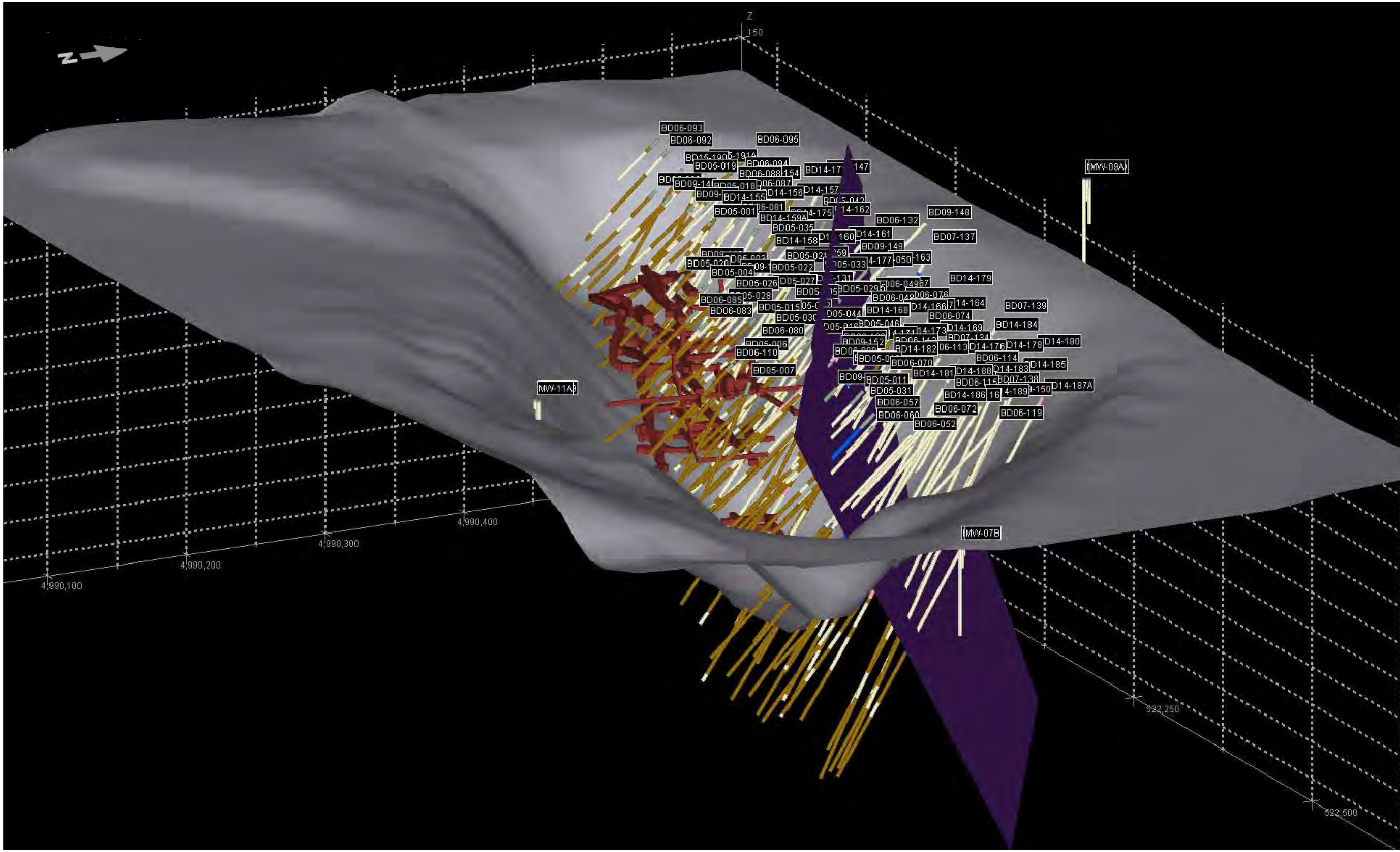
HISTORIC MINE WORKINGS

88664-00

Dec 18, 2018

FIGURE 2.8

CAD File: P:\drawings\88000s\88664\88664-reports\88664-00(009)\88664-00(009)GN\88664-00(009)GN-WA001.dwg



LEGEND

- HISTORICAL MINE WORKINGS
- PROPOSED MINE EXCAVATION
- APPROXIMATE MUD LAKE FAULT LOCATION

- OVERBURDEN
- ARGILLITE
- GREYWACKE
- MUD LAKE FAULT
- UNDEFINED

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MARINETTE, NOVA SCOTIA
BEAVER DAM MINE

88664-00

Dec 18, 2018

APPROXIMATE MUD LAKE FAULT LOCATION

FIGURE 2.9

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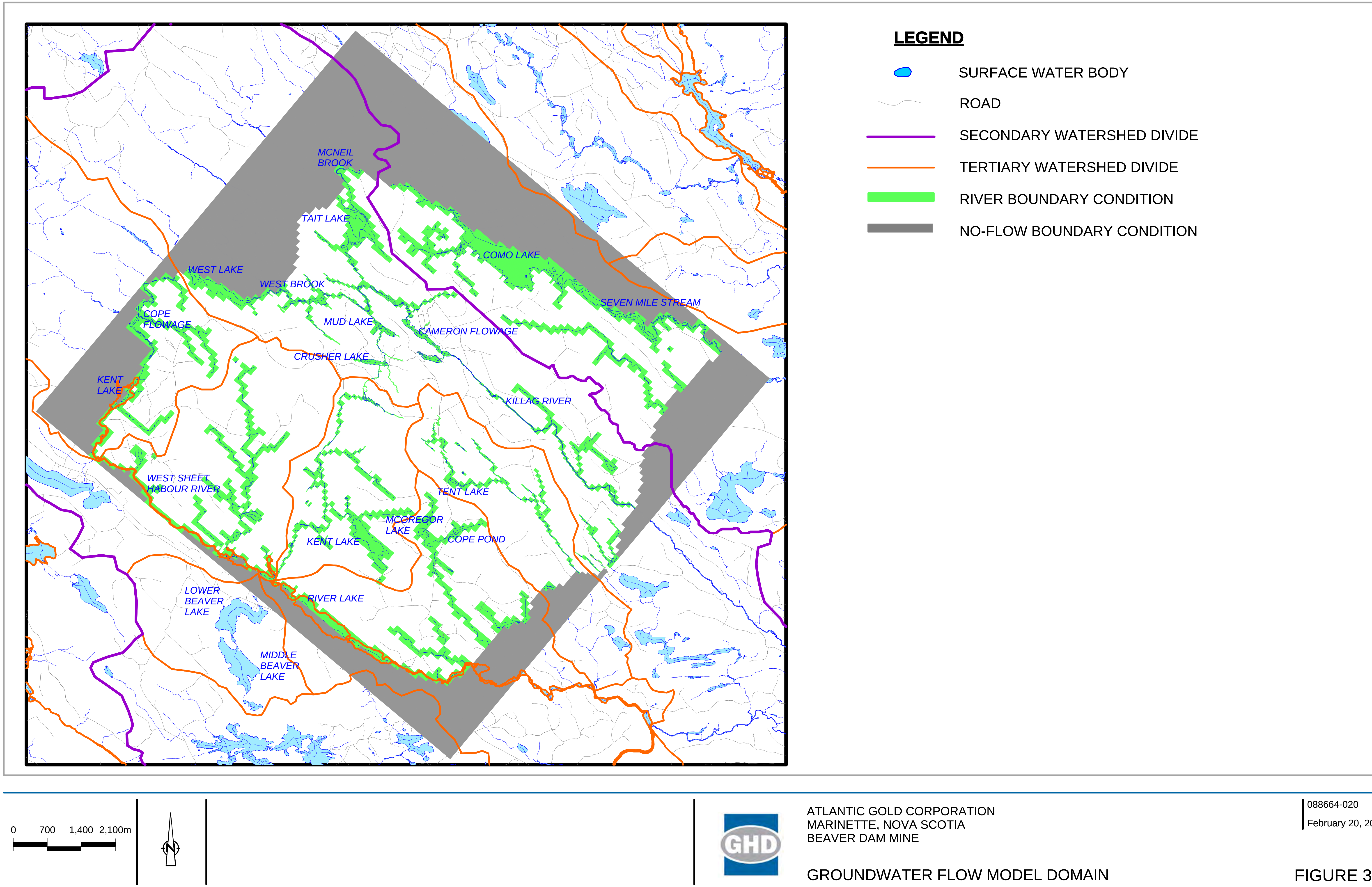

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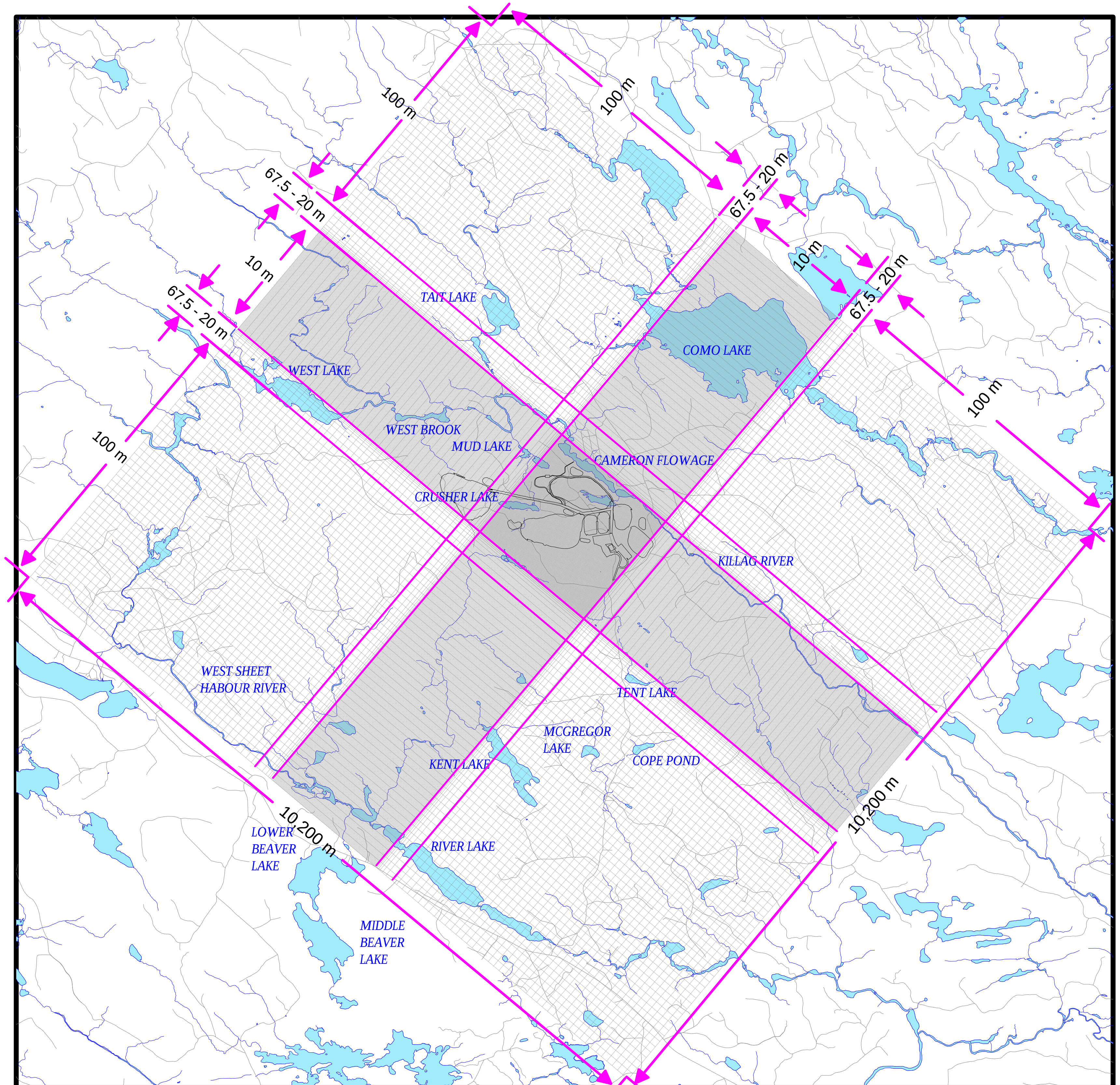
MARINETTE, NOVA SCOTIA
BEAVER DAM MINE

GROUNDWATER FLOW MODEL DOMAIN

088664-020
February 20, 2019

FIGURE 3.1

HEG file: Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\Figure 3.1 - Groundwater Flow Model Domain.srf



LEGEND

SURFACE WATER BODY

FINITE-DIFFERENCE GRID

10 m — HORIZONTAL FINITE-DIFFERENCE GRID SPACING

BEGINNING OF MODEL CELL SIZE TRANSITION

ROAD

0 700 1,400 2,100m

N

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BEAVER DAM MINE

FINITE-DIFFERENCE GRID

088664-020

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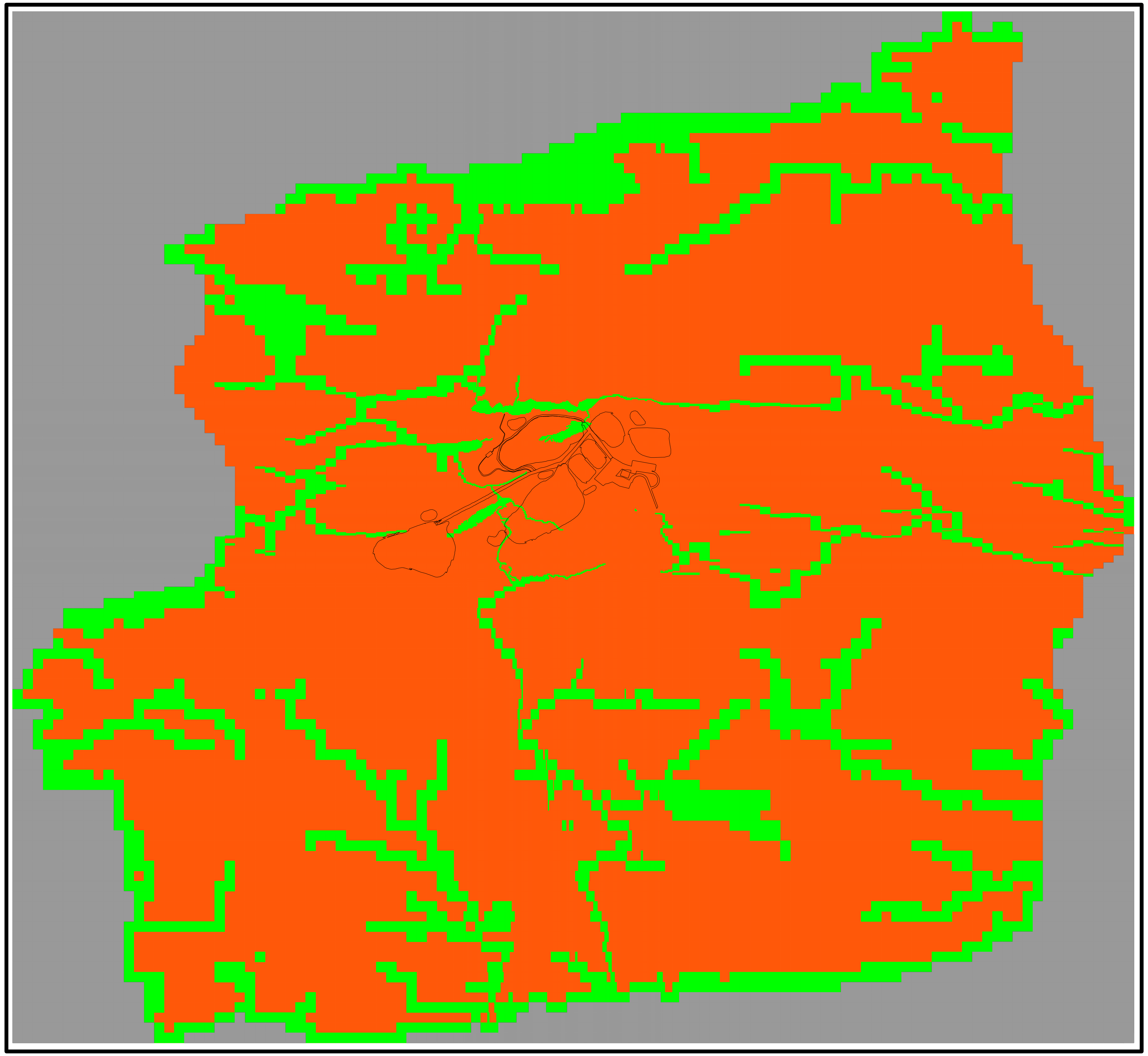
FIGURE 5.1

HEG file: Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\Figure 5.1 - Finite-Difference Grid.srf



LEGEND

RIVER BOUNDARY CONDITION

NO-FLOW BOUNDARY CONDITION

HYDRAULIC CONDUCTIVITY ZONES

OVERBURDEN

0 1.270 2,540 3,810m

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MARINETTE, NOVA SCOTIA
BEAVER DAM MINE

HYDRAULIC CONDUCTIVITY DISTRIBUTION IN OVERBURDEN (LAYER 1)

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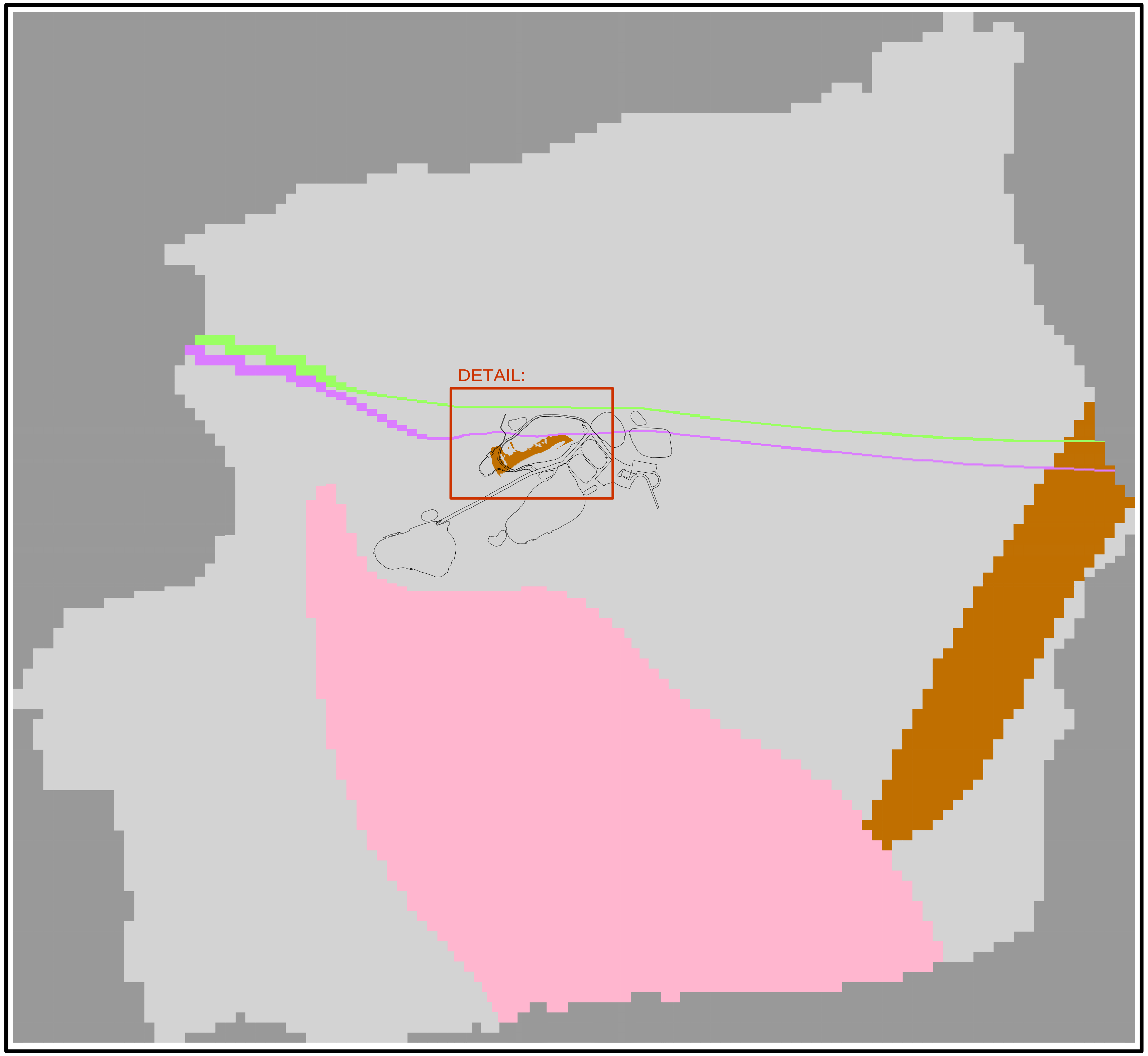
February 20, 2019

FIGURE 5.2

HEG file: Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\Figure 5.2 - Hydraulic Conductivity Distribution in Overburden (Layer 1).srf



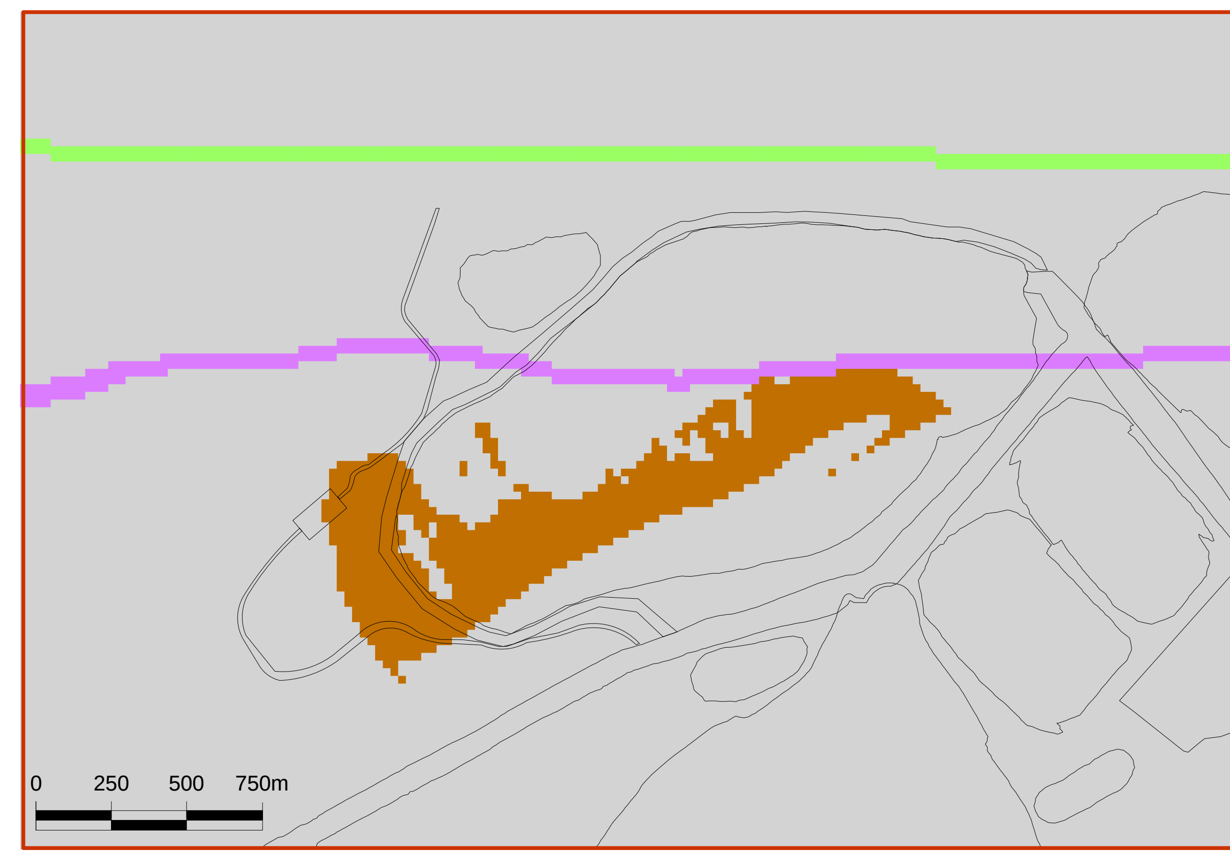
LEGEND

NO-FLOW BOUNDARY CONDITION

HYDRAULIC CONDUCTIVITY ZONES

- SHALLOW BEDROCK GREYWACKE FORMATION
- SHALLOW BEDROCK GRANITE FORMATION
- SHALLOW BEDROCK ARGILLITE FORMATION
- SHALLOW MUD LAKE FAULT
- SHALLOW CAMERON FLOWAGE FAULT

DETAIL:



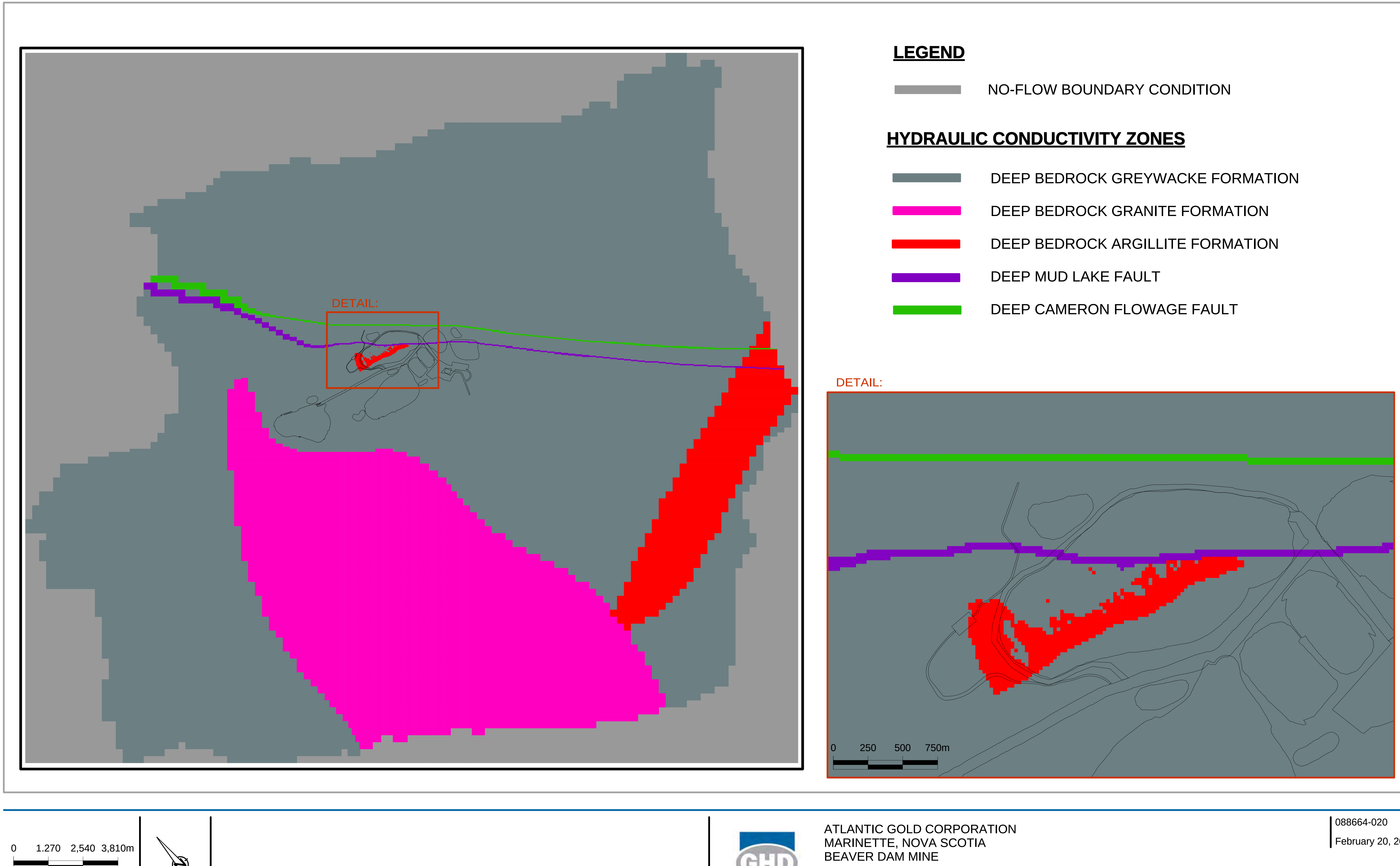
0 1.270 2,540 3,810m

ATLANTIC GOLD CORPORATION
MARINETTE, NOVA SCOTIA
BEAVER DAM MINE

088664-020
February 20, 2019

HYDRAULIC CONDUCTIVITY DISTRIBUTION IN SHALLOW BEDROCK (LAYER 2)

FIGURE 5.3



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BEAVER DAM MINE

HYDRAULIC CONDUCTIVITY DISTRIBUTION IN DEEP BEDROCK (LAYER 3)

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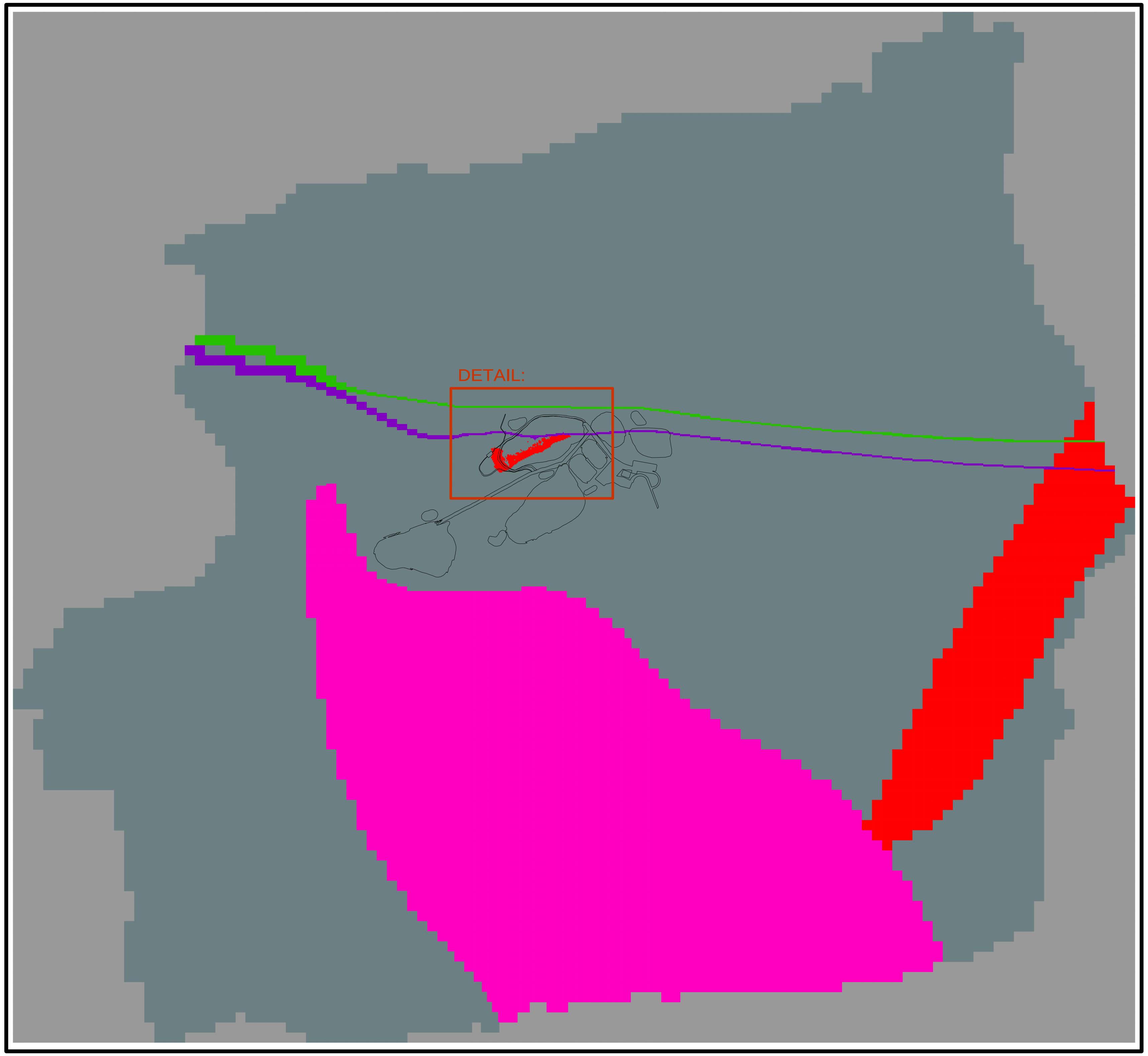
FIGURE 5.4

HEG file: Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\Figure 5.4 - Hydraulic Conductivity Distribution in Deep Bedrock (Layer 3).srf



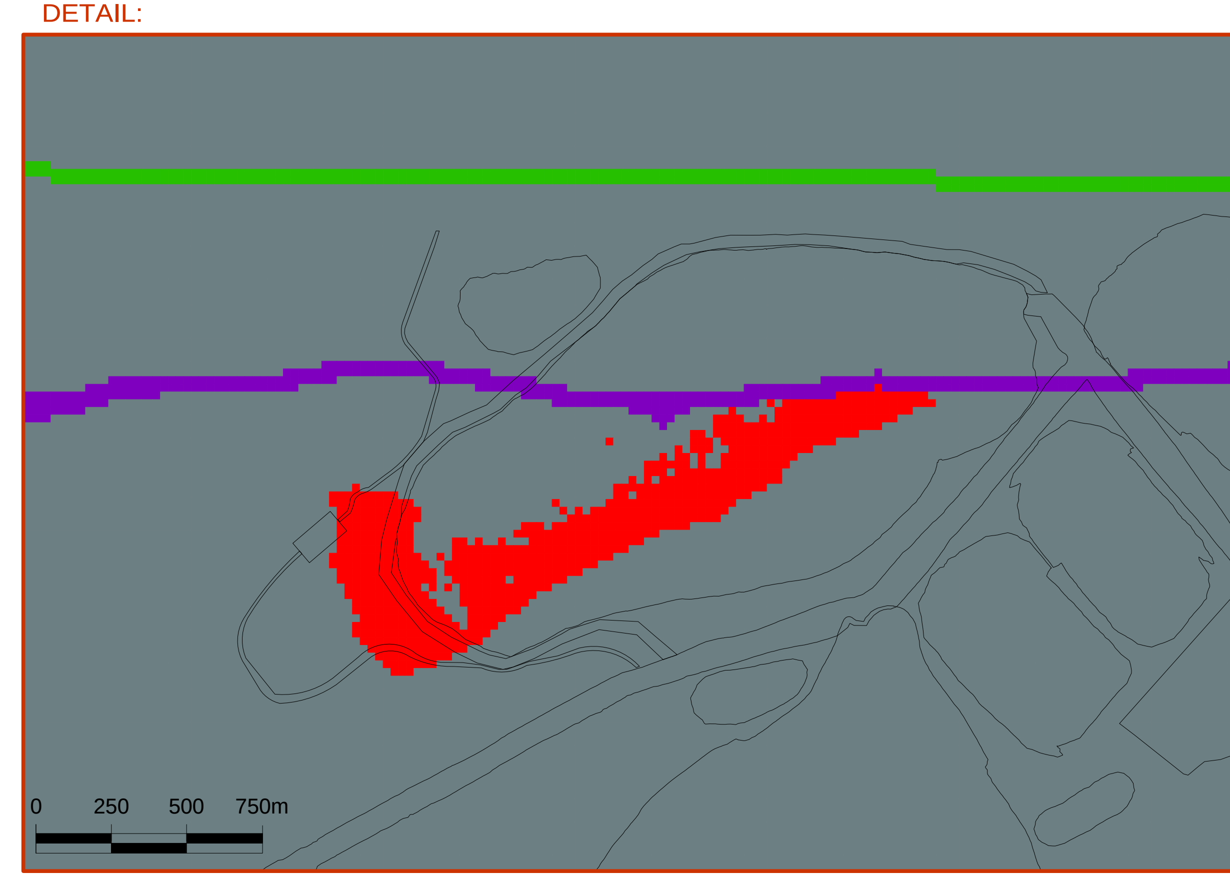
LEGEND

NO-FLOW BOUNDARY CONDITION

HYDRAULIC CONDUCTIVITY ZONES

- DEEP BEDROCK GREYWACKE FORMATION
- DEEP BEDROCK GRANITE FORMATION
- DEEP BEDROCK ARGILLITE FORMATION
- DEEP MUD LAKE FAULT
- DEEP CAMERON FLOWAGE FAULT

DETAIL:



0 1.270 2,540 3,810m

ATLANTIC GOLD CORPORATION
MARINETTE, NOVA SCOTIA
BEAVER DAM MINE

HYDRAULIC CONDUCTIVITY DISTRIBUTION IN DEEP BEDROCK (LAYER 4)

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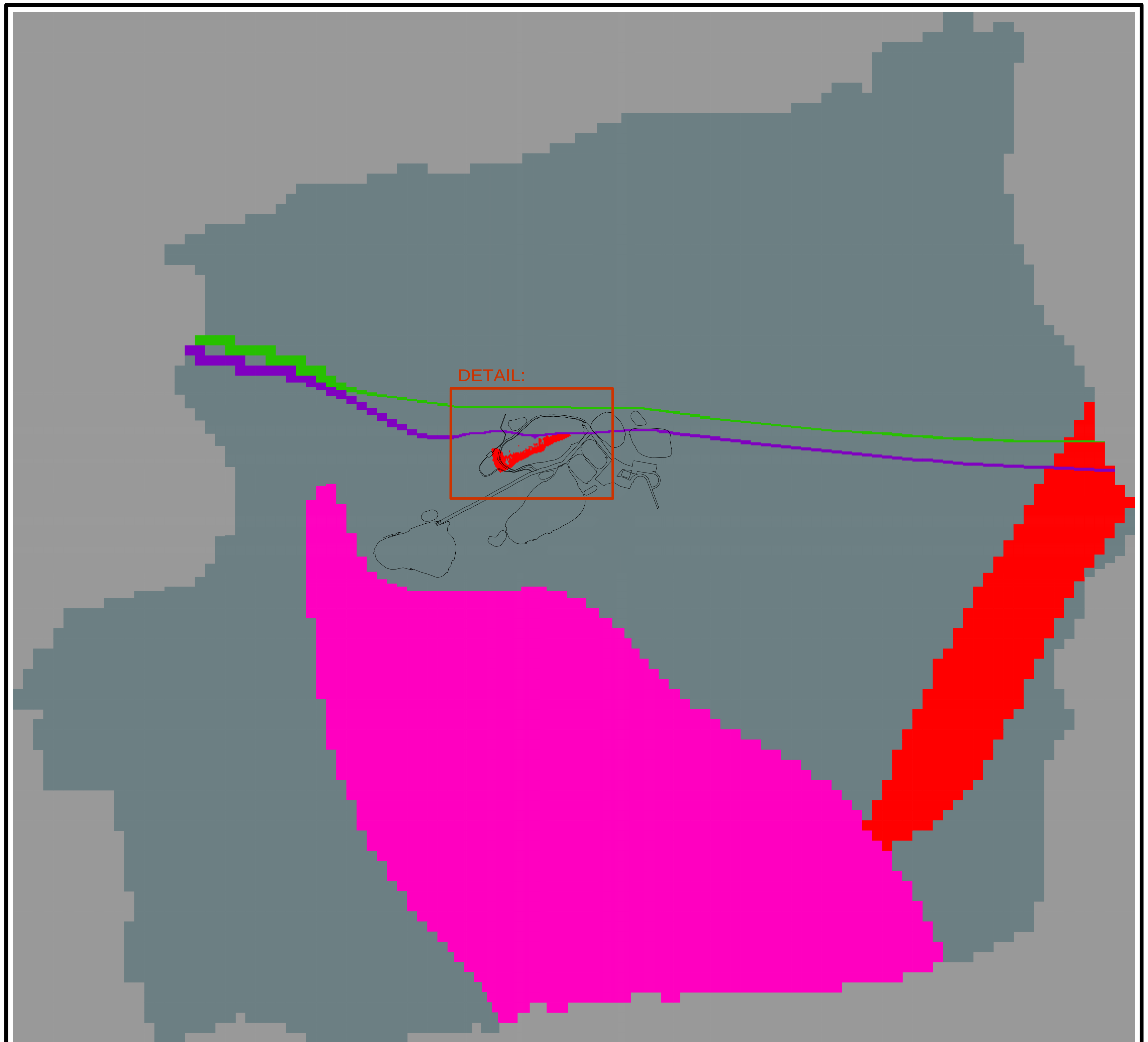
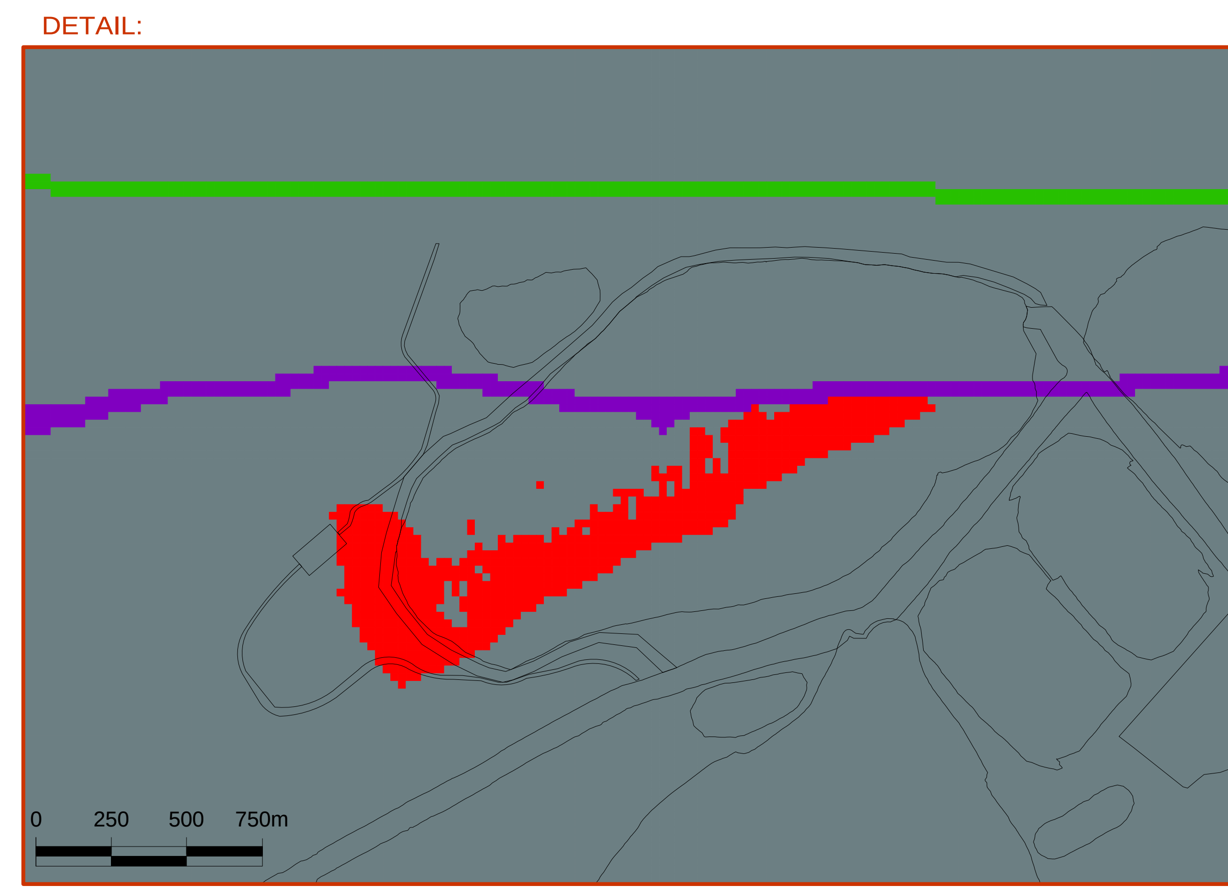
FIGURE 5.5

HEG file: Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\Figure 5.5 - Hydraulic Conductivity Distribution in Deep Bedrock (Layer 4).srf





LEGEND

NO-FLOW BOUNDARY CONDITION

HYDRAULIC CONDUCTIVITY ZONES

DEEP BEDROCK GREYWACKE FORMATION

DEEP BEDROCK GRANITE FORMATION

DEEP BEDROCK ARGILLITE FORMATION

DEEP MUD LAKE FAULT

DEEP CAMERON FLOWAGE FAULT

0 1.270 2,540 3,810m

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HYDRAULIC CONDUCTIVITY DISTRIBUTION IN DEEP BEDROCK (LAYER 5)

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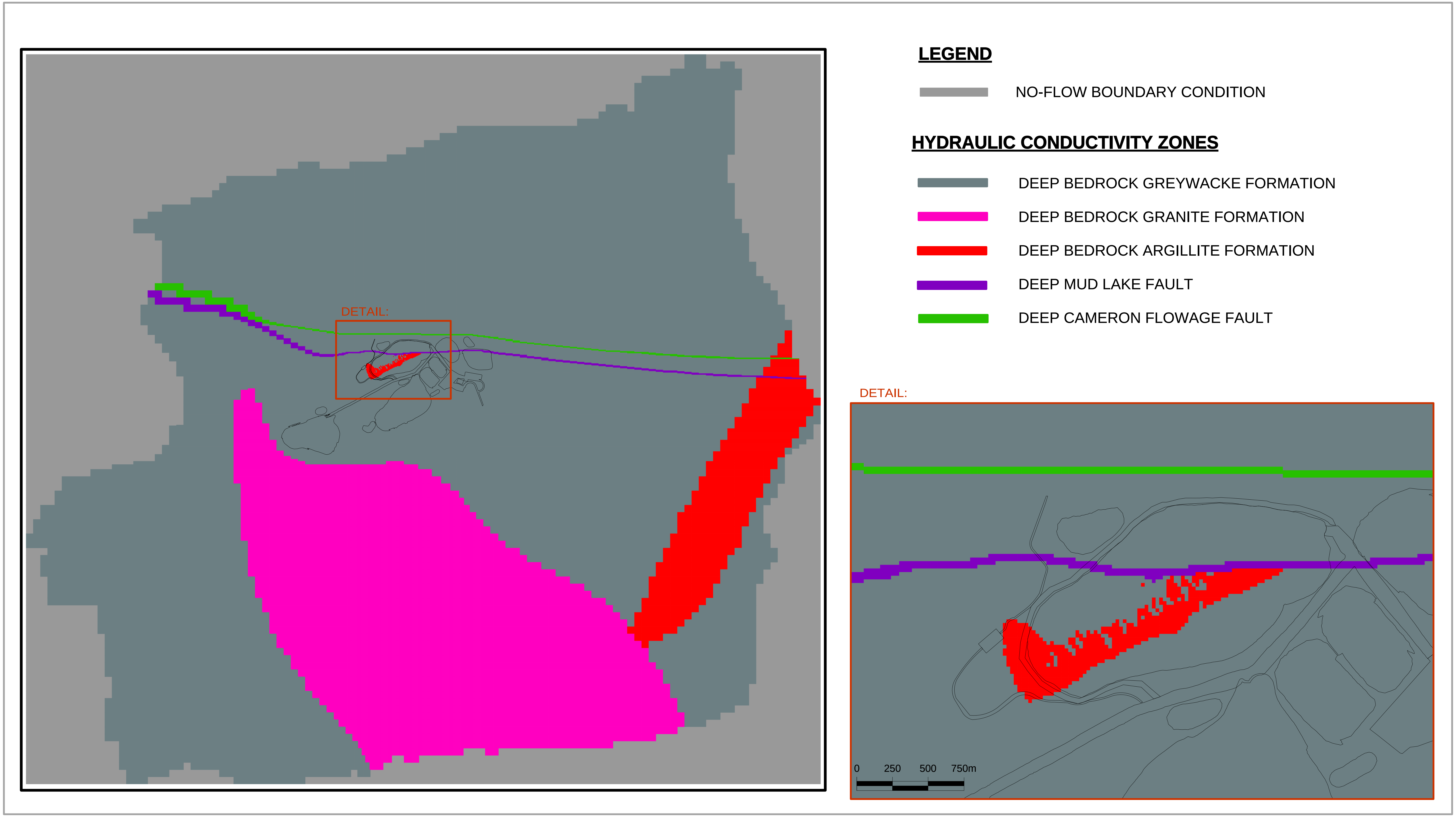
FIGURE 5.6

HEG file: Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\Figure 5.6 - Hydraulic Conductivity Distribution in Deep Bedrock (Layer 5).srf



0 1.270 2,540 3,810m

ATLANTIC GOLD CORPORATION
MARINETTE, NOVA SCOTIA
BEAVER DAM MINE

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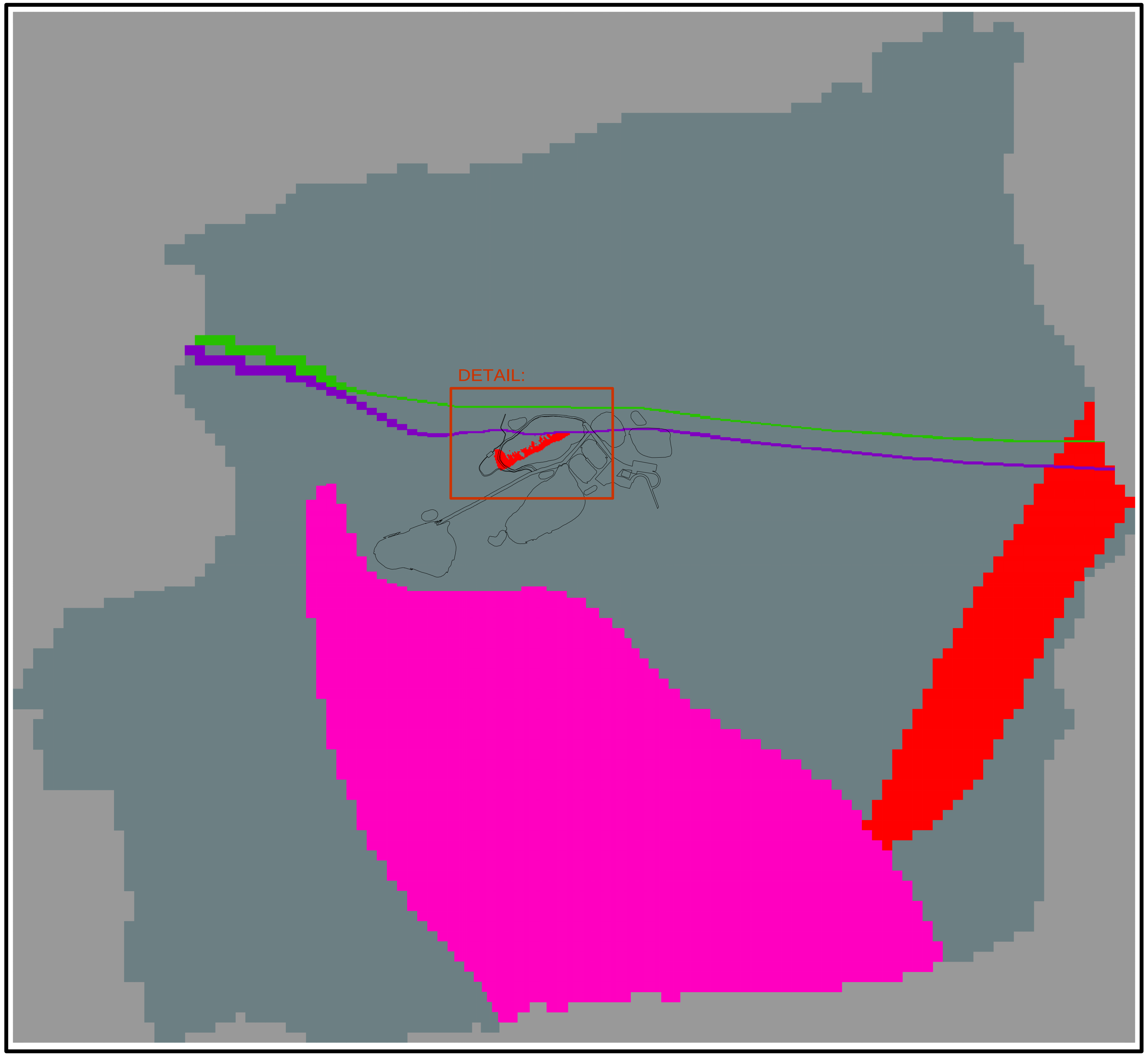
HYDRAULIC CONDUCTIVITY DISTRIBUTION IN DEEP BEDROCK (LAYER 6)

FIGURE 5.7

HEG file: Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\Figure 5.7 - Hydraulic Conductivity Distribution in Deep Bedrock (Layer 6).srf



LEGEND

NO-FLOW BOUNDARY CONDITION

HYDRAULIC CONDUCTIVITY ZONES

DEEP BEDROCK GREYWACKE FORMATION

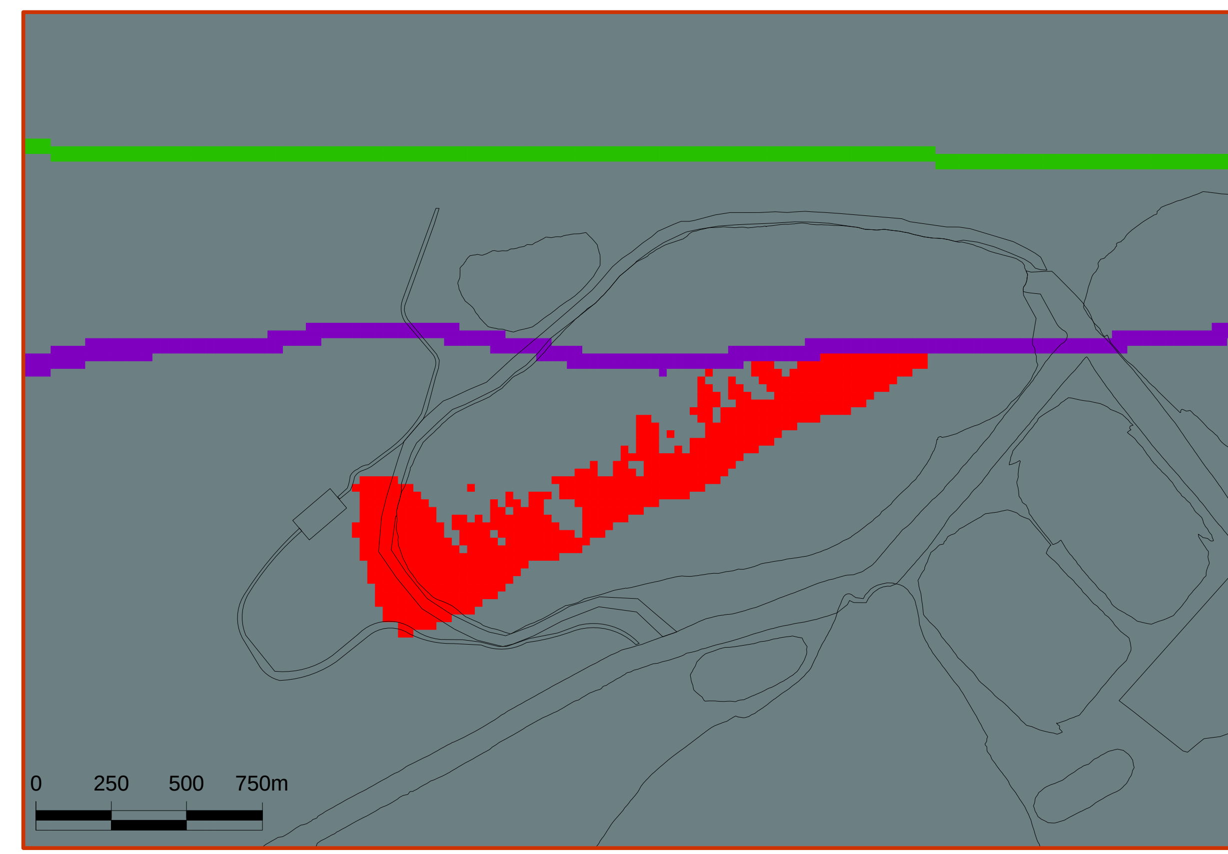
DEEP BEDROCK GRANITE FORMATION

DEEP BEDROCK ARGILLITE FORMATION

DEEP MUD LAKE FAULT

DEEP CAMERON FLOWAGE FAULT

DETAIL:



0 1.270 2,540 3,810m

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HYDRAULIC CONDUCTIVITY DISTRIBUTION IN DEEP BEDROCK (LAYER 7)

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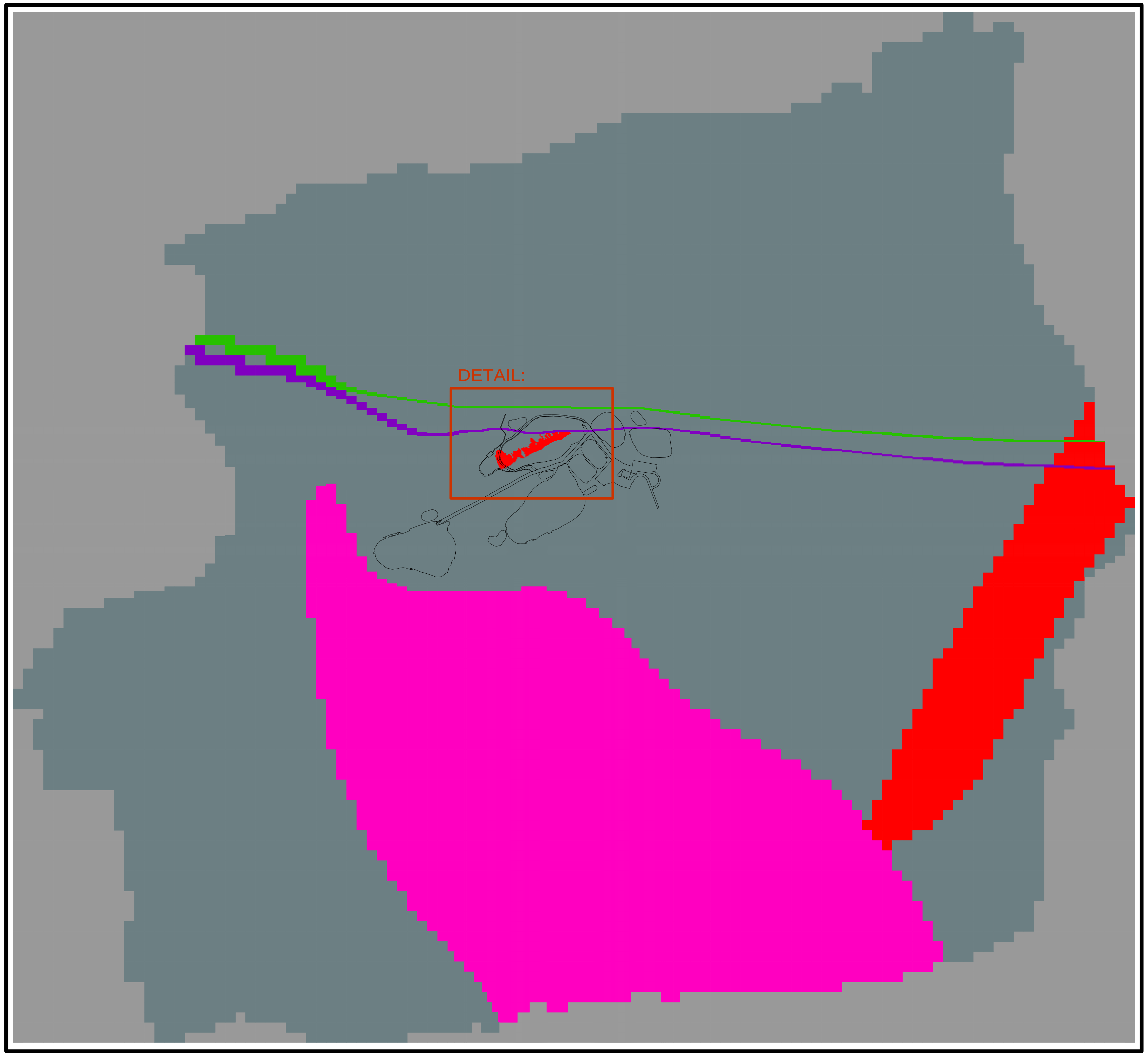
FIGURE 5.8

HEG file: Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\Figure 5.8 - Hydraulic Conductivity Distribution in Deep Bedrock (Layer 7).srf



LEGEND

NO-FLOW BOUNDARY CONDITION

HYDRAULIC CONDUCTIVITY ZONES

DEEP BEDROCK GREYWACKE FORMATION

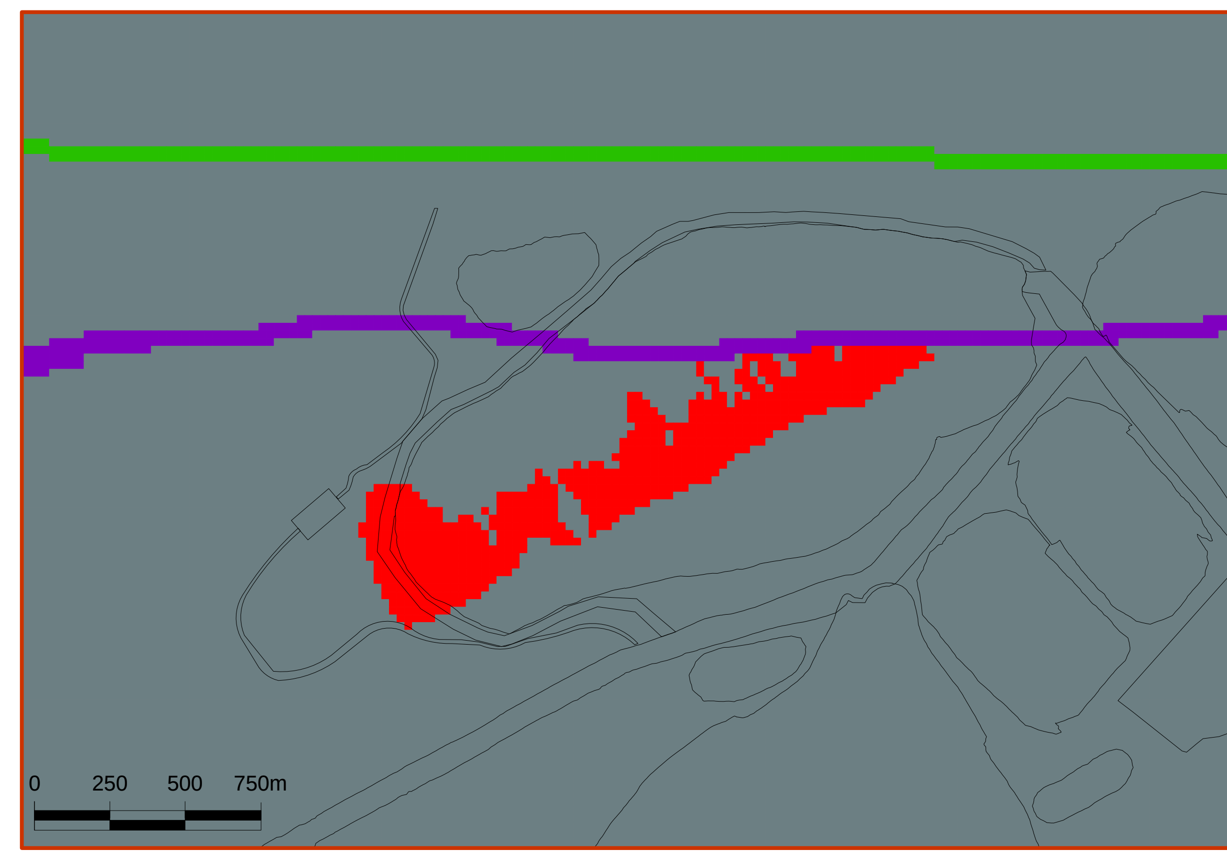
DEEP BEDROCK GRANITE FORMATION

DEEP BEDROCK ARGILLITE FORMATION

DEEP MUD LAKE FAULT

DEEP CAMERON FLOWAGE FAULT

DETAIL:



0 1,270 2,540 3,810m

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HYDRAULIC CONDUCTIVITY DISTRIBUTION IN DEEP BEDROCK (LAYER 8)

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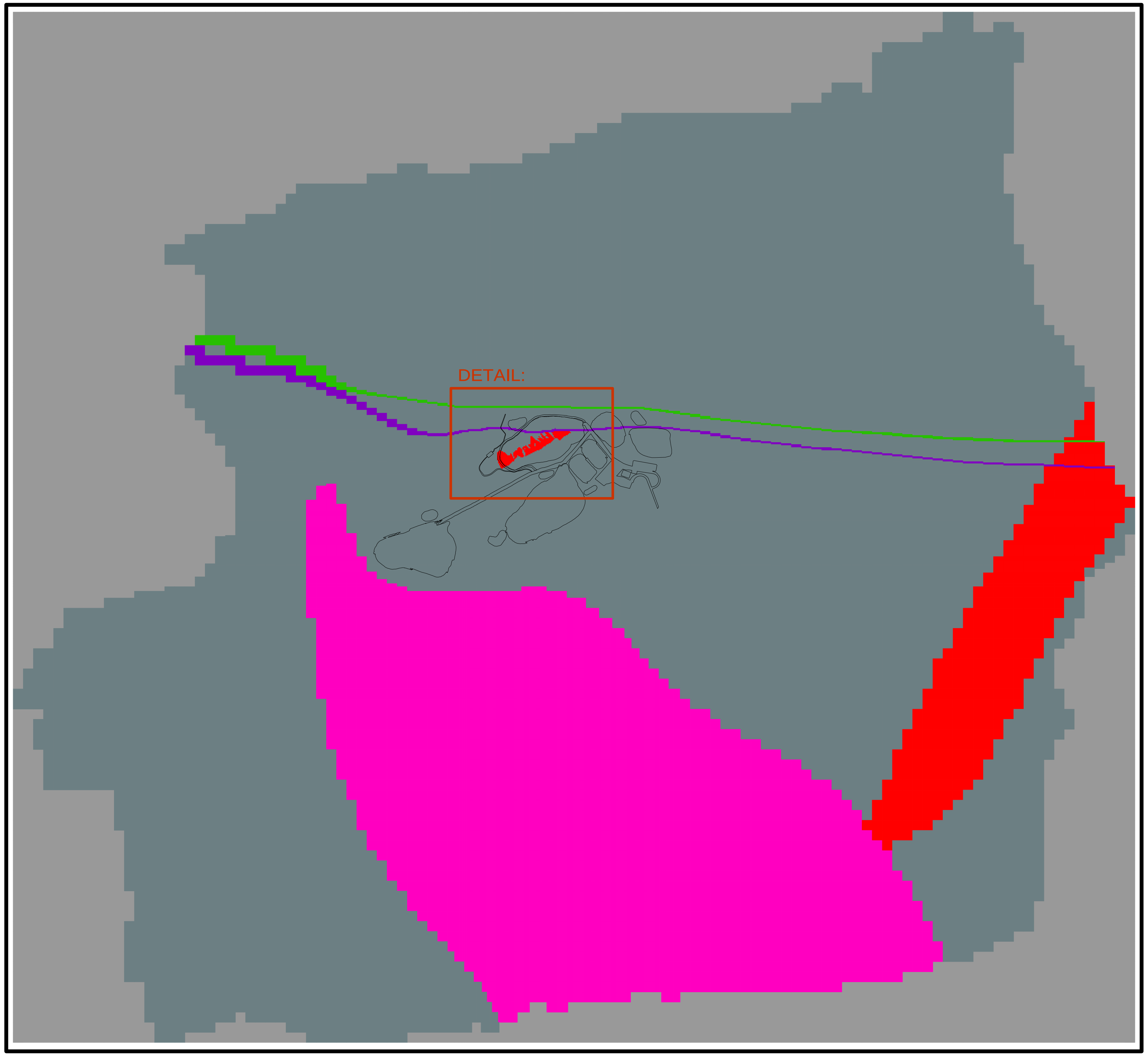
FIGURE 5.9



LEGEND

NO-FLOW BOUNDARY CONDITION

HYDRAULIC CONDUCTIVITY ZONES

DEEP BEDROCK GREYWACKE FORMATION

DEEP BEDROCK GRANITE FORMATION

DEEP BEDROCK ARGILLITE FORMATION

DEEP MUD LAKE FAULT

DEEP CAMERON FLOWAGE FAULT

DETAIL:

0 1.270 2,540 3,810m

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BEAVER DAM MINE

HYDRAULIC CONDUCTIVITY DISTRIBUTION IN DEEP BEDROCK (LAYER 9)

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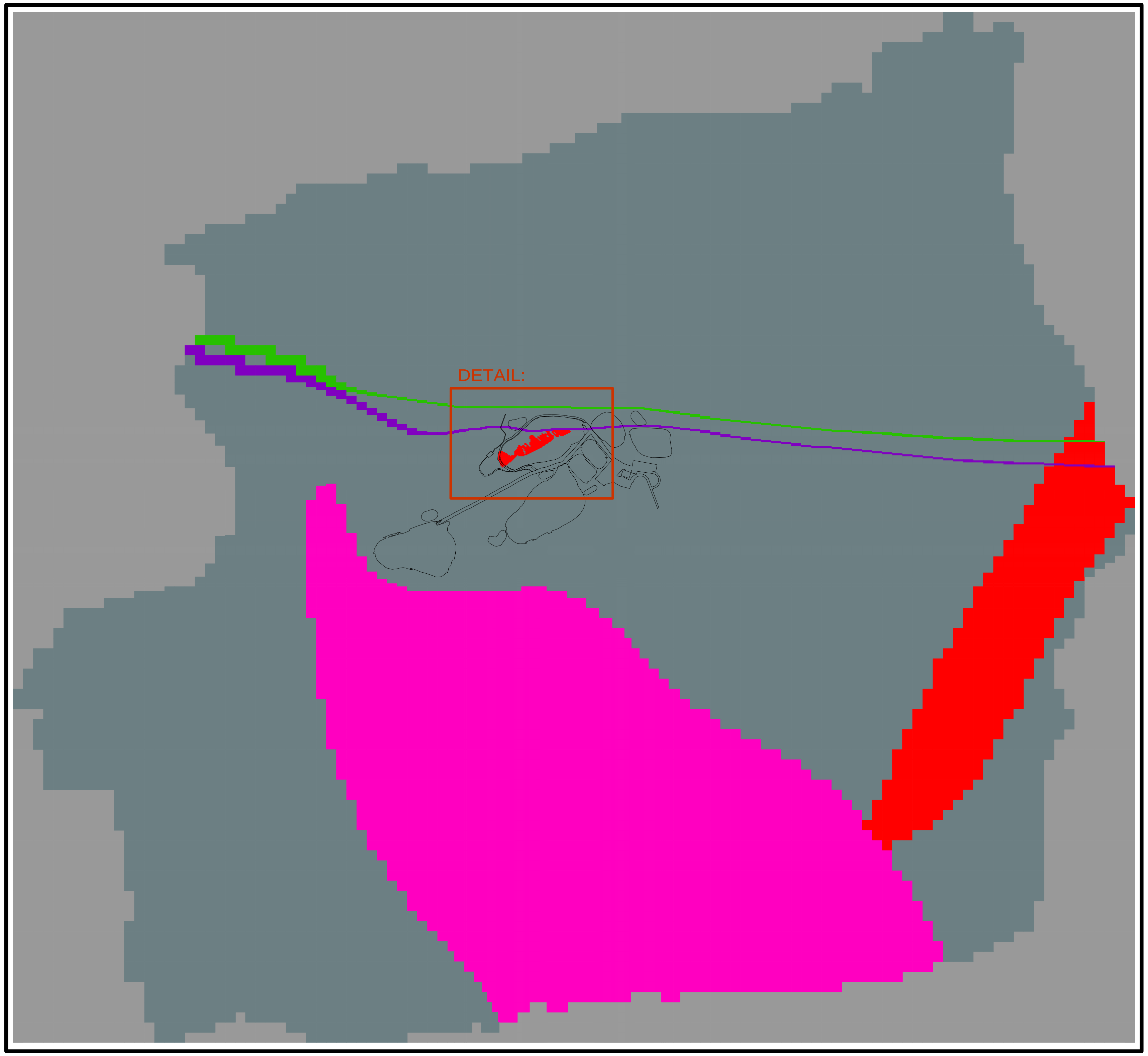
FIGURE 5.10



LEGEND

NO-FLOW BOUNDARY CONDITION

HYDRAULIC CONDUCTIVITY ZONES

DEEP BEDROCK GREYWACKE FORMATION

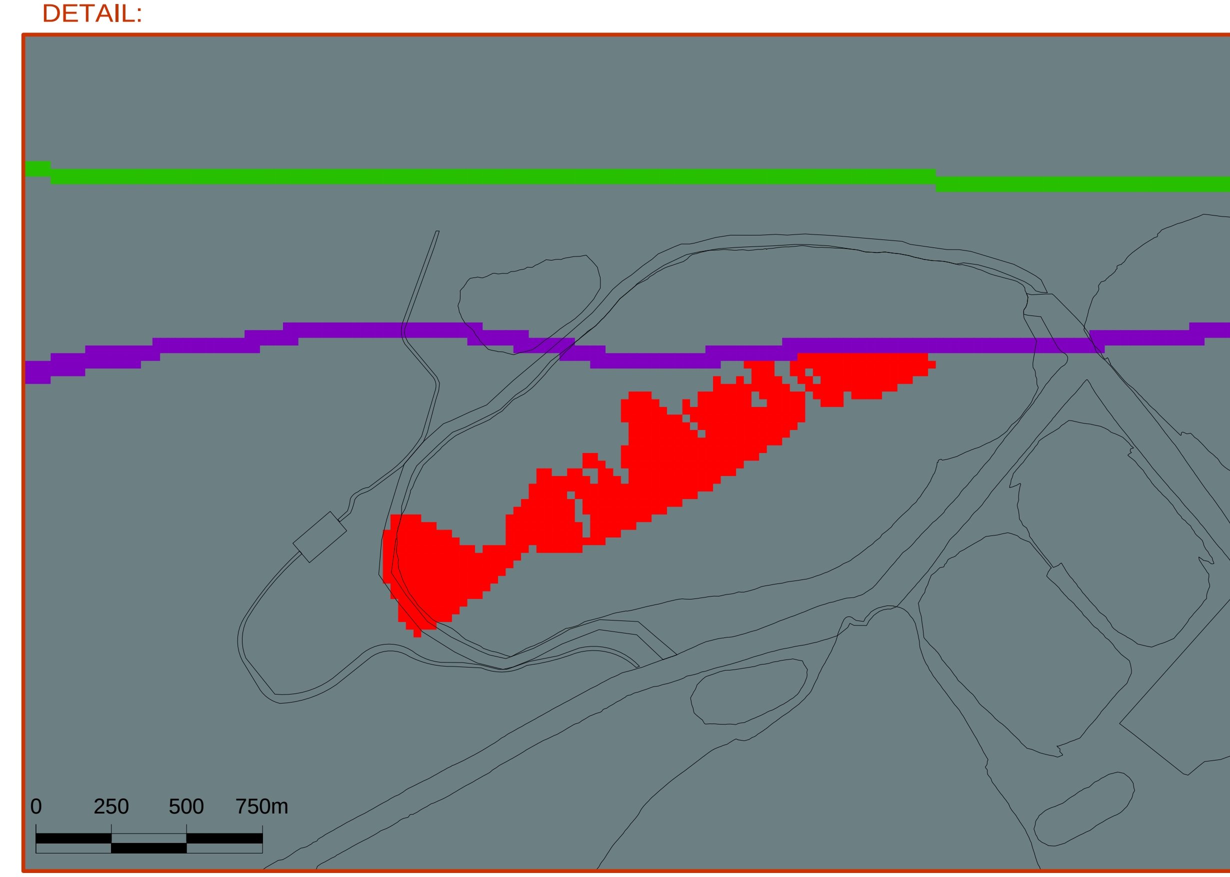
DEEP BEDROCK GRANITE FORMATION

DEEP BEDROCK ARGILLITE FORMATION

DEEP MUD LAKE FAULT

DEEP CAMERON FLOWAGE FAULT

DETAIL:



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HYDRAULIC CONDUCTIVITY DISTRIBUTION IN DEEP BEDROCK (LAYER 10)

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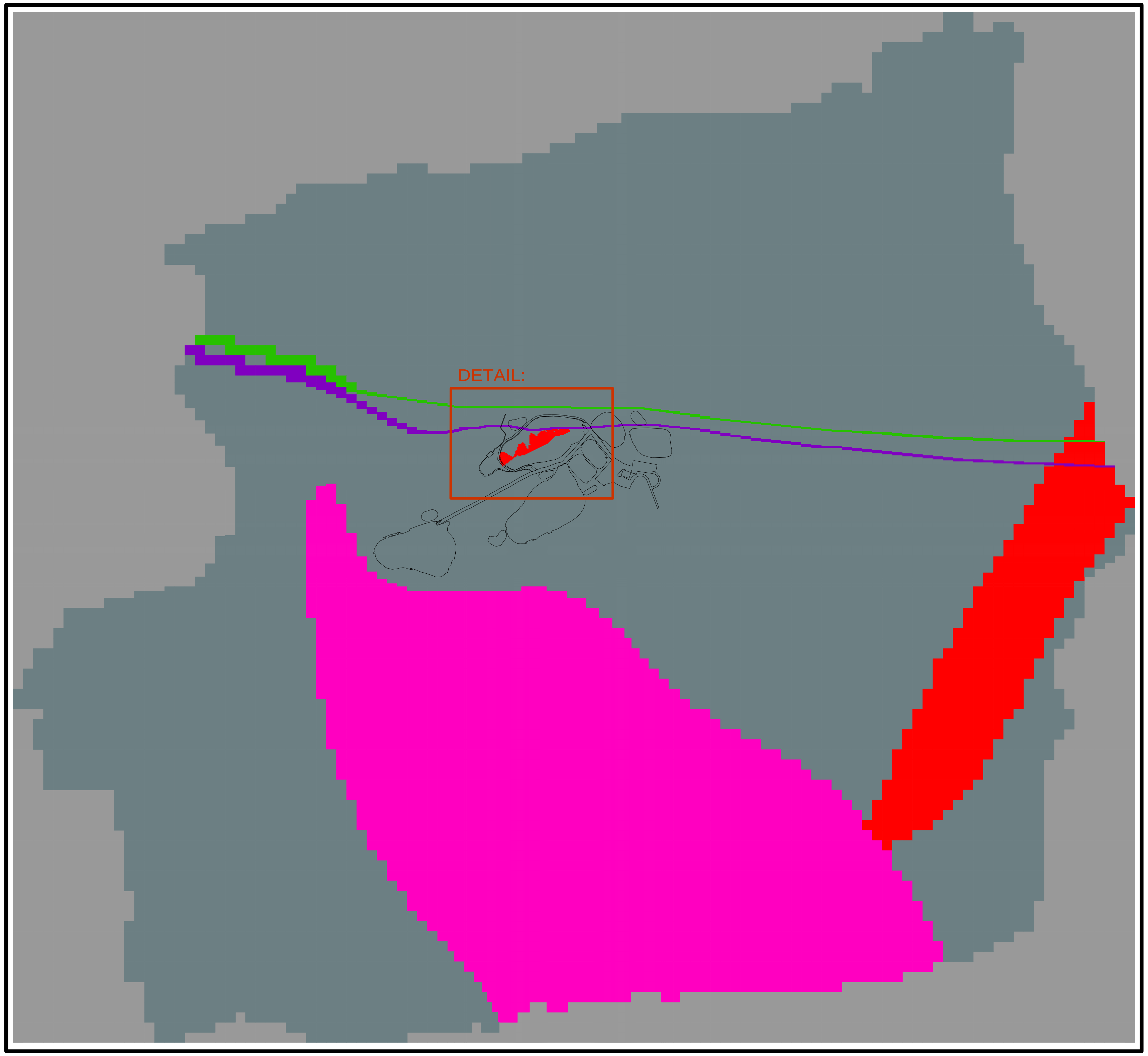
FIGURE 5.11

HEG file: Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\Figure 5.11 - Hydraulic Conductivity Distribution in Deep Bedrock (Layer 10).srf



LEGEND

NO-FLOW BOUNDARY CONDITION

HYDRAULIC CONDUCTIVITY ZONES

DEEP BEDROCK GREYWACKE FORMATION

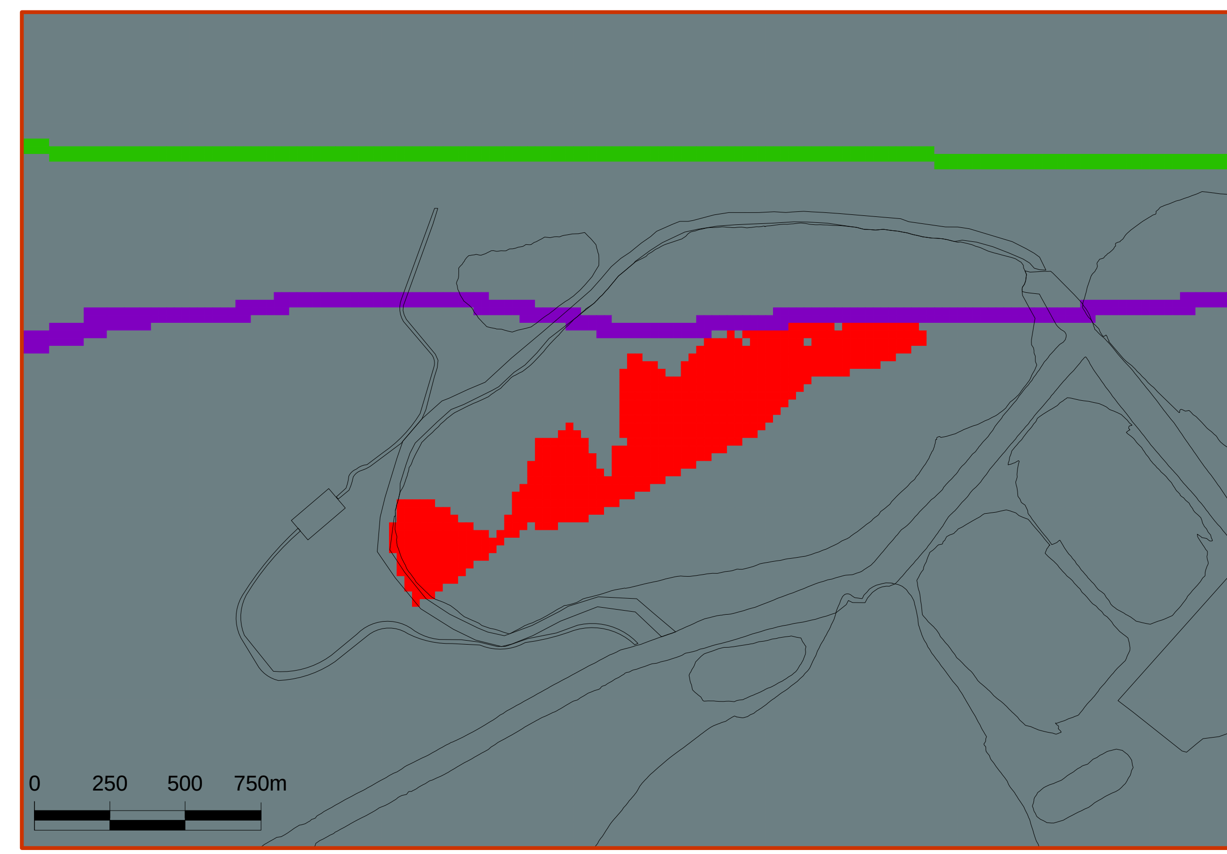
DEEP BEDROCK GRANITE FORMATION

DEEP BEDROCK ARGILLITE FORMATION

DEEP MUD LAKE FAULT

DEEP CAMERON FLOWAGE FAULT

DETAIL:



0 1.270 2,540 3,810m

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MARINETTE, NOVA SCOTIA
BEAVER DAM MINE

HYDRAULIC CONDUCTIVITY DISTRIBUTION IN DEEP BEDROCK (LAYER 11)

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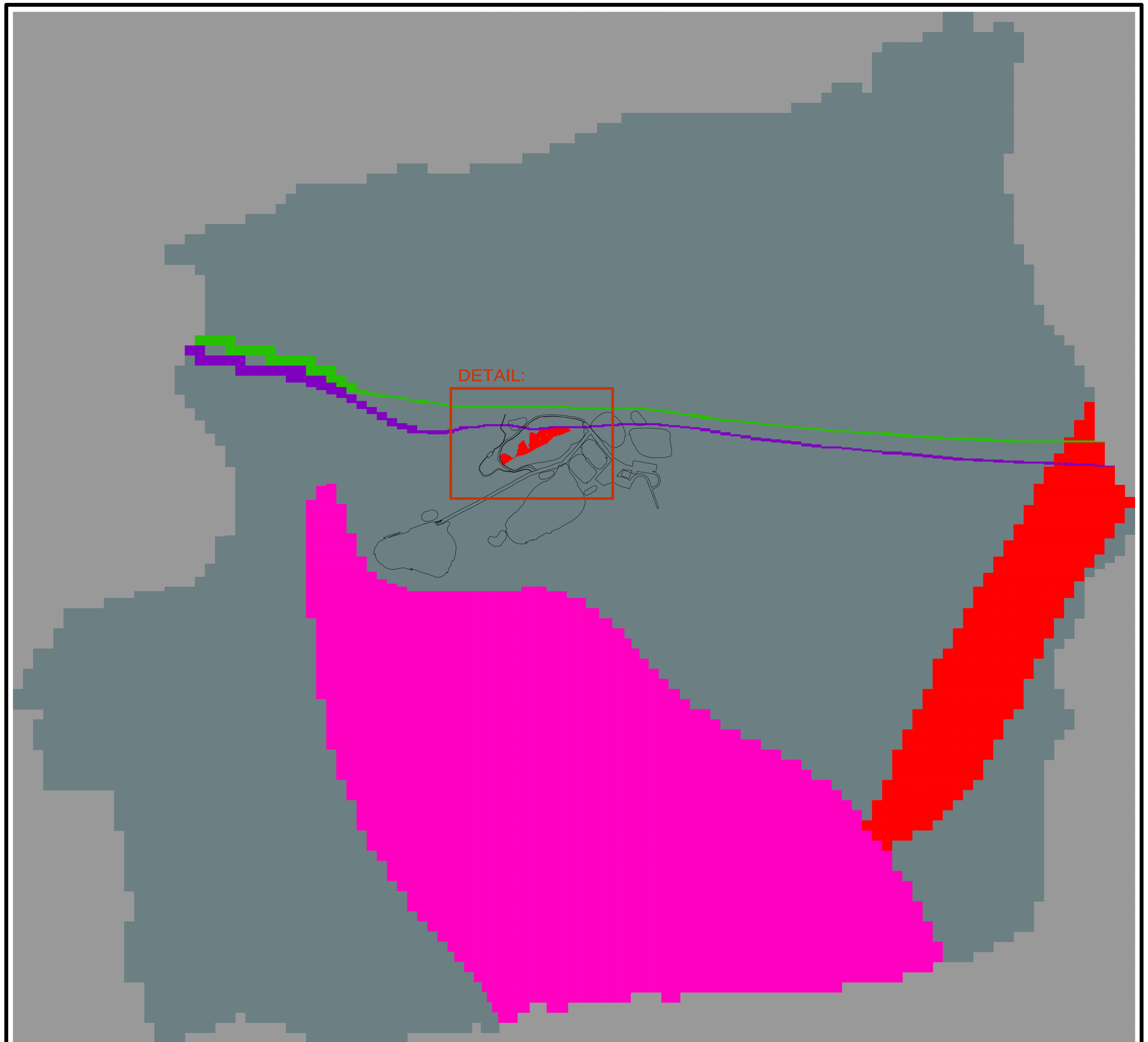
FIGURE 5.12



LEGEND

NO-FLOW BOUNDARY CONDITION

HYDRAULIC CONDUCTIVITY ZONES

DEEP BEDROCK GREYWACKE FORMATION

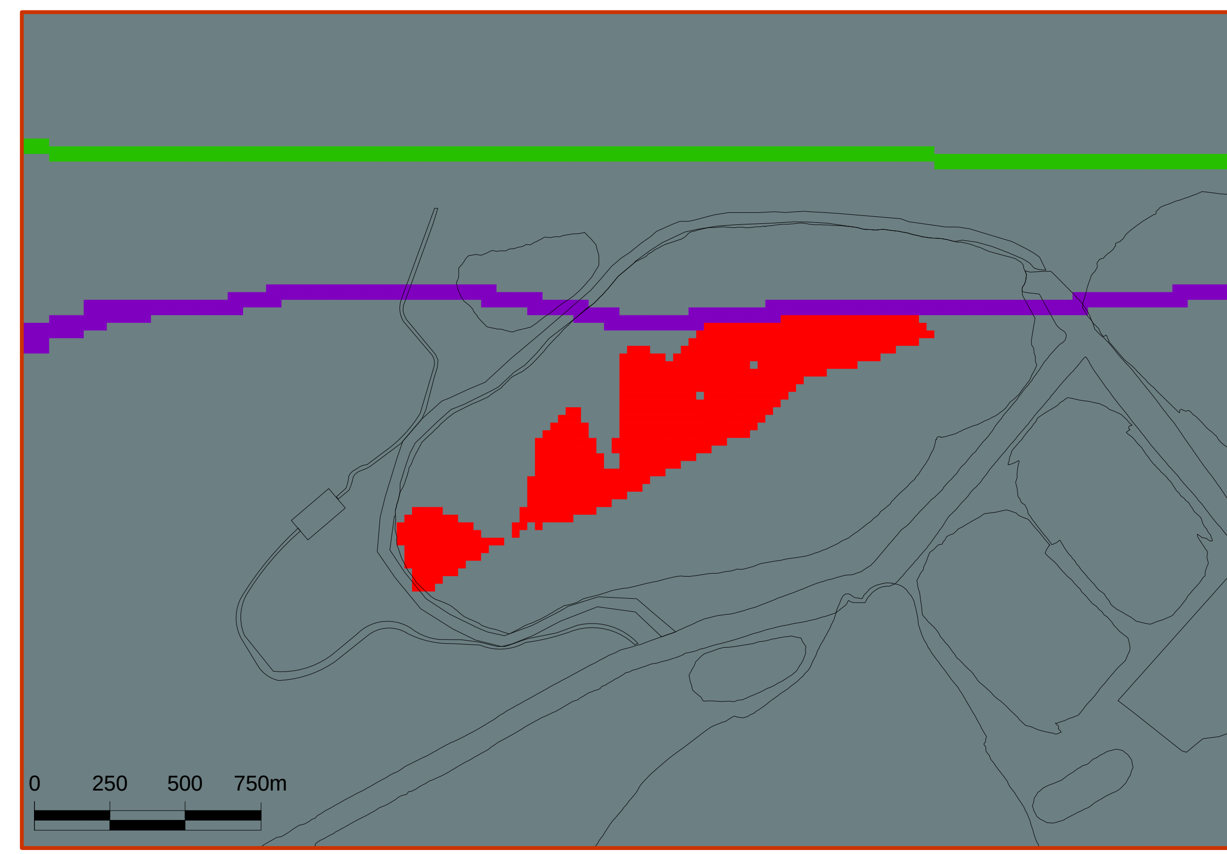
DEEP BEDROCK GRANITE FORMATION

DEEP BEDROCK ARGILLITE FORMATION

DEEP MUD LAKE FAULT

DEEP CAMERON FLOWAGE FAULT

DETAIL:



0 1.270 2,540 3,810m

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HYDRAULIC CONDUCTIVITY DISTRIBUTION IN DEEP BEDROCK (LAYER 12)

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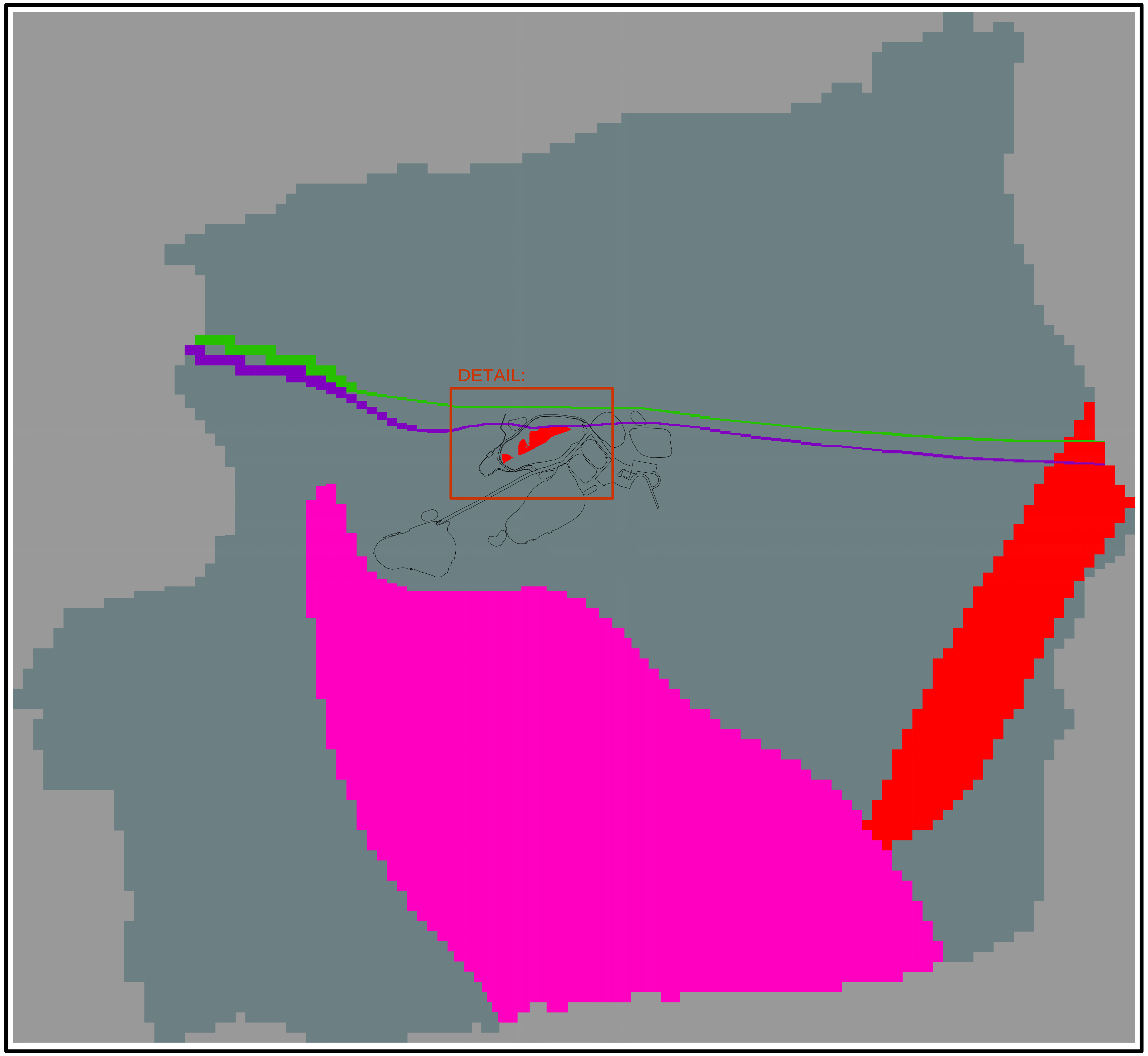
FIGURE 5.13

HEG file: Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\Figure 5.13 - Hydraulic Conductivity Distribution in Deep Bedrock (Layer 12).srf



LEGEND

NO-FLOW BOUNDARY CONDITION

HYDRAULIC CONDUCTIVITY ZONES

DEEP BEDROCK GREYWACKE FORMATION

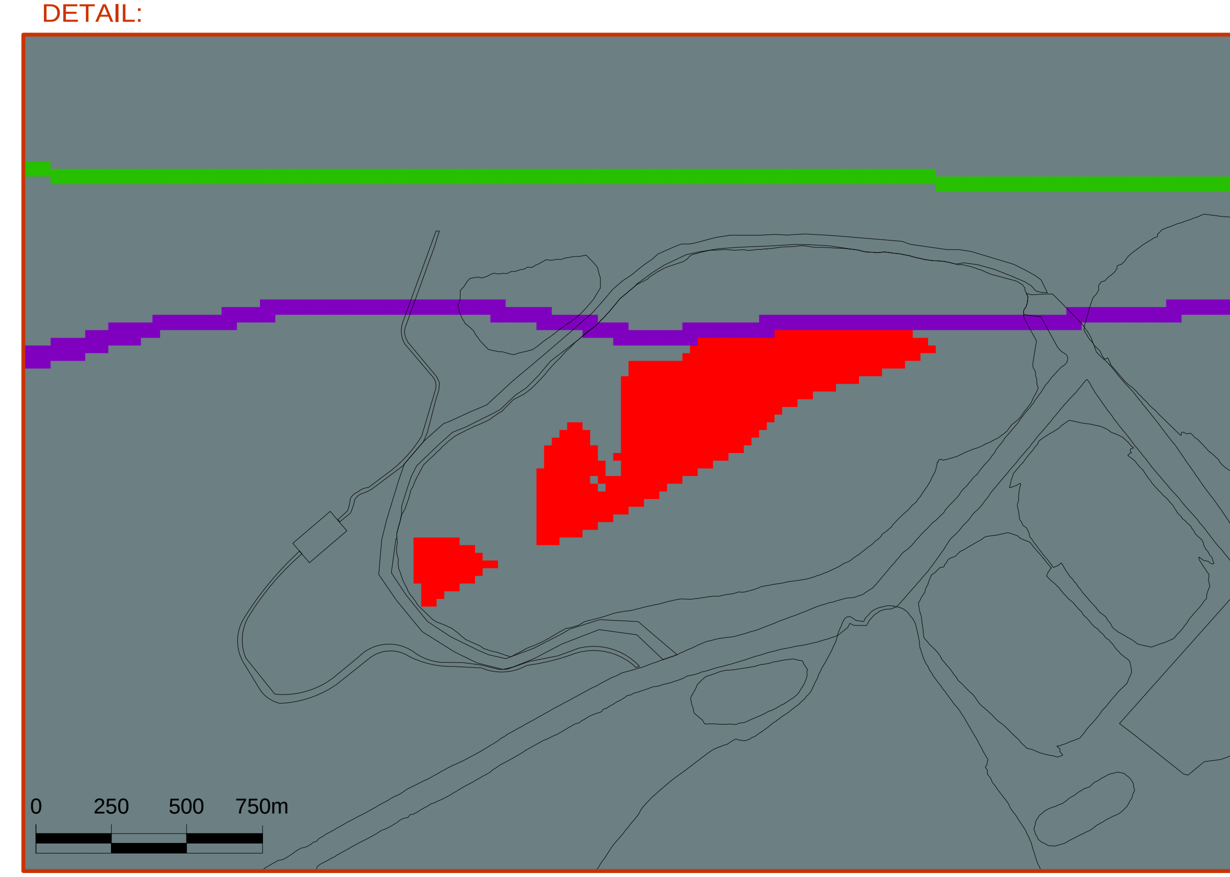
DEEP BEDROCK GRANITE FORMATION

DEEP BEDROCK ARGILLITE FORMATION

DEEP MUD LAKE FAULT

DEEP CAMERON FLOWAGE FAULT

DETAIL:



0 1.270 2,540 3,810m

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BEAVER DAM MINE

HYDRAULIC CONDUCTIVITY DISTRIBUTION IN DEEP BEDROCK (LAYER 13)

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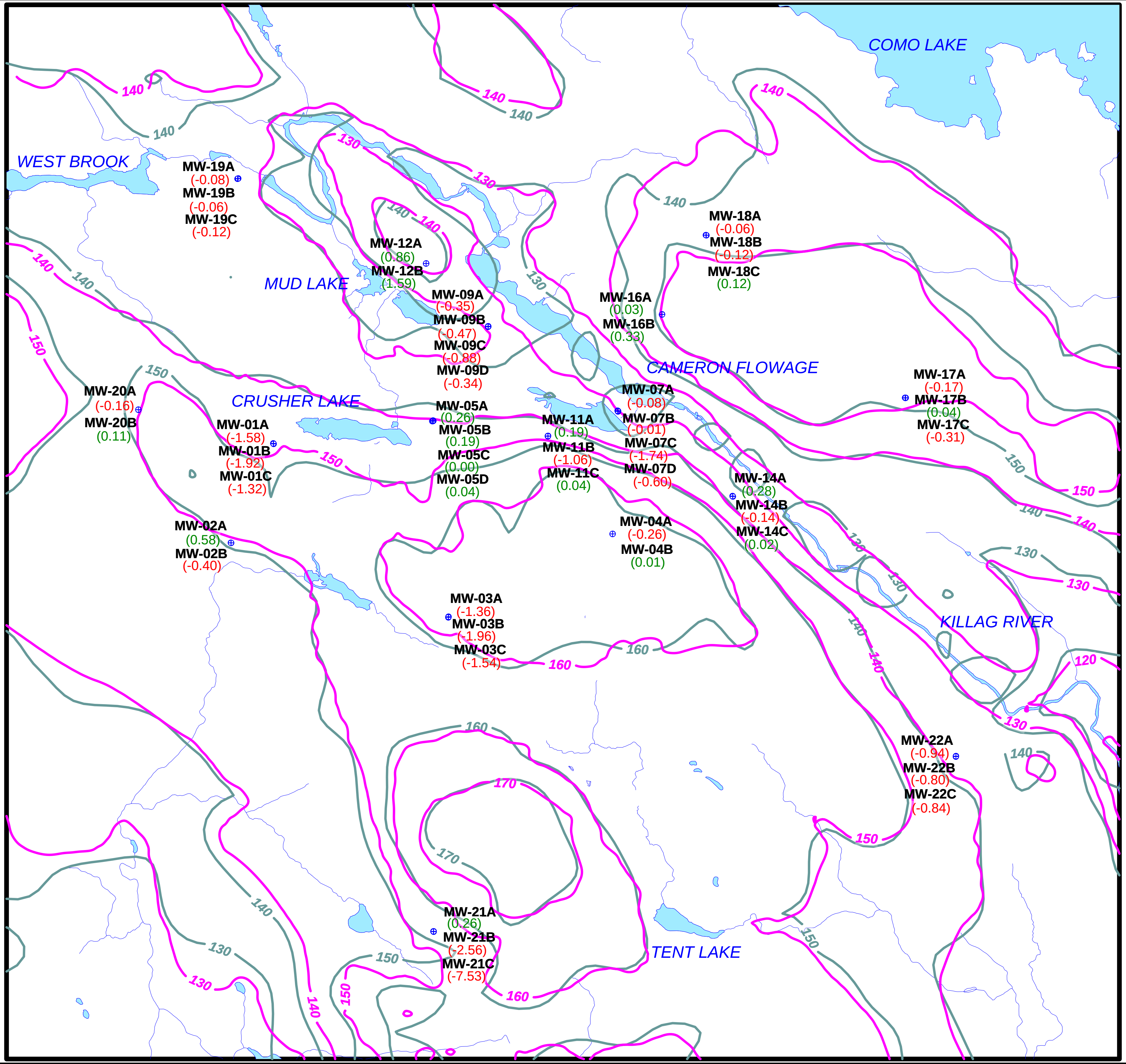
FIGURE 5.14



LEGEND

SURFACE WATER BODY

MW-17A WATER LEVEL MONITORING LOCATION

(0.04) UNDER-PREDICTION OF OBSERVED GROUNDWATER ELEVATION (m)

(-0.17) OVER-PREDICTION OF OBSERVED GROUNDWATER ELEVATION (m)

140 OBSERVED GROUNDWATER ELEVATION CONTOURS - JULY 18, 2018 (m AMSL)

140 SIMULATED GROUNDWATER ELEVATION CONTOURS - JULY 18, 2018 (m AMSL)

0 600 1,200 1,800m

N

ATLANTIC GOLD CORPORATION
MARINETTE, NOVA SCOTIA
BEAVER DAM MINE

SIMULATE VERSUS OBSERVED GROUNDWATER ELEVATION CONTOURS - BASE CASE CONDITION

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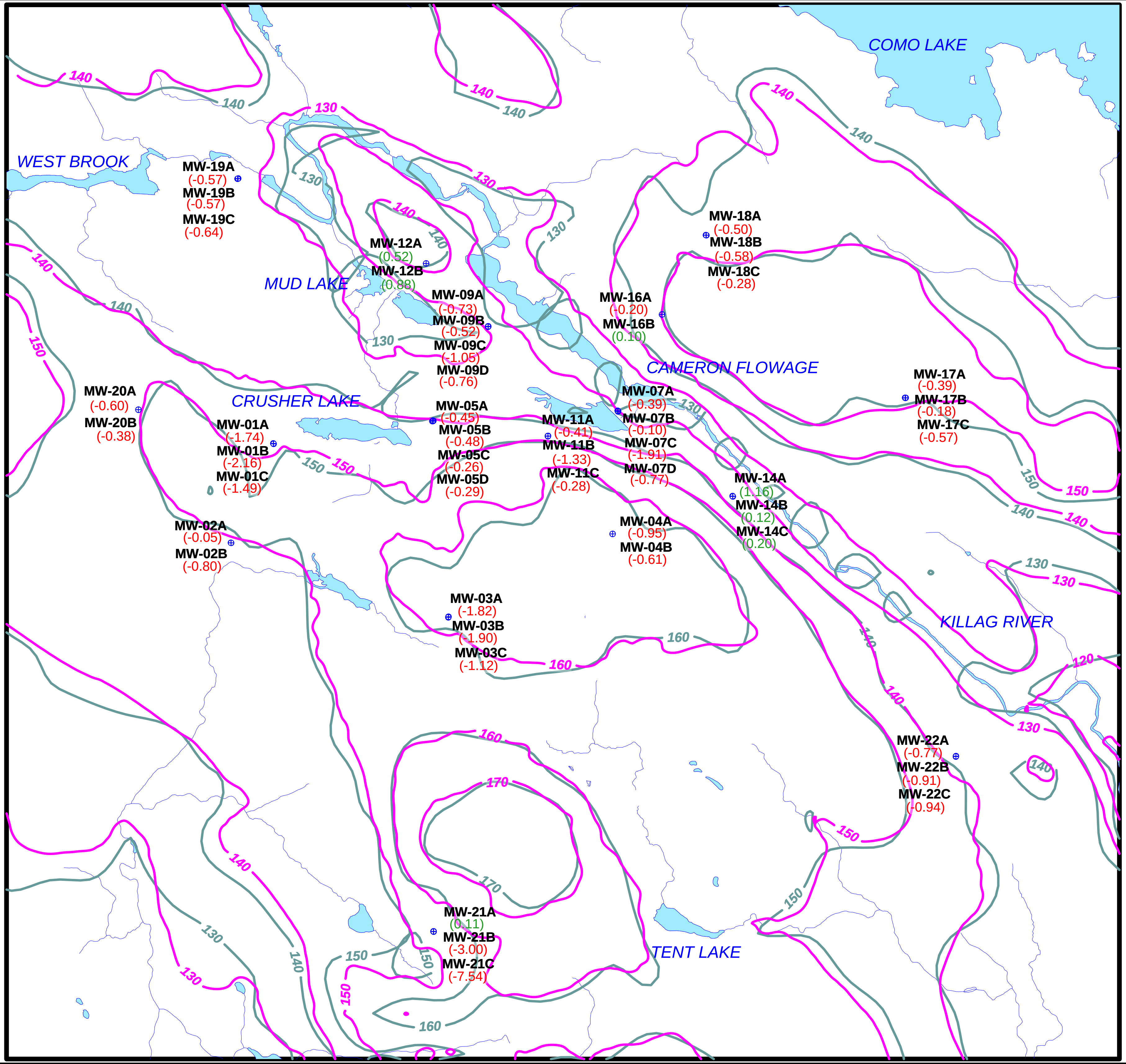
FIGURE 6.1

HEG file: Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\RPTFigures\Figure 6.1 - Simulate versus Observed Groundwater Elevation Contours - Base Case Condition.srf



LEGEND

- SURFACE WATER BODY
- MW-17A ⊕ WATER LEVEL MONITORING LOCATION
- (1.16) UNDER-PREDICTION OF OBSERVED GROUNDWATER ELEVATION (m)
- (-0.39) OVER-PREDICTION OF OBSERVED GROUNDWATER ELEVATION (m)
- 140 OBSERVED GROUNDWATER ELEVATION CONTOURS - SEPTEMBER 5, 2018 (m AMSL)
- 140 SIMULATED GROUNDWATER ELEVATION CONTOURS - SEPTEMBER 5, 2018 (m AMSL)

0 600 1,200 1,800m

N

GHD

ATLANTIC GOLD CORPORATION
MARINETTE, NOVA SCOTIA
BEAVER DAM MINE

SIMULATE VERSUS OBSERVED GROUNDWATER ELEVATION CONTOURS - DRY CONDITION

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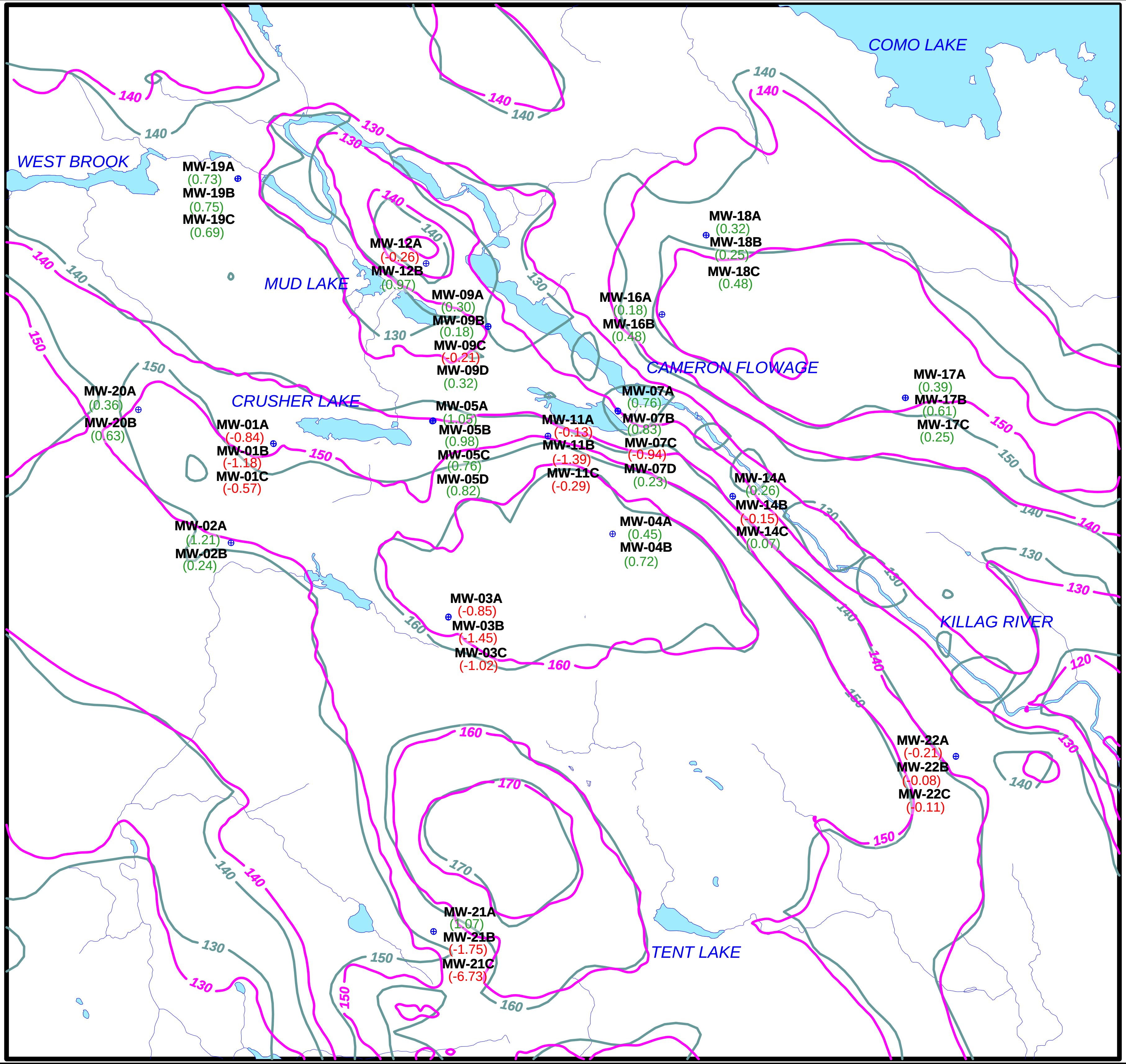
FIGURE 6.2

HEG file: Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\RPTFigures\Figure 6.2 - Simulate versus Observed Groundwater Elevation Contours - Dry Condition.srf



LEGEND

SURFACE WATER BODY

MW-17A ⊕ WATER LEVEL MONITORING LOCATION

(1.16) UNDER-PREDICTION OF OBSERVED GROUNDWATER ELEVATION (m)

(-0.39) OVER-PREDICTION OF OBSERVED GROUNDWATER ELEVATION (m)

— 140 — OBSERVED GROUNDWATER ELEVATION CONTOURS - JULY 18, 2018 (m AMSL)

— 140 — SIMULATED GROUNDWATER ELEVATION CONTOURS - JULY 18, 2018 (m AMSL)

0 600 1,200 1,800m

ATLANTIC GOLD CORPORATION
MARINETTE, NOVA SCOTIA
BEAVER DAM MINE

SIMULATE VERSUS OBSERVED GROUNDWATER ELEVATION CONTOURS - WET CONDITION

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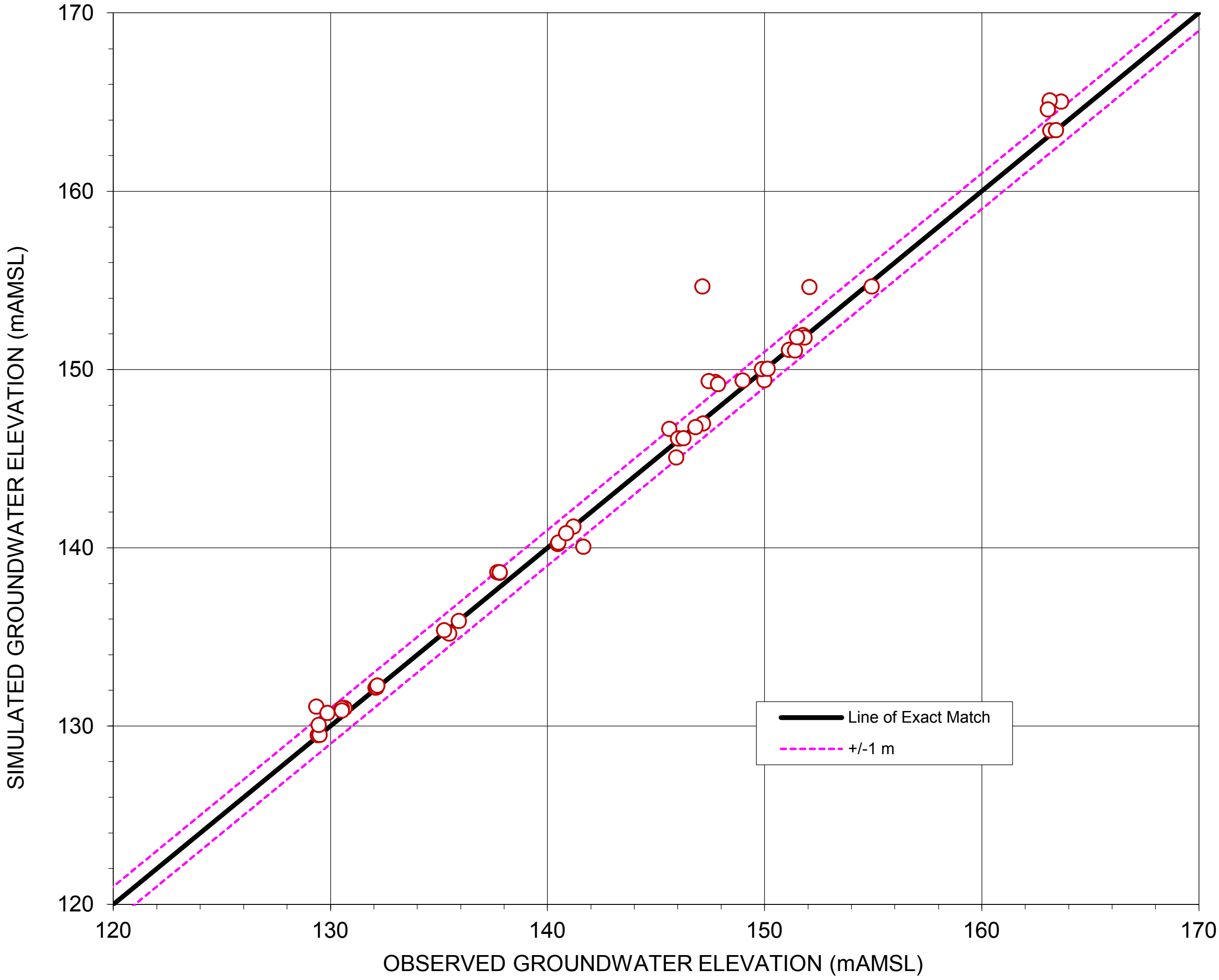
FIGURE 6.3

HEG file: Z:\HEG\088664\DOCUMENTATION\RPT\088664-RPT-9\FIGURES\RPTFigures\Figure 6.3 - Simulate versus Observed Groundwater Elevation Contours - Wet Condition.srf

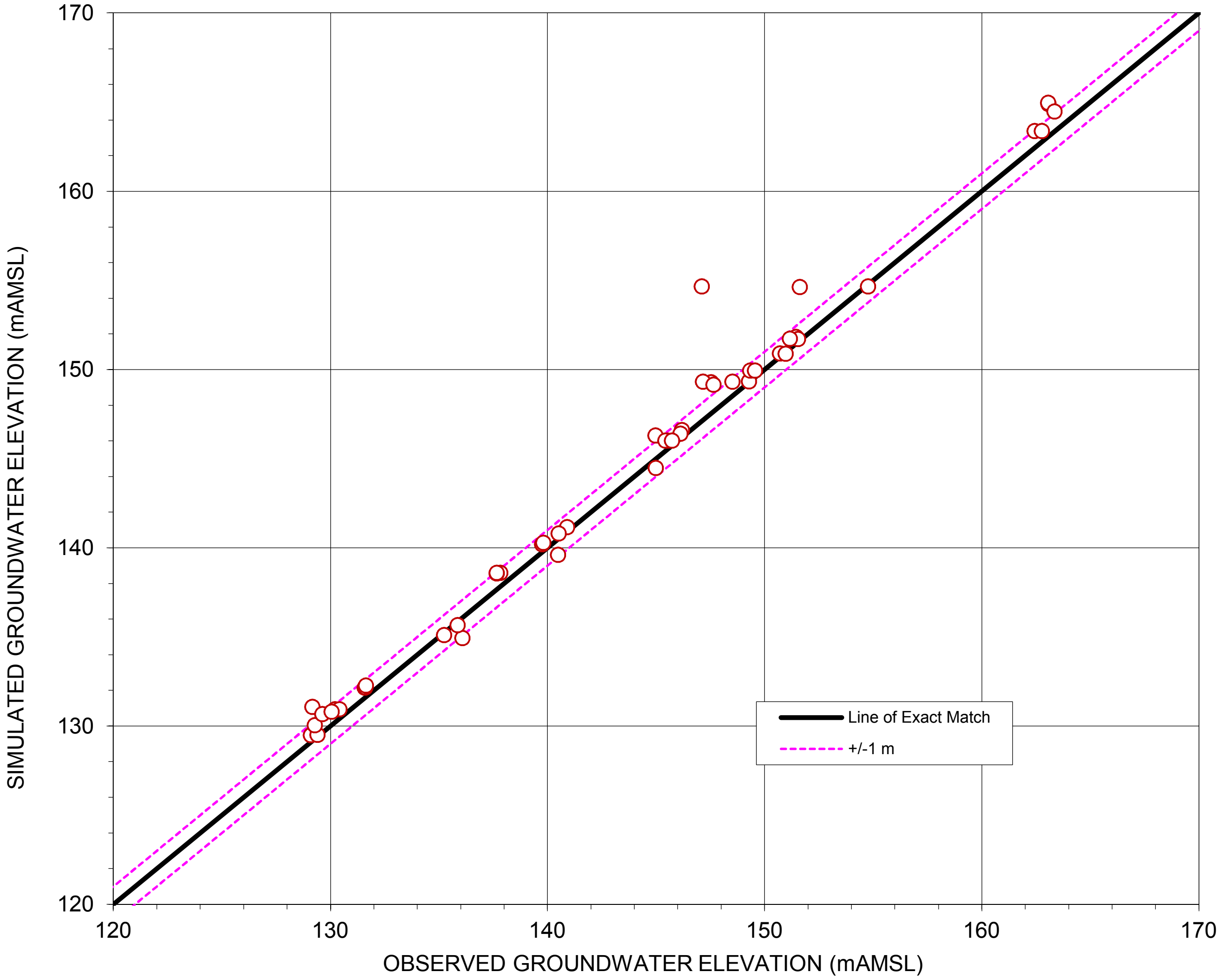


CALIBRATION STATISTICS

NUMBER OF OBSERVATIONS =	49
RESIDUAL MEAN (m) =	-0.51
ABSOLUTE RESIDUAL MEAN (m) =	0.71
RESIDUAL STANDARD DEVIATION (m) =	1.27
RESIDUAL SUM OF SQUARES (m^2) =	91.73
MINIMUM RESIDUAL (m) =	-7.53
MAXIMUM RESIDUAL (m) =	1.59
OBSERVED HEAD RANGE (m) =	34.31
STANDARD DEVIATION/HEAD RANGE =	0.037
SCALED RMSE (%) =	4.0%

figure 6.4

SCATTER PLOT OF SIMULATED VS. OBSERVED
GROUNDWATER ELEVATIONS - BASE CASE CONDITION
ATLANTIC GOLD CORPORATION
MARINETTE, NOVA SCOTIA
Beaver Dam Mine



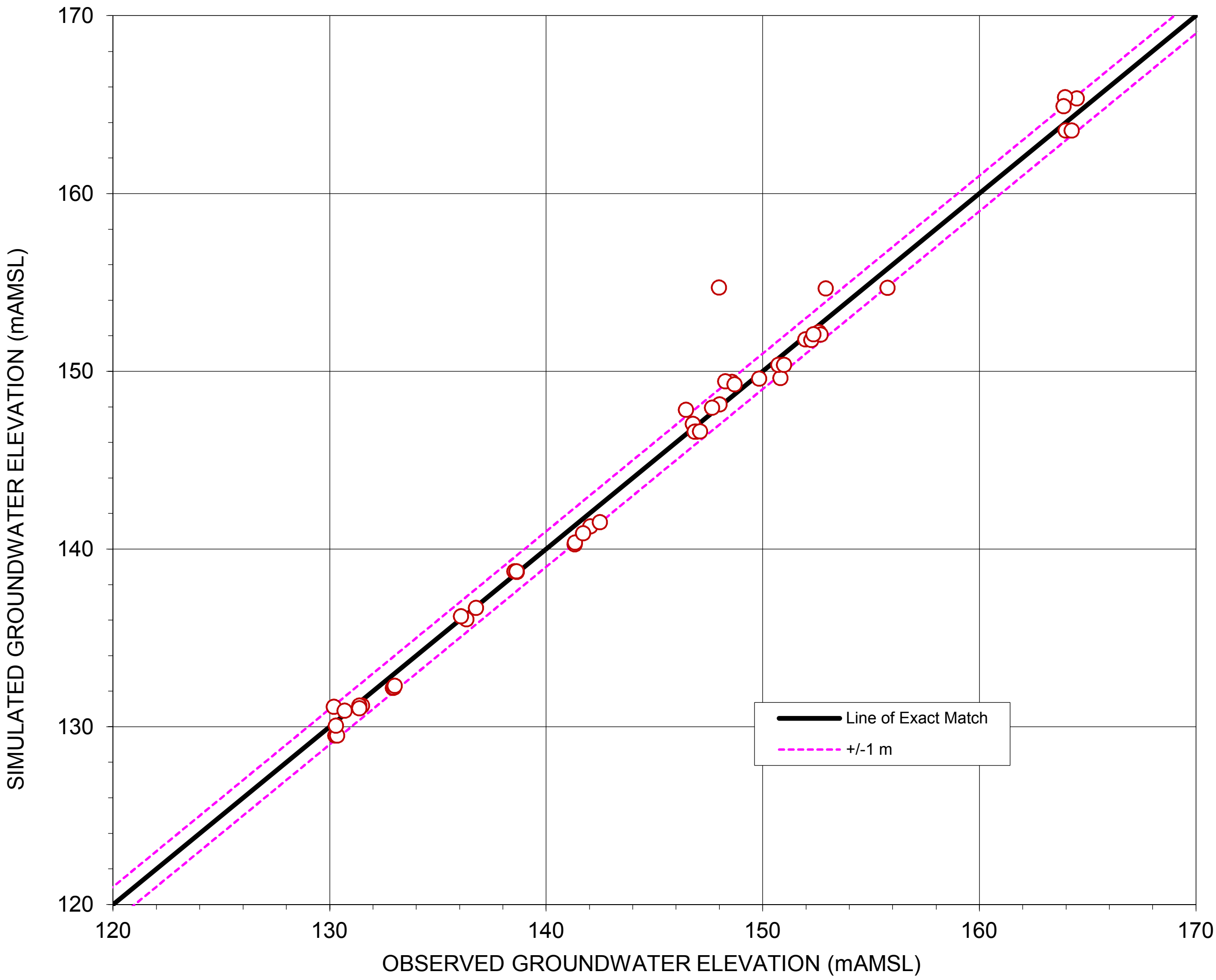
CALIBRATION STATISTICS

NUMBER OF OBSERVATIONS =	49
RESIDUAL MEAN (m) =	-0.77
ABSOLUTE RESIDUAL MEAN (m) =	0.90
RESIDUAL STANDARD DEVIATION (m) =	1.23
RESIDUAL SUM OF SQUARES (m^2) =	102.93
MINIMUM RESIDUAL (m) =	-7.54
MAXIMUM RESIDUAL (m) =	1.16
OBSERVED HEAD RANGE (m) =	34.25
STANDARD DEVIATION/HEAD RANGE =	0.036
SCALED RMSE (%) =	4.2%

figure 6.5

SCATTER PLOT OF SIMULATED VS. OBSERVED GROUNDWATER ELEVATIONS - DRY CONDITION
ATLANTIC GOLD CORPORATION
MARINETTE, NOVA SCOTIA
Beaver Dam Mine

GHD



CALIBRATION STATISTICS

NUMBER OF OBSERVATIONS =	49
RESIDUAL MEAN (m) =	-0.02
ABSOLUTE RESIDUAL MEAN (m) =	0.72
RESIDUAL STANDARD DEVIATION (m) =	1.20
RESIDUAL SUM OF SQUARES (m^2) =	70.33
MINIMUM RESIDUAL (m) =	-6.73
MAXIMUM RESIDUAL (m) =	1.21
OBSERVED HEAD RANGE (m) =	34.31
STANDARD DEVIATION/HEAD RANGE =	0.035
SCALED RMSE (%) =	3.5%

figure 6.6

SCATTER PLOT OF SIMULATED VS. OBSERVED GROUNDWATER ELEVATIONS - WET CONDITION
ATLANTIC GOLD CORPORATION
MARINETTE, NOVA SCOTIA
Beaver Dam Mine

GHD