Hydrogeological Model
Kudz Ze Kayah Project, Yukon

PRESENTED TO

BMC Minerals (No. 1) Ltd.

DECEMBER 14, 2016
ISSUED FOR USE
FILE: WTR.GWTR03021-01

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EXECUTIVE SUMMARY

Tetra Tech EBA Inc. (Tetra Tech EBA) was retained by BMC Minerals (No. 1) Ltd. (BMC) to conduct a baseline hydrogeology assessment for the Kudz Ze Kayah (KZK) Project in support of the preparation of a project proposal for assessment under the Yukon Environmental and Socio-economic Assessment Act (YESAA) and the subsequent application under the *Waters Act* for Application for a Type A Water Use Licence. This report presents the development, calibration and simulation results of a hydrogeological groundwater flow model in support of the hydrogeological baseline and effects assessments for the KZK Project. The model was also used for developing of a preliminary dewatering strategy for the area of the proposed open pit and underground mine.

The groundwater flow model was developed based on available site data, and calibrated to a best-fit statistical match for observed water-level and drawdown data. In particular, data and observations collected as part of the 2015 and 2016 field programs were used to develop an accurate calibration for the model. Efforts were made during planning stages to ensure that the model domain was large enough to prevent drawdown from pit dewatering and water supply wells to propagate to the external model boundaries.

Steady-state and transient groundwater flow models were constructed and calibrated as part of this study. The steady-state model was calibrated to pre-mining water-level elevations and Geona Creek base flows and used as initial conditions for the transient flow model. The transient flow model was calibrated to the long-term aquifer tests conducted as part of this study to determine values for hydraulic conductivity and storage. During calibration, limited sensitivity analysis was conducted on the transient flow model to help select which parameters should be adjusted in calibration and which could be left at default values.

Following the calibration process, the groundwater flow model was used to simulate the hydrological sequence associated with the nine-year excavation of the ABM pit and underground workings. Model simulations were conducted to evaluate pathways for potential contaminant migration and travel time from the pit, the storage facilities, and the water management ponds during mine decommissioning and closure. Closure of the pit consists of the segregation of the underground workings from the pit by plugging the tunnel with paste backfill to prevent the interaction of deeper groundwater with the pit lake expected to form, followed by the diversion of Fault Creek into the pit to flood it over time, as specified in the proposed mine plan. Particle tracking was implemented to examine potential contaminant pathways from each of the site features including the pit and to estimate travel times from the pit to Geona Creek.

Based on the modeling results presented in this report, Tetra Tech EBA arrived at the following conclusions:

1. A drainage trench excavated parallel to the valley axis within the surficial sands and gravels of the valley-fill overburden and pumped at a rate of 85 to 95 Litres per second [1,350 to 1,470 USgpm] for six months should be sufficient for the purposes of dewatering in anticipation of Year 1 mining.

2. With the exception of areas of faulting or fracturing, the bedrock appears to be of sufficiently low permeability to permit water seepage management to be conducted by collection of seepage face drainage and horizontal drains as necessary. Depending on the nature of the distribution of fracture sets or other prominent fault conduits intersecting the pit within the bedrock, it may be possible to implement a set of approximately 15 dewatering wells arrayed at 500-metre spacing around the perimeter of the pit. Assuming that groundwater flow occurs through a reasonably isotropic bedrock with interconnected fractures, these wells installed to a depth of 200 to 250 metres may be pumped at rates of 400-800 m^3/d and may be sufficient to dewater the bedrock around the pit to minimize seepage face flow.

3. Fault zones within the pit and underground workings may produce water at higher rates of discharge and require the drilling of horizontal drains to stabilize hydraulic conditions locally.
4. Groundwater entering the pit primarily comes from recharge along the areas of higher elevation to the west recharging the overburden and shallow bedrock.
5. Although the simulated rates of drainage into the pit or dewatering trenches reflect averaged conditions, since much of the Geona Creek water is derived from snowmelt, the snowmelt period is likely to produce higher rates of infiltration and flow to the trench and pit. This variation is expected to occur seasonally every year, but was not incorporated into the groundwater model due to the limited data with which to calibrate. As a result the degree of variation that may occur is uncertain, but elevated groundwater rates are likely to occur seasonally. A perimeter interceptor channel excavated around the pit on the eastern and western sides to the top of bedrock would likely remove any snowmelt water before it could reach the pit.
6. Following completion of mining and closing of the underground workings, the pit will begin to refill through the combination of redirected surface water flow from Fault Creek, and groundwater seepage as the drawdown associated with mining begins to subside and groundwater levels begin rising. The pit is expected to have filled to half of its original depth in 4 years, and to fill completely to the spill elevation of 1,380 m after approximately 16 years.
7. After the pit has filled, the pit is expected to act as a lake (referred to as ABM Lake) through which streamflow enters and leaves, and which is augmented by groundwater discharge of approximately 1,225 m^3/d.
8. Tracking of particles sourced at each of the storage facilities flow toward Geona Creek where they either immediately discharge to the stream, or travel through the overburden along the stream valley until they eventually discharge to the stream.
9. Tracking of particles originating at the pit-lake flow north away from the pit following the upward hydraulic gradients in the bedrock and overburden until they discharge to Geona Creek within approximately 1 km north of the ABM Lake.

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APPENDICES

Appendix A Tetra Tech’s General Conditions

ACRONYMS & ABBREVIATIONS

BMC	BMC Minerals (No. 1) Ltd.
Ft	foot
Golder	Golder Associates
hr	hour
ID	inner diameter
in	inch
IEE	Initial Environmental Evaluation
K	hydraulic conductivity
km	kilometre
KZK	Kudz Ze Kayah
Lbs	pounds
L	litre
L/s	litres per second
m	metre
m asl	metre above mean sea level
m bgs	metre below ground surface
m/s	metre per second
m^2/d	square metre per day
m^3/d	cubic metres per day
NAD83	North American Datum of 1983
NTS	National Topography System
PAC	potentially acid consuming
QA/QC	quality assurance and quality control
SPAG	strongly potentially acid generating
Tetra Tech EBA	Tetra Tech EBA Inc.
TDS	total dissolved solids
USgpm	US gallons per minute
UTM	Universal Transverse Mercator
VMS	volcanic massive sulphide
VWP	vibrating wire piezometer
WPAG	weakly potentially acid generating
YESAA	Yukon Environmental and Socio-economic Assessment Act
YESAB	Yukon Environmental and Socio-economic Assessment Board
YTT	Yukon Tanana Terrains

LIMITATIONS OF REPORT

This report and its contents are intended for the sole use of BMC Minerals (No. 1) Ltd. and their agents. Tetra Tech EBA Inc. (Tetra Tech EBA) does not accept any responsibility for the accuracy of any of the data, the analysis, or the recommendations contained or referenced in the report when the report is used or relied upon by any Party other than BMC Minerals Ltd., or for any Project other than the proposed development at the subject site. Any such unauthorized use of this report is at the sole risk of the user. Use of this report is subject to the terms and conditions stated in Tetra Tech EBA's Services Agreement. Tetra Tech EBA's General Conditions are provided in Appendix A of this report.

1.0 INTRODUCTION

BMC Minerals (No. 1) Ltd. (BMC) is currently working toward development of the Kudz Ze Kayah Project (the KZK Project), a volcanic massive sulphide (VMS) deposit within the Finlayson VMS district, South Central Yukon. The KZK ABM deposit hosts zinc-rich polymetallic (zinc-lead-copper-silver-gold) massive-sulphide mineralization. The KZK Project is located in the northern Pelly Mountains, 135 km south of Ross River, YT. The KZK Property (the Site) covering 23,000 hectares is accessible by an all-weather tote road from Yukon Highway 4 (Robert Campbell Highway) (Figure 1.0).

The study area is located in the northern foothills of the Pelly Mountains ecoregion, described as a rolling plateau topped by numerous mountain peaks and dissected in places by small rivers. The property has an approximate UTM/NAD83 location of 414700 E / 6816200 N in Zone 9Z and lies on National Topography System (NTS) map sheets 105G/10.

Tetra Tech EBA Inc. (Tetra Tech EBA) was retained by BMC to conduct a hydrogeological baseline and effects assessments for the KZK Project in support of the preparation of a project proposal for assessment under the *Yukon Environmental and Socio-economic Assessment Act* (YESAA) and the subsequent application under the W*aters Act* for Application of a Type A Water Use Licence.

This report presents the development, calibration and simulation results of a hydrogeological groundwater flow model in support of the hydrogeological baseline and effects assessment for the KZK Project. The groundwater flow model was developed for the purposes of providing a simulation of potential environmental effects associated with the development of the mine as well as to develop a preliminary dewatering strategy for the proposed open pit and underground workings. In particular, observations collected as part of the 2015 and 2016 field programs were used to determine an accurate and local as well as regional calibration for the model.

1.1 Purpose and Objective

The purpose of this effort was to develop and calibrate a groundwater flow model, then use the model to simulate future conditions associated with mining to predict their hydrological impacts. Development of a groundwater flow model serves the purpose of developing a complete understanding for the factors influencing groundwater flow in the vicinity of the mine and its various features. Once developed, the calibrated model provides the ability to predictively determine impact of hydrological changes caused by the development of the mine, as well as the potentially affected environment in the event of a release from one of the associated facilities.

As dewatering of the pit is required, significant groundwater pumping is likely to occur, and the spread of the associated drawdown effects has the potential to impact nearby surface water features and change the nature of the water table and subsurface potentiometric pressure distribution. The objective of the model will be to reasonably predict the timing and spread of these changes.

1.2 Project Background

The Site, for the purpose of this modeling study, encompasses the area of the two main mineralized zones of the ABM deposit and conceptual open pit, Class A, B, and C storage facilities, and water management ponds (Figure 2.0). A complete description of the Project physiology and general hydrology is provided in AEG (2016) and Tetra Tech EBA (2016). In summary, much of the ecoregion lies above treeline (between 1,350 and 1,500 m above mean sea level [m asl]), and permafrost has been observed in the alpine zones.

The ABM deposit area is overlain by a combination of till veneer, and glaciofluvial deposits composed of sand, gravel, diamicton, and minor silts and clay. These deposits may be over 40 m deep in the Geona Creek valley.

South of the ABM deposit, till is overlain by alluvial fan sediments consisting of gravelly sand, silt and diamicton up to 10 m or more thick and colluvial apron sediments consisting of boulder diamicton, poorly sorted sands and gravels.

Bedrock exposures are encountered at higher elevations, steep slopes and in deep ravines where post-glacial erosion has removed the overburden mantle. Geo-engineering (2000) described the metamorphosed rocks in the study area as consisting of a layered sequence of metamorphosed sedimentary and volcanic rocks subdivided into three main assemblages: (1) a “lower unit” of pre Devonian quartzite, pelitic schist and minor marble, (2) a “middle unit” of late Devonian to lower Mississippian carbonaceous phyllite and schist with interbanded mafic and locally significant felsic volcanic units, and (3) an “upper unit” comprising Pennsylvanian marbles and quartzite. Volcanism in the “middle unit” was accompanied by the intrusion of two to three late Devonian to Mississippian mafic to felsic metaplutonic suites. The ABM deposit including the Krakatoa zone are hosted within felsic volcanics of the “middle unit.” Bedrock is assumed to be relatively competent, but with a highly fractured zone about 2 m thick at the upper contact with the overlying sediments (Golder, 1995). Several northeast-southwest trending faults are mapped as intersecting the deposit area, including the East Fault, Northwest Fault and Fault Creek. Grain size analyses of fault gouge associated with these fault zones indicate that the gouge is comprised primarily of sand and gravel-sized material with a minor fine grained fraction.

1.3 Overview of Proposed Mining Operations

BMC plans to develop the Site with the intent of mining the ABM deposit using a combined strategy of excavating a pit to access the relatively shallow ore zones, and developing underground workings to reach a deeper ore zone. The pit is planned to reach a depth of approximately 170 m below the Geona Creek valley. The underground workings are expected to provide mining access to an approximate depth of 240 m below the valley floor, with an additional sump excavation tunnel to an approximate depth of 260 m.

Surficial material storage facilities will be developed to contain the excavated overburden materials in an overburden stockpile, and topsoil stockpiles. Waste rock and tailings from the mining activities will be segregated based on geochemical characteristics and ability to generate acid and/or metal leaching through contact with water. Waste rock and tailings will be placed in either a Class A, B or C storage facilities. The Class A and B storage facilities will be underlain with a low permeability till liner and leachate collection system. The Class C storage facility will be unlined as the rock contained is not anticipated to have acid generating or metal leaching potential. Leachate collection will be performed on the Class A and B storage facilities with the liquids being transferred to water collection ponds. The water collection ponds will be lined with synthetic geomembrane liners to provide containment for storage facility fluids. Additional mine operation structures include sediment control ponds to minimize the solids load on the downstream surface water bodies and a mill site. The expected location for each of these mining operation features is shown on Figure 2.0 and discussed in greater detail in Section 4 of this report.

2.0 MODEL DEVELOPMENT

2.1 Modeling Software

Development and calibration of the groundwater flow model was conducted using the framework for the United States Geological Survey (USGS) software package MODFLOW-NWT (Niswonger et al., 2011). MODFLOW-NWT is a Newton formulation for MODFLOW-2005, intended for solving problems involving drying and rewetting nonlinearities of the unconfined groundwater-flow equation. For the purposes of the KZK Project, the compiled executable for MODFLOW-NWT provided as part of the installation of the graphical pre- and post-processor Groundwater Vistas Advanced Version 6 (Environmental Simulations Inc. 2011) was used for simulations. MODFLOW-NWT was successful in achieving numerical stability. Processing of the predictive simulations for the purposes of evaluating flow paths by means of particle tracking was conducted using the USGS software package MODPATH (Pollock, 1994).

The NWT variant of MODFLOW is comparable to the MODFLOW-SURFACT code which is designed to provide similar drying-rewetting support with similar requirements and numerical framework. MODFLOW-SURFACT was developed by a third-party commercial entity (HydroGeoLogic, Inc.) and has been used for similar projects submitted for review under YESAA. Two of these projects include the Eagle Gold Project (Victoria Gold Corp, 2011) and the Casino Project (Casino Mining Corporation, 2013). MODPATH has also been widely used for similar projects including the Casino Project mentioned above.

2.2 Model Grid Extent and Discretization

The model domain was selected such that the KZK Project Site is centrally located, and extends as far north as Finlayson Lake and the stream gauge on Finlayson Creek, a distance of approximately 21 km north. The model was then extended an approximately equal 21 km to the south, east and west of the KZK Project Site (Figure 1.0). The domain of the groundwater model was selected to be significantly larger in extent than the Site to prevent the unexpected influence of external boundary conditions.

2.2.1 Model Grid

The grid was established with 500 m by 500 m cell dimensions at each of the corners, telescoping in the centre of the model at the KZK Project Site to model cells with dimensions of 50 m by 50 m (see Figure 1.0). The resulting grid consists of 122 model rows and 135 model columns, covering a geographic area of approximately 1,875 square kilometres. The grid is oriented in a north-south orientation (no angular rotation), with model coordinates at the lower left corner of 393,000 E / 6,795,025 N in Zone 9Z of UTM/NAD83. The model grid in the area of the KZK site is shown along with the mine features on Figure 2.2.1.

Vertically, the model grid was established using seven (7) model layers. In general, each layer is 2.5 to 3x thicker than the layer above it, although Model Layer 1 varies in thickness based on borehole logs of overburden thickness. Model Layer 7, the deepest layer, varies in thickness because the bottom of the layer is uniformly assigned a bottom elevation of 0 m asl, providing model thickness judged sufficient to accommodate the propagation of hydraulic stresses.

Table 2.2.1: Model Vertical Discretization

Numerical Layer	Geology	Model Thickness
Layer 1	Overburden	3 – 40 m
Layer 2	Weathered Bedrock / Overburden in vicinity of WW15-01	5 m
Layer 3	Weathered Bedrock	15 m
Layer 4	Weathered Bedrock	40 m
Layer 5	Bedrock	110 m
Layer 6	Bedrock	310 m
Layer 7	Bedrock	400 – 1800 m

2.2.2 Time Discretization

The groundwater model was developed and calibrated using six time intervals, called stress periods, during which the hydrological datasets such as groundwater pumping were allowed to vary. This time structure allowed the model to simulate the spread of hydraulic pumping-test stresses and allowed for the calibration of the model based on observed drawdown at each pumping well and the surrounding observation wells. A summary of each of the stress periods and their purposes is shown in Table 2.2.2.

Table 2.2.2: Temporal Discretization

Stress Period	Purpose	Duration	Time Steps
1	Steady-State Conditions	0 minutes	1
2	Simulate WW15-01 Pumping Test	12 hours	60
3	WW15-01 recovery evaluation	12 hours	60
4	Break between testing	144 hours	30
5	Simulate WW15-02 Pumping Test	24 hours	120
6	WW15-02 recovery evaluation	3.6 hours	16

2.3 Implementation of Geology

The geology associated with each of the model layers is based on a conceptual model that most of the local groundwater flow occurs near the surface in the higher permeability materials associated with alluvial/glaciofluvial deposits, surface colluvium/glacial till and fractured and/or weathered bedrock.

2.3.1 Surficial Geology

Model Layer 1 consists of a set of zones including high permeability fluvial sediments, glacial till and weathered bedrock (Figure 2.3.1a). The high permeability sediments combined the overburden mapping of stream alluvium, and the glaciofluvial sands and gravels. A debris-flow material associated with the mapped “Till Apron” were given their own zonation, allowing their hydrogeological status to be determined during calibration. The locations of each of these zones was based on a combination of two sources of data, including the mapping of surficial deposits (Golder, 1996: Figure 3-27) in the Geona Creek drainage, and the boring log data organized from various rounds of investigation near the proposed mine. This surficial geology map was used to assign zones within the model layer near the mine, and the boring logs were used to assign model layer thicknesses for each cell.

A small area in the footprint of the proposed ABM pit area was used to simulate the lower 25% of the overburden using Model Layer 2, thereby providing the model a mechanism to simulate confined condition pumping effects near WW15-01 (Figure 2.3.1b). As noted in Tetra Tech EBA (2016), groundwater in the basal sand and gravel unit is believed to be confined to semi-confined by the overlying compact to dense sand. At the completion of well installation in WW15-01, the water level rose approximately 6 m above the top of the sand and gravel and above the top of the inferred confining dense sand layer indicating a confining layer is present. The inference of a confining overburden unit is supported by the rapid response in the observation well during the pumping test at WW15-01, a reaction generally indicative of a confined aquifer.

In the areas of the model away from the detailed mapping associated with the Geona Creek drainage, the surficial geology was assigned as either weathered bedrock, or alluvial/glaciofluvial deposits. The stream channels were generally assumed to be present within 200 m of a mapped stream (Natural Resources Canada, 2016). Alluvium thicknesses were assumed to be 20 m at the mapped location of the stream, and decrease to a thickness of 5 m at a distance of 200 m from the stream. Weathered bedrock was assigned a thickness of 5 m where overburden was not mapped.

2.3.2 Bedrock Geology and Hydrogeology

The primary bedrock aquifer in the vicinity of the mineralized zones mainly consists of schistose felsic volcanics intersected with thick felsic tuff and sill/flow complexes that host the ore deposit. Model Layers 2 and 3 were intended to represent weathered bedrock. Model Layers 4 to 7 are used to represent the deeper, unweathered bedrock units and were also zoned to reflect the geologic mapping.

The geologic map (Colpron, 2015) published by the Yukon Geological Survey was used to assign zones within the model layer near the mine (Figure 2.3.2a). These zones include two zones to represent the metamorphic phyllites and schists present in the vicinity of the mine, and a zone for the plutonic units such as granite, monzonite, and granodiorite mapped at a distance of 1-2 km from the mine. Zonations implemented in each of the Model Layers 4-7 are identical. In the footprint of the area near the pit and WW15-01, mentioned in the previous section, the thickness of weathered bedrock in Model Layer 2 was added to Model Layer 3 to accommodate the need to subdivide the overburden between Model Layers 1 and 2. The implementation of the bedrock geology as assigned to model cells is shown in Figure 2.3.2b.

An initial evaluation of available data from aquifer tests and packer tests was performed to establish a framework for the expected hydraulic conductivity of the bedrock. As noted in Tetra Tech EBA (2016), results of packer tests conducted by Golder (1995) and Tetra Tech EBA (2016) vary over several orders-of-magnitude, ranging from between 1×10^{-6} m/s to 1×10^{-5} m/s in upper weathered and more fractured bedrock to 1×10^{-8} m/s to 1×10^{-7} m/s in deeper and relatively massive bedrock. Packer test results are only representative for the short discrete test intervals and the immediate vicinity of the wellbore. Single features like fractures, faults, or shear zones can significantly affect and dominate the hydraulic conductivity of the test interval, which explains the variability of inferred hydraulic conductivities observed on site.

To better gauge the bulk hydraulic conductivity in the vicinity of the ABM deposit, a single long-term (24 hr) pumping test was conducted at bedrock well WW15-02 during the 2015 hydrogeological investigation program. The test itself is described in detail in Tetra Tech EBA (2016) and is summarized later in Section 3.4.3. Testing at this location indicated the bedrock has a hydraulic conductivity of about 2×10^{-6} m/s. The geometric mean of 5×10^{-7} m/s for all packer tests and hydraulic response tests conducted in shallow bedrock (<50 m deep) agrees reasonably well with the results of the pumping test and provides a reasonable average hydraulic conductivity for the bedrock aquifer at KZK to depths of about 50 m bgs.

2.3.3 Storage

Storage properties (specific yield and specific storage) were assigned based on geologic zones, with values determined during calibration. In general specific yield represents the fraction of drainable pore space at the water table with values typically between 0.01 and 0.3 (Freeze and Cherry, 1979). Specific storage represents a per-thickness value for which an aquifer produces water under confined conditions and is expected to be between 10^{-4} and 10^{-7} per metre (Domenico and Mifflin, 1965). Zonations were established with the assumption that the unconsolidated sediments including the till, and glaciofluvial overburden could be represented as one zone, and that the weathered and unweathered bedrock generally could be represented as a second zone. In general consolidated geology such as the metamorphic bedrock beneath the Site conducts water principally through a network of fractures with an associated low porosity, whereas unconsolidated sediments typically are characterized by the higher porosities of porous clastic media. During calibration no need was identified to justify adding complexity in the form of adding further zone differentiation.

2.3.4 Faults

Multiple structural faults have been mapped in and around the Site. Under different circumstances, faults can behave as barriers to flow perpendicular to the feature, or conduits to flow parallel to it. Faults may restrict flow where low-permeability materials are offset adjacent to others of higher permeability, or where fault gouge acts as a barrier to flow. Where a fault acts as a form of enhanced permeability in the form of a conduit surface, it may be best represented using a zone of higher permeability for the purposes of simulation. For the sake of simplicity, the initial assumption in development of the model was that the faults were not significant influences on groundwater flow, with the expectation that this assumption might need to be subsequently changed during calibration. In particular, two faults were considered for use during calibration. These included a southwest-northeast oriented structural-block bounding fault present at the north end of Geona Creek, and a southwest-northeast oriented fault present in the vicinity of the proposed pit, mapped in alignment with Fault Creek. During calibration, the inclusion of two additional fault zones associated with the East Fault and Northwest Faults were included. The locations of these last three faults in the vicinity of the proposed pit is shown on Figure 2.3.2b.

2.4 Precipitation and Climate

An evaluation of the water budget for the area near the mine was conducted as part of Cominco's Initial Environmental Evaluation for the KZK Project (Cominco, 1996). The evaluation estimated the surface run-off rates based on the streamflow records, and approximated the monthly evaporation and evapotranspiration rates for the basin. The monthly data were used to create an estimate of annual recharge rates and surface run-off rates for the model domain.

The climatic conditions in the area of KZK were summarized by Geo-engineering Ltd. (2000) with additional data collected by Alexco Environmental Group (AEG) since 2015 (AEG, 2016). Total annual precipitation is estimated to be approximately 493 mm. Annual lake evaporation is estimated to be approximately 330 mm. The snow pack generally peaks in early April although snow may continue to accumulate later in the year at higher elevations. Snow melt and ice breakup in streams generally occurs between late April and early May.

2.4.1 Water Budget Assumptions

The northerly nature of the location of the Site is such that for much of the year (November to April) all precipitation falls as snow and very little is mobilized in the form of recharge. During and after freshet, the snowpack diminishes and the resulting water rapidly saturates all soil and porous media present at the surface. Evaporation and plant transpiration occurs during spring and summer months before ceasing in November. It is assumed that there is negligible change in storage from year to year.

2.4.2 Groundwater Recharge

As permafrost acts similar to a low-permeability, confining layer above the aquifer, recharge is assumed to be significantly affected in areas where permafrost is present. For the purposes of initial model construction, the permafrost recharge rate was assumed to be 1.0×10^{-2} mm/d (3.7 mm/yr), a non-zero value of less than 5% of the estimated recharge rate. This value was subsequently evaluated during calibration.

During model calibration, recharge was initially estimated as a proportion of the total precipitation based on estimated average annual precipitation (655 mm est., Cominco, 1996) and on simulated versus observed stream baseflow in 2015. Based on recommendations provided as part of a review of the hydrogeological model during the calibration process (AEG, 2016b) recharge rates were revised with the goal of matching the baseflow stream discharges observed during the fall/early winter months of October, November and December in 2015. Initially comparison was performed with flows gauged at station KZ-17 located at the base of Geona Creek near its confluence with Finlayson Creek which averaged approximately 3,850 m^3/d. Since run-off during this part of the year is likely to be very low, the gauged flow was evaluated to be entirely baseflow and representative of the rates of fall groundwater recharge in the absence of run-off. A review conducted for the 2014-2015 precipitation dataset estimated that the annual precipitation during this time period was approximately 527 mm (pers. comm. with A. Bier, AEG, 2016).

Permafrost is estimated to cover 45% of the Geona Creek catchment. Taking the permafrost-free area into account, this is an approximate recharge rate of 89 mm/yr. However, there is some uncertainty associated with flow at the gauge for KZ-17 due to marshy conditions where standing water and surface flow occur over a wide area (pers. comm. with A. Bier, AEG, 2016).

Due to the complicating conditions observed at the base of the Geona Creek drainage, the same analysis was performed for the gauging station at KZ-7. Baseflow at the gauge in April 2015 before snowmelt began was approximately 1,840 m^3/d. Based on hydraulic gradients, the underflow at the locations was estimated at 395 m^3/d. Distributing the combined total over the available entire basin area at or above this elevation resulted in an aggregate recharge rate of 74 mm/yr. The calibrated recharge rate represents approximately 14.0% of the 2014-2015 annual precipitation rate. Combined with underflow likely to be occurring through the alluvium fill in the channel, this is an approximation for the overall recharge for the drainage. This recharge rate was used as initial conditions with which to calibrate the model in 2015, then a final recharge rate as a percentage of precipitation was determined through a process of matching average streamflows at the KZ-2, KZ-7, KZ-9 and KZ-17 gauges.

Based on the run-off to precipitation ratio from 2015, approximately 77 mm/yr in aggregate over the basin has been estimated to be the recharge component and the remaining 350 mm is expected to immediately run off as surface flow into the drainage network. Based on calibration to 2015 conditions, the approximately 77 mm/yr is expected to enter the ground as recharge in the areas not underlain by permafrost. In areas with permafrost, this value has been assumed to be minimal during model calibration.

2.4.3 Run-off

As described above, annual run-off rates have been estimated for the Geona Creek catchment basin (350 mm/yr). Monthly rates of run-off for 2015 were estimated to range from 5.3 mm in March to 129 mm during snowmelt in June. The average annual run-off rate of 350 mm/yr was used as an initial run-off rate in the model and evaluated as part of the calibration process.

It should be noted that following the completion of the model development and calibration exercise, revisions made to the estimate for the mean annual water budget suggest that approximately 388 mm of an estimated annual 611 mm/yr of precipitation represent the run-off component for the upper Geona Creek basin (pers. comm. with A. Bier, AEG, 2016).

2.4.4 Evapotranspiration

Evapotranspiration likely occurs only during the spring and summer months. During the spring, the available water is significantly greater than the evaporation or transpiration rates and results only in the administrative reduction in run-off from a budget perspective. During the summer, the precipitation rates and estimated evapotranspiration rates are nearly equivalent, and the ongoing snowpack melt into early summer is sufficient to continue to provide the water for this part of the budget. Annual evapotranspiration (estimated at 88 mm/yr based the annual precipitation, run-off and recharge estimates above) will therefore not be explicitly simulated in the model, but rather subtracted off from the water budget before recharge is applied.

It should be noted that following the completion of the model development and calibration exercise, revisions made to the estimate for the mean annual water budget suggest that approximately 161 mm of an estimated annual 611 mm/yr of precipitation represent the evapotranspiration component for the upper Geona Creek basin and an additional 62 mm/yr leaves the basin due to sublimation (pers. comm. with A. Bier, AEG, 2016).

2.4.5 Permafrost

During field activities, the presence of permafrost in some areas was confirmed above the valley floor along the eastern hillside. Although the extent of permafrost within the Geona Creek basin have not been thoroughly mapped, the Terrain Assessment investigation performed by Knight Piésold included the excavation of a number of soil pits in the vicinity of the proposed pit and mine features. This investigation generally supported the following assumptions used in assigning an extent of permafrost during model development. First, permafrost tends to be present in the area at elevations greater than 1,400 m. Second, permafrost primarily occurs on north and west-facing slopes. Third, permafrost is generally not present below the water table near the creek where deeper groundwater moves upward from slightly warmer zones at depth. Where present, permafrost is assumed to be typically 10-40 m thick. Permafrost is estimated to cover 45% of the Geona Creek catchment based on this analysis.

In the areas meeting the criteria stated above (Figure 2.4.5), a separate zonation was introduced to the model in Model Layers 2 and 3. In general the permafrost is expected to form an essentially impermeable seal to infiltration. The hydraulic conductivity of the zone was initially assigned a low value (1.2×10^{-8} m/s) but was evaluated as part of model calibration. A separate zone was designated in the recharge dataset as well (described above in Section 2.4.2) to simulate significantly reduced recharge rates where permafrost was present.

2.5 Surface Water Features

Drainage of groundwater in the model occurs through a network of streams and lakes (Figure 2.5). In general, groundwater flow is convergent on the features (gaining reaches) rather than the streams serving as sources of water. Three different numerical flow packages were evaluated for use in the model. As a result, the network was implemented differently within 5 km of the Site than at greater distances. Streams and lakes were incorporated into the groundwater flow model using three separate MODFLOW packages including the streamflow routing package (SFR2), the lake package (LAK3), and the drain package (DRN).

2.5.1 Streams

In the vicinity of the Site (within 5 km), the stream network constituting Geona Creek and the associated stream network down to Finlayson Lake have been monitored using stream gauges that have been constructed to measure streamflows (Figure 2.5). Part of the model calibration efforts involved simulation of the stream discharge for comparison to the gauged streamflow. Therefore, the interactions of groundwater and surface water systems were simulated using the Streamflow Routing (SFR2) package (Niswonger and Prudic, 2005). At distances greater than 5 km from the Site, the drainage network was represented using the MODFLOW Drain package (DRN). This has the advantage of being more numerically efficient for the model solver, but does not allow for streamflow gauging to be simulated.

Stream elevations were assigned using the best available digital elevation data for an area. Near the Site, elevations were derived from the LiDAR dataset provided by BMC. Where LiDAR data was unavailable, the 20-metre land-surface elevation contour dataset was used to assign elevations. The conductance term for the streambed sediments was initially assumed to be equal to the surface alluvial/glaciofluvial-deposit vertical hydraulic conductivity value, allowing for relatively unrestricted communication between the alluvium and the streams.

2.5.2 Ponds/Lakes

Surface water features including ponds and lakes are generally simulated within the model structure using the MODFLOW Lake package (LAK3). Each of the ponds along the Geona Creek catchment were included as part of the model development. During calibration several of the ponds in the vicinity of the proposed mine were removed from the LAK3 package and simulated as a wider part of the streamflow-routing package because of the implementation mechanism of the package with MODFLOW-NWT which prevents the translation of pumping stresses through the cell containing the lake. Subsequent simulation of the formation of the pit lake (ABM Lake) after mine closure was also conducted using the LAK3 package.

2.6 Observation Datasets

Observation datasets or targets used for model calibration included water levels recorded in wells and piezometers, streamflow discharge measurements collected at 10 locations on Geona Creek or downstream from Geona Creek (data provided by Access Consulting, 2016), and drawdown observations associated with pumping tests for two separate wells near the planned pit area. By using three different types of calibration targets, the approach reduced the number of solutions possible to achieve model calibration and made the model more unique. These calibration observations are described further below.

2.6.1 Implementation of Wells

During modeling, the groundwater wells, both pumping and observation wells, were simulated using the MODFLOW multi-node well package (MNW) (Halford and Hanson, 2002). This package distributes the pumping from individual model cells that are contained within the screened interval for a well, based on the cell conductivities and the water-level calculated for each cell. For example, if the well penetrates two different cells, one with a high conductance (because the rock represented by the cell is very permeable) and another with low conductance, most of the water pumped from the well will be simulated as being produced from the high-conductance cell. The MNW package also takes the simulated hydraulic heads in the individual cells into consideration when distributing the pumping among several cells, and simulates wellbore flow resulting from different values of hydraulic head in different model layers in which the well is screened.

2.6.2 Water-Level Measurements

Water-level observations were collected at 40 different wells near or on the Site during 2015, and at six vibrating wire piezometers located in two piezometer nests near the pit area (Tetra Tech EBA, 2016). Four monitoring events were performed including May, August/September, September 22-23 and November 2015. Most of the observations were from well screens installed near surface, monitoring shallow groundwater conditions. However, 22 observations were collected from wells screened in the bedrock associated with Model Layers 2 or 3. In addition, hydraulic heads measured in the VWPs were used as calibration targets in Model Layers 4, 5 and 6. These data are based on the depth-head relationship in the vicinity of the pit itself and represent observation guidance on vertical gradients. Further details on the water levels and vertical gradients measured in these wells and piezometers are presented in Tetra Tech EBA (2016).

2.6.3 Pumping-Test Drawdown Observations

Several pumping tests were conducted in the vicinity of the pit at two recently installed groundwater wells, WW15-01 and WW15-02. The first well WW15-01 was installed with a screen interval in the surface sands and gravels comprising the alluvial/glaciofluvial deposits near Geona Creek. The second well WW15-02 was installed north of the pit in the shallow fractured bedrock beneath the alluvium. The locations for each of the two pumped wells along with other monitoring wells used during the model calibration are presented in Figure 2.6.3. The pumping tests at WW15-01 and WW15-02 are briefly described below. Further details are provide in Tetra Tech EBA (2016).

<u>WW15-01</u>

An initial step-test was performed at WW15-01 on October 4, 2015 to determine the rate to use for the subsequent longer-duration pumping test. During this step-test operation, it was noted that drawdown of nearly equal magnitude was almost immediately observed at a nearby well, BH95G-23 which is located at a distance of 24 m from WW15-01.

On October 5, 2015, a constant-rate pumping test was conducted in which 4.4 L/s [70 USgpm] were pumped from the well for a duration of 12 hours (Tetra Tech EBA, 2016). A maximum drawdown of 3.28 m was observed in WW15-01 at the end of the test. Following the test, a 12-hour period of recovery was monitored, during which time water levels recovered to within 0.12 m of initial conditions. At BH95G-23, drawdown was observed to begin immediately after the initiation of pumping. At the end of the pumping period, the maximum drawdown was measured to be 3.14 m. Following the recovery period, water levels were observed to have recovered to within 0.12 m of initial conditions.

Ordinarily drawdown propagation from a pumping to an observation well takes time to spread and the drawdown of the potentiometric surface decreases with increasing distance from the pumping well. Additionally it is typical to observe more drawdown in the pumped well itself due to losses associated with the turbulence generated as water passes through the well screen. This means that the drawdown of water levels in the aquifer are typically 60-90% of those observed in the pumping well itself. During the WW15-01 test, the drawdown measured in the observation well appears to be essentially equal to that of the pumped well with a very quick response observed at the observation well.

Several possible conditions might lead to these observed drawdown patterns. If vertical flow of water from the level of the water table occurred via the borehole for the pumped well, that might cause a relative reduction in observed pumping-well drawdown. For the observation well to show essentially the same drawdown, however, a zone of high permeability must exist to convey drawdown stresses directly to the observation well. In this case the observation well would have to be under essentially confined conditions capable of rapid transmission of pumping stresses. Either a high-permeability channel or fracture network must be present directly linking the two locations and minimizing the spread of drawdown otherwise. During analysis of the aquifer test it was interpreted that an observed overlying fine-grained sedimentary layer (suggested to be an observed tight-sand layer in the documentation for the aquifer test) may be acting as a confining layer limiting the vertical spread of pumping stresses. As a result the model layers used to represent the shallow alluvium were locally subdivided to permit the simulation of an overlying fine-grained confining unit for the purpose of simulating these conditions.

<u>WW15-02</u>

On October 9, 2015, a stepped pumping test was performed. As documented in Tetra Tech EBA (2016), an initial planned pumping rate was identified for the well, but was subsequently scaled back for the purpose of the extended duration pumping test. On October 10, 2015 the extended pumping test was performed. During this 24-hour period of pumping, conducted at a constant-discharge rate of 0.19 L/s [3 USgpm], a maximum drawdown of 3.3 m was observed in WW15-02. Recovery in the well occurred rapidly following the cessation of pumping, recovering to essentially initial conditions within three hours, and increasing to water-level conditions 0.3 m above those originally observed by three hours after that.

Two monitoring wells, BH95G-21 and BH95G-22 were located at distances of 132 and 97 m, respectively, from the pumped well. Both were also screened in the fractured bedrock. Drawdown was not observed in either well during the pumping test. It is likely that the spread of drawdown was limited by the proximity to overlying saturated alluvial/glaciofluvial deposits which would have served as a buffer to drawdown due to the specific yield limitations associated with being a water-table sand and gravel aquifer.

Calibration Datasets

Drawdown observations from each pumped well and observation well were used for the purposes of calibration of the simulated aquifer to the effects of the tests. In the case of WW15-01, drawdown observations were used to evaluate conditions in the overburden/alluvium. At WW15-02, drawdown observations were used as calibration targets for Model Layer 3 in the shallow, weathered/fractured bedrock.

2.6.4 Streamflow Discharge

Stream gauging stations were constructed at multiple locations on Geona Creek and Finlayson Creek downstream. At each station, monthly discharge has been collected during 2015/2016, representing a high quality set of observations for streamflow which consist of a combination of precipitation run-off and groundwater discharge from the KZK and downstream areas (Figure 2.6.4). Each gauging location was implemented in the model as a location along a stream network where simulated stream discharge was observed. Since the calibration period was constructed to be a steady state period followed by stress periods for the two aquifer tests, the averaged streamflow for each stream gauging location was used as a target. At the time of model calibration, the data set only included times when the streams were not frozen. Discharge during the periods where frozen conditions are typically observed were therefore assumed to be equal to the lowest observed gauged flow data at the location.

2.7 Parameter Estimation Approach

The parameter estimation software utility PEST (Doherty, 2013) was utilized extensively during model calibration. PEST provides the capability to estimate model parameters using a non-linear regression procedure in an effort to match a set of observations. PEST uses a nonlinear regression approach to minimize an objective function, which is the sum of the squares of the weighted residuals. A residual is the difference between a measured and simulated value. The use of weighting factors allow items such as measurement errors, differences in type of measurements, differences in the number of measurements, and the goals for the model to be taken into account.

Each of the various types of data were evaluated to determine their importance in model calibration. Weights were assigned to the observations to allow PEST to make parameterization decisions which placed higher emphasis on observations with higher weights. Weights for streamflow discharge observations were based on a multiple of the inverse of the standard deviation for the average baseflow. The weights for drawdown in the observation well BH95G-23 during the WW15-01 pumping test were reduced due to uncertainty associated with the results (see Section 2.6.3).

As part of the calibration process, PEST was used to optimize the aquifer parameter values that would produce the best match to observed data. This process involved providing PEST with some constraints and guidance on what the expected range and values might be for each parameter, and allowing it to estimate within that set of constraints.

The calibration process is described in more detail in the following chapter.

3.0 CALIBRATION

Model calibration was performed with a specific set of goals in mind. The calibration goals were generally quantitative, with a focus on minimizing the difference between simulated and observed values at a specified location. These goals included:

1. Matching observed hydraulic heads in the widest distribution of wells in the vicinity of the Site;
2. Visually matching observed drawdown behavior in wells during the two aquifer pumping tests conducted in 2015; and
3. Matching observed streamflow at the gauging stations mentioned in the previous section of this report.

3.1 Calibration Process

The model was calibrated using PEST in a manner which balanced the simulation of pumping tests with steady state hydraulic head observations and streamflow discharge for 2015 conditions. The agreement between measured and simulated drawdowns in the pumping-test wells is very good, and the distribution of heads is responsive to precipitation-based recharge in the higher-elevation areas as well as the subsequent discharge of groundwater in streams while maintaining the water balance dictated by the streamflow gauging stations.

Both manual and automated calibration approaches were used to guide development of the model. After construction of the initial data sets, the model calibration process progressed in the following manner.

1. Simulated streamflows were consistently lower than observed. Initially it had been assumed that a low, relatively constant rate of surface run-off was appropriate, but when even very high rates of recharge failed to increase simulated streamflows, run-off was applied explicitly to each stream segment. Although there is constant groundwater discharge to the streams, a significant proportion of the annual flow apparently is from precipitation run-off which never enters the groundwater system. Run-off is implemented in the model using an assumption that the water does not enter the budget of the model until it enters the stream system. It is introduced to the stream system using an estimated stream segment capture area calculation. For each segment in a stream, the area of the catchment which the segment drains is estimated using the contoured topography associated with the digital elevation model. The total area is then multiplied by the 350 mm/yr rate to produce a run-off discharge loading rate in cubic metres per day (m^3/d), which is introduced into the streamflow routing package of MODFLOW and becomes part of the simulated stream discharge. Later during calibration, the run-off rate for Fault Creek was increased to 484 mm/yr to account for wind-driven accumulation of snow in the local catchment.
2. Lakes were initially all represented within the model structure using the MODFLOW Lake package (LAK3); however the LAK3 construction has the effect of replacing the model cell with the lake cell itself, thereby not allowing for groundwater flow (or drawdown propagation) to occur beneath the lake as it would in reality. Since several lakes occur in the immediate vicinity of the pumping-test wells and the planned open pit, the presence of the lakes resulted in an inability to match drawdown in the observation and pumping wells. As a result, the lakes were converted to be part of the stream drainage network.
3. Head observations in monitoring well BH95G-9 near the northern end of Geona Creek consistently indicated that water levels are mounding higher than the mapped geology would otherwise suggest. In addition, simulated stream discharge for Geona Creek in the vicinity were lower than observed. To improve the calibration, one fault was incorporated into the flow model as a vertical barrier to groundwater flow. This fault represents an interruption in the mapped geology at the surface and likely results in the emplacement of more permeable

geologic units adjacent to less permeable geologic units resulting in the potential for a hydraulic barrier. The fault was implemented in an attempt to dam water behind it, raising heads in wells and forcing deeper groundwater upward to discharge at the surface streams. The hydraulic conductivity of the fault zone was determined during model calibration.

4. In response to a model review memorandum (AEG, 2016b), as noted earlier, recharge was determined using baseflow stream conditions as a calibration target. Recharge was determined through calibration to 2015 conditions to be consistent with a rate of 77 mm/yr for the 2015 calibration time period. For simulation of pit dewatering and eventual pit-lake filling, since average annual conditions were being assumed and 2015 was judged to be a wetter than average year, this rate was scaled for the expected average annual precipitation value of 493 mm/yr to 56 mm/yr.

5. At the end of the calibration phase, discussions with the project team indicated that the fault lineations near the pit were fairly prominent and expected to be potentially influential to flow in the area. Several potential evaluation scenarios were conducted to determine if fracture patterns in associated parallel joint-sets played a critical role in matching the observed water levels in the vicinity of the proposed pit, particularly at depth in the bedrock. Three fault lineations were evaluated to assess the potential sensitivity of their influence on the pit-area hydrology through varying fault-zone width and conductivity. In each case, parameter estimation techniques using PEST were employed to determine the best combination of hydraulic conductivities both for the fault-zone as well as for the surrounding bedrock zone.

6. Packer-testing results for the bedrock and fault zones were made available following initial calibration. These were used as guidance to perform a limited recalibration in which the hydraulic conductivity for the bedrock was re-evaluated, and the baseflow for the streams was used to constrain the calibration for the recharge rate assigned in non-permafrost areas.

7. Although a horizontal-to-vertical anisotropy ratio of 10x was judged appropriate for the sands and gravels of the alluvium during calibration, the weathered and/or fractured bedrock was not. Although efforts were made to keep the anisotropy ratio to 100x or less, the horizontal and vertical hydraulic conductivity values for each geologic zone were considered independently most of the way through calibration. Due to the observations of hydraulic head at depth, the automated calibration process had determined that in several zones the vertical hydraulic conductivity values should be nearly two orders-of-magnitude higher than the horizontal values. This was because in the vicinity of the pit horizontal gradients were necessary to match the variation in hydraulic head within a depth range, however overall pressure at the depth was typically simulated as being too high without a “pressure-release” built in to allow water to vertically drain to the surface. As a result, the fault zones were determined to have a horizontal-to-vertical anisotropy ratio of 0.1x. The non-faulted bedrock was held at the same hydraulic conductivity as determined by the packer-test data with a horizontal-to-vertical anisotropy ratio of 0.1x for the same reasons as the fault zones.

8. The final calibration stage involved taking the best current model parameterization, which to this point used a generalized set of storage conditions, and doing a series of model simulations to find the best combination of storage and calculated values for hydraulic conductivity, essentially calibrating the storage to the pumping tests results.

9. During the calibration process more than 100 manual runs were performed along with a similar number of automated PEST runs, each of which included multiple rounds of automated runs performed by PEST. Generally the most significant improvement of the model statistics occurred when structural changes were made to the model (run-off and recharge assumptions, conversion of lakes to streams, etc.) after which the automated parameter estimation quickly converged on the optimal solution based on the associated set of assumptions.

The following three sections (Hydraulic Properties; Model Mass Balance; and Simulated Water Levels) describe the parameter values used in the model, and the resulting model behavior. The combined use of water-level elevation targets, transient pumping-related drawdown targets and streamflow discharge targets result in an effectively constrained model of groundwater flow at the Site.

3.2 Hydraulic Properties

Table 3-2 provides the hydraulic-conductivity values used in the model for each of the hydrogeological units. The values for horizontal hydraulic conductivity are generally consistent with those measured at the Site from pumping tests or packer tests. The calibrated hydraulic conductivity for the channel sands and gravels of the overburden (Zone 1) was determined to be higher than that estimated during the aquifer testing. This is likely due to a combination of well construction in the pumped well WW15-01, the assumed aquifer thickness in the test analysis, and the assumption during the test analysis of infinite aquifer extent. In reality, pumping effects likely propagate quickly away from the pumped well, reaching the edges of the overburden where the bedrock comes to the surface within a short time after the initiation of pumping. As a result, the aquifer does not conform completely to the assumptions inherently required by the test analysis. The model simulation is not subject to these constraints and may therefore represent a better estimate for the hydraulic conductivity of the overburden as a result. Storage parameterization was evaluated during calibration to determine the most appropriate values. Without more constraints on the model parameterization however, a specific yield of 10% for the overburden and 0.1% for the bedrock was selected as appropriate.

Parameter estimation generally suggested that overburden specific yield values between 5 and 10% would best produce simulated results that matched those observed during the pumping test, but values below 10% were judged to be too low for use in simulating a high-energy alluvial depositional environment.

Table 3.2: Zoned Aquifer Hydraulic Properties

Geology	Zone	Aquifer Test	Kx	Kz	Sy	Ss
		m/s (avg)	m/s	m/s		1/m
Fluvial/ Glaciofluvial	Zone 1	1.10E-04	2.26E-04	2.26E-05	0.10	6.44E-05
Confining Layer by Pit	Zone 9	-	1.19E-06	1.16E-08	0.10	6.44E-05
Till Apron	Zone 10	-	1.59E-05	1.59E-06	0.10	6.44E-05
Glacial Till	Zone 4	-	5.79E-07	5.79E-09	0.10	6.44E-05
Weathered Bedrock	Zone 2	1.0E-07 - 4.1E-05	1.16E-07	1.00E-08	0.001	1.00E-06
Metamorphics Bedrock	Zone 6	-	1.17E-09	2.65E-08	0.001	1.00E-06
Weathered Pit Bedrock	Zone 13	6.5E-08 - 7.5E-06	6.83E-07	6.83E-08	0.001	1.00E-06
Pit Bedrock	Zone 7	3.5E-09 - 6.00E-06	2.40E-08	1.42E-07	0.001	1.00E-06
Plutonics	Zone 3	-	1.16E-09	1.16E-09	0.001	1.00E-06
Permafrost	Zone 5	-	1.16E-08	1.16E-08	0.001	1.00E-06
Fault Creek Zone	Zone 8	3.5E-06	7.78E-08	9.27E-07	0.001	1.00E-06
East Fault Zone	Zone 11	3.5E-06	7.78E-08	9.27E-07	0.001	1.00E-06
Northwest Fault	Zone 12	3.5E-06	7.78E-08	9.27E-07	0.001	1.00E-06

Overburden
Bedrock

Kx and Kz = horizontal and vertical hydraulic conductivity

Sy and Ss = specific yield and specific storage

3.2.1 Streambed Conductance

The streambed conductance along Geona Creek was determined to play a somewhat significant role in simulating the hydraulic head patterns observed in the measured data. The reduction of streambed conductance below the vertical hydraulic conductivity of the valley-fill alluvial deposits resulted in increased hydraulic heads beneath the streams as drainage was restricted. Realistically, the properties of the stream deposits acting as a moderating layer between the simulated geology and the streams would likely be equal to, or slightly less than that of the geology itself. The streambed for Geona Creek was administratively assigned to be 1.0 m thick with a hydraulic conductivity approximately 5 times lower than that of the vertical hydraulic conductivity of the alluvium near the pit (4.8×10^{-6} m/s).

3.2.2 Fault Conductance

The northeast/southwest trending fault present at the northern end of Geona Creek (Figure 2.3.1a and 2.3.1b) was evaluated as a barrier to flow as part of the calibration effort. The HFB package was used to simulate the fault zone, treated as 1 m wide. The fault zone was determined to represent an obstruction to horizontal flow, believed to be in part responsible for elevated water levels observed in monitoring well BH95G-9. As a result, the fault conductance was administratively assigned to be low enough that it represents an essentially impermeable barrier to flow. The fault zone was assigned a hydraulic conductivity of 10^{-12} m/s or approximately five orders-of-magnitude lower than weathered bedrock at the surface through which most of the groundwater flows. The calibration of this value is relatively unconstrained due to limited data, and likely could be much higher without significantly impacting the model results. As simulated groundwater levels are still underpredicted at the monitoring well (BH95G-9) that prompted the initial implementation of the fault zone, it is likely that other barriers to flow exist near this well.

As noted in Section 3.1, three faults have been mapped in the vicinity of the proposed pit area. Each of the three faults was evaluated for its potential to act as a higher-permeability conduit or drain that might affect deeper water levels as part of the calibration effort. Each of the three faults was implemented as a separate zone of hydraulic conductivity with a width of approximately 2-3 model cells or 100-150 m to ensure hydraulic connection along the feature where the model grid was oriented at an angle compared to the fault. The calibration process suggested that some increased flow was likely associated with the mapped fault zones. The calibrated hydraulic conductivity of the fault zones was determined to be similar to that of the surrounding weathered bedrock zone, and more conductive than the surrounding unweathered bedrock zone (approximately 6x as high vertically, and over 4x as high horizontally.).

While the final calibrated value for the horizontal fault conductance is lower than that observed in the packer testing, the distribution of heads observed in the vibrating-wire piezometers within a model layer indicates that a significant hydraulic gradient must be present between the piezometers, spatially. Each fault measured in the field was expected to be approximately 1-5 metres wide, however in the model this feature is represented by a zone 100-150 m wide in an otherwise low-permeability bedrock host. As a result the calibrated value for the fault zone should be expected to be an aggregate of the bedrock and the fault zone. The vertical hydraulic conductivity for the fault zones is less than a factor of 4 times lower than that observed in the packer testing as well.

3.2.3 Recharge Zones

The applied non-permafrost recharge rate in the calibrated 2015 model was determined to be 135 mm/yr (3.7×10^{-4} m/d). In the areas with permafrost, it was decided that essentially no infiltration occurred during much of the year, and minimal amounts during the summer since vertical downward flow remained restricted. The permafrost recharge rate was therefore assigned a value of 3.7 mm/yr (1×10^{-5} m/d). The net 2015 calibration recharge rate for the Geona Creek basin is therefore the equivalent of 77 mm/yr. Although the extent and depth of permafrost remains somewhat uncertain it is not expected to have a large impact on the model results because the precipitation is redistributed to streamflow as runoff and infiltrates along stream channels. If the extent of permafrost is less than interpreted, the effect could be that more water would enter the shallow groundwater and potentially increase groundwater flows to the pit during mining. The steep hillsides around the mine area result in rapid elevation change increasing the chances of encountering permafrost with progress away from the mine. This limits the extent to which the assumed permafrost extent can impact the model. If much greater permafrost is present than has been interpreted, then the expected result would be that run-off would be higher than expected and groundwater recharge lower.

3.3 Model Mass Balance

In the groundwater flow model, the only source of water is recharge due to precipitation and water released from storage by declining water levels. Outflows include only streamflow discharge, implicitly evapotranspiration, groundwater pumping, and replenishment of aquifer storage in the event that water levels rise.

Model-Wide Water Budget

The simulated rates of water entering and leaving the model for the pre-pumping simulation are presented in Table 3.3.1, along with an initial approximation for the expected flux for each category. The mass-balance error (based on the difference between simulated inflow and outflow), which is one indicator of how well the modeling equations were solved (but not the uncertainty in the various mass balance components), was 0.0%, indicating that the equations were accurately solved. The values are presented in cubic metres per day.

Storage represents the volume of water which enters or leaves aquifer storage due to changes in aquifer stresses. During non-pumping conditions, storage change should be essentially zero because no stresses are changing other than seasonal changes which were not incorporated into the model calibration. During spring snowmelt, infiltration of snowmelt recharges groundwater, increasing the volume of water in storage. After snowmelt has occurred the saturation of the subsurface decreases as it discharges to Geona Creek or other surface drainage features. If seasonal variation was incorporated into the model, the result would likely be variation in simulated streamflow and water levels in wells. During mining seasonal simulations would likely produce significantly higher rates of pit inflow during the spring snowmelt and lower-than-average rates of groundwater discharge to the pit after the overburden had finished draining the water from the spring.

Table 3.3.1: Model-Wide Mass Balance

	Flux In m^3/d	Flux Out m^3/d	Net m^3/d
Storage	0	0	0
Drains	0	438,648.1	-438,648.1
Recharge	509,103.5	0	509,103.5
Stream Leakage	30,254.1	88,706.6	-58,542.5
Lake Seepage	11,025.5	23,028.3	-12,002.8
Wells	3.9	3.9	0
Total	**550,386.9**	**550,386.9**	**0.0**

Notes:
The NET column takes into account the difference between flux in and out of stream channels and the lakes. As the flux terms represent water entering and leaving the groundwater, negative values in the NET column for streams and lakes indicate that water is leaving the model through these surface water features.
Nominal flow associated with wells represent wellbore flow in wells screened across multiple model layers due to the presence of upward groundwater gradients, rather than actual pumping.

The simulated recharge from precipitation is 509,103.5 m^3/d. Discharge out of the model is primarily through the stream channels simulated by model drain cells, as the vast majority of the streams in the model are simulated as drain cells. Lesser fluxes occur through the smaller network of streams simulated explicitly using the streamflow routing package and appearing as “Stream Leakage” or through the Lake package. The exiting flux associated with streamflow represents the sum of the discharge to surface from groundwater within the model domain where streams are simulated using the streamflow routing package. Notably it does not constitute the entirety of the flow in the stream at KZ-26. Due to the explicit application of surface water run-off and direct precipitation applied to the stream segments, this component of water never enters the groundwater budget, and is treated separately.

<u>Geona Creek Catchment Mass Balance</u>

A more detailed review of the mass balance for the catchment that routes water to Geona Creek provides greater insight into the model functionality in the KZK Project area of interest. A mass balance analysis was performed for the steady-state conditions of model stress period 1 and the influx and outflux values for the immediate catchment. The results are presented in Table 3.3.2. Precipitation within the catchment is distributed between recharge and surface run-off. Groundwater recharge within the catchment represents a net influx of 3,993.9 m^3/d. Most of the subsurface flow discharges to, and subsequently out of the Geona Creek catchment occur via Geona Creek at an annual average daily rate of approximately 2,241.2 m^3/d. The flux in component of water from associated with stream leakage represents the sum of the few gaining stream reaches of Geona Creek. As in the model-wide mass balance, it is worth recognizing that the stream flux in this mass balance table is not the same as the gauged streamflow simulated by the model, but the contributions to streamflow from groundwater discharge. As the average annual simulated streamflow at the KZ-17 gauge at the base of Geona Creek is slightly over 32,000 m^3/d (compared to the early-fall baseflow rate of 3,853 m^3/d), a clear implication of the model is that a very high proportion of observed annual streamflow in the vicinity of the Site is due to overland flow of precipitation which never becomes part of groundwater flow budget on an annual accounting basis.

Table 3.3.2: Mass Balance in the Geona Creek Catchment

	Flux In m^3/d	Flux Out m^3/d	Net m^3/d
Groundwater Flux	1,252.0	3,004.7	-1,752.7
Drains	0	0	0
Recharge	3,993.9	0	3,993.9
Stream Leakage	11,062.6	13,303.8	-2,241.2
Wells	3.9	3.9	0
Total	**16,312.4**	**16,312.4**	**0.0**

Notes:
The NET column takes into account the difference between flux in and out of stream channels. As the flux terms represent water entering and leaving the groundwater, negative values in the NET column for streams indicate that water is leaving the model through these surface water features.
Nominal flow associated with wells represent wellbore flow in wells screened across multiple model layers due to the presence of upward groundwater gradients, rather than actual pumping.

3.4 Simulated Water Levels

Model calibration was performed to identify the combination of parameter values which produced the best match between simulated and observed water levels, both pre-pumping and during the pumping tests from the 2015 field season. Comparisons were performed based on a 1-to-1 comparison basis, evaluated to determine the nature of the statistical differences between the simulated and observed datasets (model residuals).

3.4.1 Comparison of Measured and Simulated Water levels

Figure 3.4.1a presents the simulated hydraulic heads for Model Layer 1 (Overburden and weathered bedrock at surface), and Figure 3.4.1b presents the simulated heads for the lower portion of the weathered/fractured bedrock (Model Layer 3). These figures represent water-level conditions for the steady-state simulation used as initial conditions leading into the transient pumping simulation.

The model was calibrated to target water levels based on the average of those measured during the 2015 field observation period, as well as selected drawdown observations. The simulated head conditions make the assumption that the averages of the observed 2015 hydraulic head measurements collected over the summer months of the field season are representative of general flow conditions. This assumption ignores short-term changes in precipitation that occur, assuming that these changes have only local effects on water levels and discharge rates. Thus, the small changes caused by short-term changes in recharge were considered to have insignificant impact on the use of these wells for calibration.

Simulated heads in the overburden reflect the observations that groundwater flow starts occurring in the higher elevation areas, particularly those with stream-channel alluvial fill, and follows the alluvial and glaciofluvial deposits toward lower elevations. Generally at each point along Geona Creek, the predominant hydraulic gradient is toward the stream, rather than parallel to it, until it emerges due to upward gradients caused by discharge at the surface. From that point water flows downstream until it leaves the model area. Essentially all stream reaches are gaining reaches rather than sources of surface water feeding groundwater.

Simulated heads in the weathered bedrock generally are muted versions of those seen at the surface; however, there is more influence from recharge evident. Since recharge occurs primarily where permafrost is not present, this tends to dominate on the eastern and southern-facing slopes. Near the proposed open pit, this means that most of the groundwater flow occurs from west to east since less recharge is simulated on the east side of the drainage (i.e., west-facing slopes).

3.4.2 1:1 Line

Figure 3.4.2 depicts the graph for the model simulation results in which the observed hydraulic heads are plotted on the X-axis and the corresponding simulated hydraulic head is plotted on the Y-axis. An ideal simulation would result in all points falling on a 1:1 line from the lower-left hand corner of the plot to the upper-right corner. For example, when the simulated water level is greater than the observed water level, the data point is plotted above the 1-to-1 line. The poorer the agreement between a simulated value and the observed value, the farther from the 1-to-1 line the point falls.

The observed range of water levels in the KZK model is approximately 146 m. The higher degree of scatter of the deeper bedrock units indicates that the accuracy of the simulation of the bedrock is slightly lower than that of the overburden. Although both the overburden and weathered bedrock water-level points straddle the 1:1 line, a slight bias is present where bedrock aquifer water levels are over simulated. Simulation of water levels in the overburden is generally unbiased. 74% of the overburden and weathered-bedrock water levels simulated by the model plot within 6 m of their observed value on the 1-to-1 line, and 60% were within 4 m of their observed values. In the deeper bedrock, over half of the simulated hydraulic heads were within 6 m of their observed values.

3.4.3 Simulation of Aquifer Tests

As discussed in Section 2.6.2, stress periods 2 through 5 were used to simulate the effects of the pumping tests conducted at wells WW15-01 and WW15-02. Figures 3.4.3a and 3.4.3b show simulated and observed time-series drawdown plots for the two pumping tests. Even though these aquifer test durations were 12 and 24 hours, respectively, and there was only one observation well that showed a response, the observed data were adequate to constrain the aquifer parameters associated with the units in which each of the pumping wells are installed.

<u>WW15-01</u>

Figure 3.4.3a shows the observed data associated with the 12-hr pumping test at WW15-01, in the pumped well itself as well as the observation well BH95G-23 located 24 m to the southeast. Total drawdown in WW15-01 is higher in the simulation than is observed by approximately 1 m, likely because of the construction of the well itself. If water flows down the borehole and around the packer present above the screened interval, then the observed drawdown is likely to be less than simulated. Simulated drawdown in BH95G-23 is very closely matched to the observed drawdown, as discussed previously. Simulated drawdown does not precisely follow the observed data because the pumping test is likely functioning under partially confining conditions. The lack of high resolution vertical or horizontal discretization of the model locally likely impacts the accuracy of the model simulation as well. The construction of the model was altered to simulate the confining conditions as best as possible by splitting the overburden into two separate model layers.

<u>WW15-02</u>

Figure 3.4.3b shows the observed data associated with the 24-hr pumping test at WW15-02. Zero drawdown was measured in nearby observation wells BH95G-21 and BH95G-22 located 132 m south-southwest and 97 m east-southeast respectively. Simulated drawdown in WW15-02 is slightly lower than observed by the end of the test by approximately 0.2 metres. This may be due to anisotropy in the weathered bedrock not accounted for in the model,

or the combination of storage values used for specific yield and specific storage may be slightly low. The simulated match to observed data is still statistically good as documented by the calibration statistics described below.

Minimal drawdown (<0.1 m) was simulated in either observation well.

3.5 Residual Statistics

It is standard practice in documenting model calibration to provide quantitative evidence of the match of the model simulated results to those observed. In this section the model residuals with respect to observed water levels are discussed. The term "residual" is defined in this report as the simulated value (such as hydraulic head) minus observed value, so that the residual has a positive value when the simulated value is higher than the observed value. The different calibration statistics used in this section are defined using the following equations (Equations 3.5.1 -3.5.4) as follows:

Mean Residual (MR): the average difference between simulated (x_s) and measured (x_m) observations

$$MR = \frac{\sum(x_s - x_m)}{n} \qquad 3.5.1$$

Residual Standard Deviation (RSD): the summed square of the average difference between simulated (xs) and the mean ($\bar{x}$) of the observations divided by the number of observations

$$RSD = \frac{\sum(x_s - \bar{x})^{\,2}}{n} \qquad 3.5.2$$

Absolute Residual Mean (ARM): the absolute average difference between simulated and measured observations

$$ARM = \frac{\sum|(x_s - x_m)|}{n} \qquad 3.5.3$$

Root Mean Square Error (RMSE): the square of the quantity represented by the sum of the difference between simulated and observed value squared divided by one less than the number of observations (n-1).

$$RMSE = \sqrt{\frac{\sum(x_s - x_m)^2}{n-1}} \qquad 3.5.4$$

Correlation Coefficient (R^2): A measure of the correlation between (covariance of) the simulated and observed values divided by the product of their standard deviations. This produces a range of values between 0 and 1, where 0 indicates no correlation and 1 indicates ideal correlation.

3.5.1 Hydraulic Head

Residual statistics for hydraulic heads are presented in Table 3.5.1. The goals of the model calibration process, besides the model being a reasonable representation of the hydrogeological system and of the processes involved in recharge, movement, and discharge of water, include several quantitative measures. The mean residuals (weighted and unweighted) should be small (close to zero), the residuals should be randomly distributed (in magnitude and spatially), and the spread of the residuals around the mean should be small compared to the range in values of the pertinent observations.

Table 3.5.1: Hydraulic Head Model Statistics

Category	Statistic
MR	-1.23
RSD	7.34
ARM	5.28
RMSE	7.44
Observation Count	44
Range	163.34
Norm. MR	-0.76%
Norm. RSD	4.49%
Norm. RMSE	4.55%

For the total model, the MR (Equation 3.5.1) is -1.23 m and the RSD (Equation 3.5.2) is 7.34 m. ARM for the model (Equation 3.5.3) is 5.28 m indicating that in combination with MR, the average residual is 5.23 m, and that the model has a slight bias to the high side, with hydraulic heads being simulated as slightly higher than those observed. The RMSE (Equation 3.5.4) is 7.44 m. These values should be compared with the overall range in measured water levels of 163 m. The MR and RSD are approximately 0.76 and 4.49% of this range, respectively. The RMSE is approximately 4.55% of this range. (Although the ability of a model to match observed water levels is a function of the complexity of the groundwater system, values of RMSE less than 10% are commonly considered to indicate good agreement.) The correlation coefficient (R^2) for the simulated versus observed water-level data across all layers in the model is 0.99 indicating a very high degree of correlation.

3.5.2 Drawdown

As discussed in Section 2.6.2, several modifications were made to the drawdown dataset for the purposes of producing an accurate representation of hydrogeological conditions in the vicinity of the Site. The adjustments for the WW15-01 pumping test in the alluvium involved changes to the increase in weighting of the drawdown in the observation well, and decrease in weighting for the observed values in the pumping well itself.

Table 3.5-2: Drawdown Model Statistics

Category	Statistic
MR	-0.04
RSD	0.16
ARM	0.11
RMSE	0.16
Observation Count	512
Range	3.30
Norm. MR	-1.3%
Norm. RSD	5.0%
Norm. RMSE	5.0%

An evaluation of the residuals of drawdowns associated with simulation of the two pumping tests shows that the MR is -0.04 m and the RSD is 0.16 m. The ARM is 0.11 m and the RMSE is 0.16 m. These values should be compared with the overall range in adjusted observed water levels of 3.28 m. The MR and RSD are approximately 1.3 and 5.0% of this range, respectively. The RMSE is approximately 5% of this range. The correlation coefficient (R^2) for the simulated versus observed drawdown data across all layers in the model is 0.99.

3.5.3 Streamflow

The model simulates streamflow at each regularly monitored gauging station along the Geona Creek drainage network. Residual statistics for surface water discharges have not been calculated since there are not multiple measurements that change over time. Instead the simulated versus mean-observed streamflow rates for each station are presented in Table 3.5.3 along with the calculated residual.

Table 3.5.3: Streamflow Discharge Residuals

Gauging Station	Observed (m^3/d)	Simulated (m^3/d)	Residual (m^3/d)
KZ-2	2,427.1	1,666.2	-761.0-
KZ-7	8,976.2	11,120.7	2,144.4
KZ-9	22,572.0	20,431.5	-2,140.5
KZ-13	8,427.6	8,121.0	-306.6
KZ-15	55,374.5	69,660.3	14,285.8
KZ-16	32,532.5	33,559.1	1,026.6
KZ-17	35,763.1	34,250.1	-1,513.1
KZ-21	60,889.5	42,964.0	-17,925.5
KZ-22	119,296.1	140,804.7	21,508.6
KZ-26	170,000.6	162,070.8	-7,929.8

3.6 Uncertainty

The calibration process adds to the understanding of the model parameterization. Properties such as the hydraulic conductivity of the weathered bedrock in the vicinity of the proposed open pit and the stream alluvium were found to be relatively constrained, in part due to the availability of pressure data and in part due to the aquifer testing performed. Other properties such as the characteristics and influence of the permafrost and glacial till were deemed far less certain. In some cases, the uncertainty associated with a parameter is due to the lack of data with which to accurately calibrate. In other cases, observations for some of the wells appear inconsistent with other nearby data. A list of hydrogeological characteristics with significant degrees of uncertainty was compiled. This list was not quantitatively derived, but the result of a backward look at the calibration process.

Observations

1. Drawdown observed in WW15-01 versus that observed in BH95-21 are essentially the same, even though one is the well in which pumping was conducted and the other an observation well located over 20 m distant. This behavior is unexpected, and atypical. It suggests that pumping stresses are conducted under essentially confined conditions or via some form of conduit flow. Neither of these conditions is consistent with the logged sands and gravels of the overburden at the location. Uncertainty associated with these unexpected conditions could be reduced by repeating the aquifer test with the knowledge gained from the first test. Ideally an aquifer test is best performed by observing the results of pumping at multiple locations at varying distances from the pumped well.
2. The potential boundary-condition influence of Geona Creek and related ponds on the observed results of the WW15-01 pumping test (radius of influence extends to and beyond the ponds) is uncertain. Drawdown may be limited by increased infiltration of water from these bodies.
3. Unexpectedly high water levels observed in MW15-01 and unexpectedly low water levels in BH95-146. These may reflect localized influences such as fracturing or low-permeability conditions leading to groundwater mounding.
4. Drawdown observed in WW15-02 is expected to be significantly dependent on the efficiency of the well. Typically water levels in a pumped well are substantially lower than those in the immediately surrounding aquifer. For the purposes of calibration, an assumption was made that the well efficiency for WW15-02 was 100%. This is possible if the construction of the well is such that laminar flow through the wells screen can be maintained and the well screen can function essentially as no barrier to flow.
5. There is a 10-metre observed head difference between piezometers VWP33430 and VWP33431, both of which are completed in the deeper zones of the bedrock near the planned pit. It is uncertain whether one or the other of the observed heads is inconsistent with actual heads at the depth, or whether natural variation in the bedrock simply results in a high local groundwater gradient. This uncertainty influences the calibration for the vertical hydraulic conductivity of the unweathered bedrock.

Uncertain Model Parameters

1. The extent and hydraulic properties of the glacial till.
2. Extent, depth and hydraulic properties of the permafrost.
3. Degree of variation in hydraulic conductivity and depth of weathered/fractured near-surface bedrock.

4. Fault Lineation extent and properties (width, length, how extensive the features are to the east and west away from the proposed open pit, as well as fault permeability) for the East Fault, Northwest Fault and Fault Creek Fault.
5. Potential presence of other fault zones not in the immediate vicinity of the proposed pit.

3.7 Confidence

The combination of being able to calibrate to surface-water discharge measurements, combined with a distribution of groundwater level elevation data, unit-specific aquifer tests, and locally mapped surface geology results in a model of the groundwater flow that is fairly well constrained. Confidence in the ability of the model to accurately predict water levels in the area of interest is expected to be high, within the range of natural and seasonal variation.

At present the model is believed to be well constrained from the perspective of an annual stress-period simulation. It is likely that the greatest degree of variation from what is currently envisioned would come through the year-to-year fluctuation in precipitation/snowpack, and the timing of the spring freshet. Slower rates of snowmelt combined with higher than expected precipitation would be expected to result in higher rates of effective recharge during the spring. These would in turn result in sustained higher rates of flux of groundwater into the pit.

4.0 SIMULATED MINING PLAN

Following the calibration process described in Section 3.0, the groundwater flow model was used to simulate a hydrological sequence associated with the proposed nine-year excavation of the pit and underground workings. The model was then used to simulate the post-closure effects of closing the underground workings, redirecting Fault Creek to discharge into the pit causing the pit to fill with water, and monitoring the associated return to new steady-state conditions.

To make mining feasible, an initial phase of overburden dewatering will be performed, followed by further dewatering throughout the life of the mine. The groundwater model can be used to evaluate the rates of groundwater withdrawal necessary to dewater the mine as it is developed and worked. To accomplish this goal, mine development was divided into a sequence of periods associated with the planned advancement of the open pit and underground workings throughout the nine-year mine life. The model was then used to evaluate the groundwater dewatering rates necessary to permit each phase of mining.

4.1 Anticipated Pit Mine Development

The ABM and Krakatoa zones of the ABM deposit will be accessed by excavation of a pit and underground mine. The pit and underground workings will be mined out over a nine-year period of time, initially starting with the ABM zone, then expanding to include the Krakatoa zone. Prior to the first phase of excavation, a six-month period of dewatering will be performed to allow the overburden to be stripped and the initial open pit to be advanced. To simulate the different stages of mining and associated dewatering, drains were placed in each of the model cells anticipated to be part of a particular phase of mining.

4.1.1 KZK Mine Features

In addition to the open pit and underground workings, the locations of the Class A, B, and C storage facilities as well as other supporting features were incorporated into the model as part of simulating mining operations. The locations for the proposed mine layout features including the storage facilities as well as ancillary structures are shown in Figure 4.1.1. Water drainage conveyances are also planned to be constructed as part of the mining operations. These conveyances included diversion canals for the accumulation and re-routing of snowmelt water in the spring and surface run-off.

Surface drainage and seepage collection ditches were simulated in the model using stream cells. Seepage coming from the Class A and B storage does not interact with groundwater since it is collected and routed for water-quality treatment as necessary prior to being discharged to Geona Creek. Snowmelt diversion ditches are also incorporated into the groundwater model using stream cells. Estimates for surface run-off were developed based on the calibrated method of explicitly introducing an area-weighted 350 mm/yr of run-off to each diversion ditch.

Lined waste rock storage facilities were simulated by the removal of applied recharge within the model cells of the footprint of each facility.

4.1.2 Mine Plan Schedule of Excavation Development

The mine pit configuration was planned as a series of yearly build-out phases (Figure 4.1.2). Initially the pit is limited to the area around the ABM zone, but expands to include the Krakatoa zone in the fourth year. During year three, underground workings are initiated in the form of a set of access tunnels which spiral downward to permit the stope-mining of the deeper mineral deposits beneath the planned pit. No detail on the underground workings other than the final anticipated extent and geometry was provided for dewatering rate approximations at the time of model construction. Implementation of the underground workings was assumed to occur at a rate of 20 m per year, reaching the maximum extent and depth by year nine. Based on the model construction, the pit is present in Model Layers 1 through 5, and the underground workings in Model Layers 5 and 6. If mining progresses at rates different than the assumed 20 m per year, the effect will be proportional to the depth and extent of the workings. Deeper mine workings will present exposure to groundwater under higher pressure which will likely result in higher rates of flow. More extensive workings than planned will expose more rock surface area into which seepage can occur. Due to the relatively low hydraulic conductivity of the bedrock, the differences in simulated seepage into the workings is not likely to be significantly different than simulated, but may change the timing of when dewatering sumps and pumps need to be installed.

Prior to mining, a 6-month period of initial dewatering is planned. Once the overburden has been desaturated, the overburden will be removed to permit access to the bedrock deposits. As part of dewatering simulations, minor surface water re-routing is performed. Fault Creek is diverted from where it currently serves as the headwaters for Geona Creek, and is instead routed into the catchment immediately south of Geona Creek. Similarly a smaller stream that merges with Fault Creek to form upper Geona Creek is also diverted to the south. Drainage ditches and canals as discussed above are constructed before start of mining. Most of these conveyance structures are above the water table and do not interact with the groundwater.

4.2 Model Implementation of Mining

Dewatering of the pit and underground workings were simulated using the Drain Package of MODFLOW-NWT. After establishing steady-state conditions based on the calibrated model parameterization, a single stress-period of 182.5 days was conducted to simulate an initial 6-month dewatering phase prior to the initiation of mine excavation. Nine transient stress periods of one year duration for each of the modeled nine years of mine life were then simulated sequentially. Drain elevations were assigned based on the pit shell surface and underground workings for each of the annual periods.

4.2.1 Overburden Dewatering

Prior to the initial mine development, overburden drainage will be conducted by excavating a trench to the top of the fractured/weathered bedrock approximately along the alignment of the former Geona Creek watercourse (Figure 4.2.1). Based on borings, the trench is expected to be approximately 15 to 20 m deep. The overburden deposits range in thickness and it is anticipated that the final location of the trench may be slightly different than the conceptual location shown on Figure 4.2.1. Simulations show that a trench excavated to the top of the weathered bedrock will permit efficient drainage of the overburden in the area of the proposed open pit. Excavation of the trench will begin near the northern-most extent of the ABM Zone in the form of a sump extending to bedrock and used to dewater the overburden. As water levels are reduced in the overburden by pumping from the sump, the trench will be further expanded to the south along the channel of Geona Creek until it reaches the southern extent of the proposed Krakatoa pit.

To more efficiently dewater the overburden between the footprint of the Year 1 pit and Geona Creek, two approximately 300 m long trenches will be excavated west from the central drainage trench. The establishment of the trench extending the entire length of the eventual pit will minimize the likelihood of the overburden re-saturating as drainage paths will be kept short. Permanent sumps will be established at the north and south ends of the trench to remove water on an ongoing basis.

4.2.2 Pit Bedrock Dewatering

Dewatering of the underlying weathered/fractured bedrock is anticipated to be a longer-term sustained process. Based on packer-testing data for the bedrock collected in 2016, the hydraulic conductivity for the bedrock may be high enough that a set of dewatering wells would be effective in controlling water flow into the pit area. Simulations of pit dewatering were performed assuming that collection and pumping of wall seepage would be the most effective way to control groundwater influx to the pit. These rates alternately represent a good approximation for the water which would need to be pumped from an estimated 15 dewatering wells which could be installed at approximately 500-metre spacing around the pit and screened from the top of the bedrock to an estimated depth of 200 metres below land surface. Preliminary simulations suggest that wells constructed in this manner and pumped at an estimated rate of 400-800 m^3/d each would likely dewater the bedrock around the pit. Pumping rates on the higher end of this range will initially be necessary, but as the thickness of saturated bedrock decreases the lower rates will likely be sufficient. The problem may be in selecting locations which intersect the zones of fractured bedrock through which water would flow to the pit. If the fractures are of sufficiently high angle, they may bypass a system of wells effectively enough to make the dewatering well strategy less efficient.

Without installation of dewatering wells the modified conceptual dewatering strategy for bedrock consists of a combination of fault-zone dewatering wells and a system of horizontal drains within the pit for dewatering and pit-wall depressurization. Dewatering wells are planned to intersect each of the three major fracture zones associated with the East Fault, the Northwest Fault and Fault Creek Lineation (Figure 4.2.1). Each of these wells will be drilled to a depth of 150-200 m. The current configuration of the groundwater model predicts that these wells should each be pumped at a rate of 3.1 to 10 L/s [50-150 USgpm] for the six months of initial dewatering. As each of these faults is anticipated to represent a significant contribution of water flow to the pit, an early strategy of dewatering from the lineations will likely result in less flow to the pit during later years. After the initial dewatering period, the rate at which each of these wells can be pumped decreases as the saturated thickness declines. Higher permeability, more connected, extensive fracture zones will likely produce water at the higher end of this pumping range.

The decision on selecting the strategy of a system of dewatering wells should be made after a careful evaluation of the available structural geology information from drill core and exposed bedrock outcrops around the perimeter of the pit to determine the orientation and extent of the faults that intersect the pit. The final design of the dewatering system including perimeter dewatering wells and in-pit dewatering infrastructure is usually completed at the detailed design phase of the mining project.

The in-pit dewatering strategy is essentially unchanged from that originally proposed by Golder (1996). Competent bedrock will drain naturally through the high and end walls of the open pit. Horizontal drain holes will be installed in areas of high pore pressure or structural instability. Competent, unfractured bedrock is not anticipated to generate significant rates of seepage due to its low permeability; however, it is anticipated that zones of fracturing are likely to be present and represent sources of higher rates of flow. Installation of horizontal drains in these zones will be used to dissipate the hydraulic head as necessary. Drainage from the walls and horizontal drains will be conveyed to sumps located on each of the bench levels and at the pit floor. Collected water will be pumped from the sumps to the surface where it can be routed to the water treatment or storage facilities.

While overburden dewatering will initially be performed for a six-month period to permit access to the bedrock, dewatering of the bedrock will be performed concurrently with mining as the pit is deepened. Bedrock dewatering in the form of groundwater pumping is seen as a contingency, necessary only if flow through fractures turns out to be higher in some areas than expected. During this time if excess water proves to be generated by the overburden beyond what is envisioned by simulation, this water will be managed along with the water produced by bedrock dewatering, provided the water treatment doesn’t pose a conflict to this goal.

4.2.3 Underground Workings Dewatering

Similarly to the strategy for in-pit dewatering, the dewatering strategy for the underground workings involves the collection of seepage water augmented by horizontal drains as needed to reduce bedrock saturation near the tunnel face in the event of elevated flow rates or structural instability. Drainage from the walls and horizontal drains will be conducted to a series of sumps to be located at the deepest level of the workings. Collected water will be pumped from the sump to the surface where it can be routed to the water treatment or storage facilities.

4.3 Dewatering Rates

A post-processing package (Zonebudget) was used to extract the groundwater flux data from the model simulation by zone for subsequent evaluation (Harbaugh, 2008). Zones were created to reflect the parts of the pit and workings that intersected the overburden, the weathered bedrock, the unweathered bedrock, and the fault zones within the mine area. The simulated drainage results, for Week 2, Month 12, and average annual conditions in units of m^3/d are presented in Table 4.3.1.

Table 4.3.1: Dewatering Flux Rates (m^3/d) [USgpm]

	Annual Mean	Week 2	Final Month
Pre-Mining	7,642 [1,402] (6-month mean)	13,955 [2,560]	4,161 [763]
Year 1	3,617 [664]	4,116 [755]	3,320 [609]
Year 2	3,504 [643]	3,794 [696]	3,386 [621]
Year 3	4,596 [843]	5,890 [1,081]	4,198 [770]
Year 4	4,458 [818]	4,740 [869]	4,315 [792]
Year 5	4,503 [826]	4,659 [855]	4,429 [812]
Year 6	5,445 [999]	6,308 [1,157]	5,190 [952]
Year 7	5,381 [987]	5,652 [1,037]	5,281 [969]
Year 8	6,230 [1,143]	7,012 [1,286]	5,998 [1,100]
Year 9	6,047 [1,109]	6,205 [1,138]	5,982 [1,097]

Simulated flow rates for the first week following the start of simulation for a new pit shell are hugely elevated because a significant fraction of the water within the full extent of the Year 1 pit shell comes directly out of storage instantaneously in the model. In reality, the time required to drain and excavate would be such that this rate of discharge will never occur. In the interest of presenting a more realistic evaluation of the scope of the initial required dewatering rates, the simulated results for the second week are therefore presented instead.

To evaluate the causes and sources of the fluxes in Table 4.3.1, a zone-based evaluation of the distribution of simulated drain flux was conducted (Table 4.3.2). Zonebudget additionally provides the ability to determine how much storage change during a stress period results from a change in pit configuration. This change in storage was reported as a fraction of total drain flux by year, and represents the dewatering of pore space in the overburden or bedrock. The fluxes reported by zones represent the simulated flow of water into the drain cell through the particular zone. During the pre-mining dewatering period, approximately 78% of the water comes directly from the overburden and drainage of storage from the overburden. The remainder occurs within Model Layers 3 and 4 (weathered bedrock) of the pit. In mining years 5 through 9, discharge from the overburden is reduced to less than 6% of the total (i.e. dewatered), even though in reality seasonal water contributions from snowmelt are likely to temporarily add to overburden flux rates. Instead of the overburden, the source of the water is primarily from flow through the bedrock and associated fault zones in years 5 through 9.

Table 4.3.2: Annual Dewatering Rates by Zone (m^3/d) [USgpm]

	Storage	Overburden	Pit Fault Zone	Pit Bedrock	Workings Fault Zone	Workings Bedrock
Pre-mining	78.2%	7,078 [1298]	0 [0]	564 [103]	0 [0]	0 [0]
Year 1	18.1%	3,013 [553]	0 [0]	604 [111]	0 [0]	0 [0]
Year 2	7.6%	2,487 [456]	200 [37]	817 [150]	0 [0]	0 [0]
Year 3	16.4%	839 [154]	436 [80]	818 [150]	0 [0]	2,503 [459]
Year 4	4.8%	543 [100]	744 [136]	794 [146]	0 [0]	2,376 [436]
Year 5	2.8%	562 [103]	518 [95]	758 [139]	0 [0]	2,664 [489]
Year 6	5.8%	465 [85]	474 [87]	683 [125]	1,424 [261]	2,399 [440]
Year 7	2.1%	414 [76]	635 [116]	707 [130]	1,203 [221]	2,422 [444]
Year 8	3.5%	325 [60]	541 [99]	664 [122]	2,599 [477]	2,100 [385]
Year 9	0.8%	292 [54]	510 [94]	627 [115]	2,809 [515]	1,808 [332]

Flow entering the underground workings is simulated to be between 2,370 and 4,700 m^3/d [430 and 865 USgpm]. During years 3 to 5, all flow entering the underground workings occurs through deep bedrock at rates of less than 2,670 m^3/d [489 USgpm]. From mine years 6 through 9, workings intercept the fault zones and seepage into the underground workings occurs increasingly through these zones. However, flux through the faults is subject to a fair degree of uncertainty, mostly related to their spatial extent. The farther a connected fault extends, the more area it may be connected to and potentially connect to the pit or underground workings during dewatering. Although the hydraulic properties of the faults have been evaluated using packer testing in the upper 200 m of bedrock, it is not uncommon for fractures to reduce in size with increased lithostatic pressure at depth. When this happens, the hydraulic conductivity of the faults may decrease. If this is the case, then less flow through the fault zones may occur particularly as the underground workings reach their maximum depths in mining years 8 and 9.

4.4 Mining Drawdown and Area of Hydrological Impact

Development and operation of the mine and its associated structures have a hydrological impact on the immediate and surrounding environment. Water removal processes associated with pit dewatering result in the formation of a cone-of-depression in which the rock is depressurized. In this zone, the water table is lowered which induces increased rates of infiltration of surface water from streams and precipitation. During the mining itself, the water which is removed as part of the dewatering process will be pumped to the water management ponds, treated as appropriate and eventually discharged to Geona Creek or Finlayson Creek. In the immediate vicinity of the pit, groundwater flow converges at the pit. At a certain distance from the mine, which is variable depending on the underlying rock and the presence of streams and lakes, the groundwater flow ceases to be in the direction of the pit and begins to flow in a manner consistent with pre-mining conditions. The travel paths for water and any aqueous chemistry associated with mining features can be evaluated by tracking the fate of particles released at various locations around the mine and its related features.

The impact of dewatering operations in the vicinity of the pit and underground workings causes the development of a cone-of-depression around these features. Figure 4.4.1 shows the extent of drawdown in Model Layer 6, which is representative of the unweathered bedrock at the depth of the underground workings. This Model Layer was selected for depicting the representative extent of drawdown in the low-permeability competent bedrock unit layers.

The calibrated groundwater model was used in conjunction with the USGS modeling package MODPATH to simulate particle pathlines in an upstream direction from the pit to determine the approximate radius of groundwater capture of the pit during the nine years of mining. Figure 4.4.2 shows the pathlines traveled by each of the particles. Particles originating along Fault Creek travel the farthest to reach the pit, as they are conducted via the higher permeability fractured rock within the zone. Particles in the bedrock and overburden generally travel radially toward the pit, although within the unweathered bedrock the distances traveled are very short since the hydraulic conductivity of the bedrock is low. Travel distances associated with the overburden are typically limited to its spatial extent and represent evidence of complete dewatering of the overburden within the width of the valley. Parallel to the Geona Creek drainage, particles flow toward the pit in the overburden from a distance of 300 m. As the overburden thins to the east and becomes unsaturated, very little flow contribution to the pit comes from this direction.

4.5 Simulation of Post-Mining Reclamation

Following mining year 9, excavation of the ABM pit and underground workings is anticipated to be complete. Following mining year 9, the entrance to the underground workings will be closed to prevent flow from occurring between the pit and the abandoned underground workings. The pre-mining diversion of Fault Creek will then be removed, allowing this creek to flow directly into the pit, accelerating the rate of filling the pit void. Filling of the pit is therefore simulated by removal of drain structures from the pit and underground workings areas, and replacement with lake cells in the model, allowing water levels to return to a final post-mining configuration. Upon filling to capacity (elevation of 1,380 m asl) the pit will spill directly into Geona Creek.

A simulation of the pit filling and the formation of a pit lake (referred to as ABM Lake) through the combination of precipitation, evaporation, surface-water flow and groundwater seepage through the walls of the pit was performed using the calibrated groundwater model. Following the establishment of the pit and its associated dewatering cone-of-depression, the underground working features were removed and the pit allowed to form ABM Lake. Table 4.5 shows the progression over time of pit infilling from each of the various sources and the resulting lake stage and volume at the time. Precipitation additions are based on the total areal extent of the pit (831,343 m^2) and assume 100% of the precipitation contributes to the pit lake volume, and that evaporation increases over time as a function of the lake surface area.

During ABM Lake formation, a significant portion of the water entering the lake comes from the redirected Fault Creek. Based on the stream-gauging data set for Fault Creek, and information from Access Consulting, the average flow in Fault Creek was assigned to be 3,225 m^3/d. An additional small flux of water was assumed to enter the pit in association with the small portion of Geona Creek located south of the pit into which precipitation discharges. This flux was estimated based on the drainage area to the east to be an additional 559 m^3/d. As water levels rise in the pit, the hydraulic gradient between the rock and the lake decreases and the rate of groundwater flux into the pit also decreases. As a function of the pit depth, the lake is 50% full (> 1,306 m) after approximately 3.5 years, and 75% full (>1,348 m) after 9 years. During the last 2-3 years of pit filling, the overburden has begun to saturate and discharge from the lake to the groundwater increases, while the rate of groundwater flow into the pit is reduced to less than half of its original rate at the end of mining.

The lake level reaches its spill elevation of 1,380 m at approximately 16 years of simulation and begins discharging to the Geona Creek drainage. From this time on, the lake acts as a flow-through cell for Geona Creek. Essentially all of the surface water entering ABM Lake spills into Geona Creek. The upward gradients associated with recharge in the higher-elevation areas particularly on the west side of the Geona Creek drainage result in simulated groundwater flux into the lake which travels upward, partially discharging to the higher-permeability overburden sands and gravels, and partially augmenting the streamflow into Geona Creek. At equilibrium after 50 years, the overall net water balance for the lake includes a simulated positive flow of groundwater into the lake of approximately

1,225 m³/d [225 USgpm], which when combined with precipitation and evaporation, results in a slightly higher rate of surface water flow into the Geona Creek drainage (5,564 m³/d) relative to the rate at which it enters the lake (3,732 m³/d).

Table 4.5: ABM Lake Formation and Water Budget (m³/d)

Years after Mine Closure	Precipitation (m³/d)	Evaporation (m³/d)	Streams		Groundwater		ABM Lake	ABM Lake	Pit
			Inflow (m³/d)	Outflow (m³/d)	Inflow (m³/d)	Outflow (m³/d)	Stage (m)	Volume (m³)	Lake Area (m²)
0	1,122	1	3,316	-	7,836	-	1,224	3,022	1,598
1	1,122	103	3,321	-	3,034	-	1,271	2,355,783	113,700
2	1,122	150	3,333	-	2,984	-	1,288	4,621,094	165,700
3	1,122	184	3,344	-	2,950	-	1,300	6,858,305	203,700
4	1,122	216	3,355	-	2,913	-	1,311	9,075,671	238,870
5	1,122	243	3,364	-	2,890	-	1,319	11,276,370	269,190
6	1,122	271	3,373	-	2,865	-	1,327	13,463,160	299,320
7	1,122	295	3,382	-	2,840	-	1,334	5,630,780	326,540
8	1,122	319	3,391	-	2,820	-	1,341	17,786,220	352,400
9	1,122	342	3,399	-	2,797	-	1,347	19,928,180	378,100
10	1,122	362	3,407	-	2,779	-	1,353	22,057,160	400,940
15	1,122	452	3,719	-	1,249	4	1,376	32,503,170	499,810
16	1,123	467	3,726	4,818	1,149	49	1,380	34,360,280	516,840
17	1,123	467	3,729	5,509	1,203	49	1,380	34,355,810	516,800
20	1,123	467	3,730	5,553	1,215	48	1,380	34,355,650	516,800
25	1,123	467	3,731	5,560	1,221	48	1,380	34,355,760	516,800
30	1,123	467	3,731	5,562	1,223	48	1,380	34,355,800	516,800
40	1,123	467	3,732	5,564	1,224	48	1,380	34,355,820	516,800
50	1,123	467	3,732	5,564	1,225	48	1,380	34,355,840	516,800

4.5.1 Groundwater Recovery

A water-level evaluation of the simulated area around the mine following the initial reclamation and pit flooding was conducted for each at 5 years and 30 years after the end of mining. Figure 4.5.1a shows the simulated water-level elevations in Model Layers 2 and 5 associated with the mining activities at 5-years post-mining. Shallow groundwater flow in the vicinity of the pit is convergent upon the pit and beneath Geona Creek water levels are slightly higher in the deeper bedrock (Model Layer 5) than in the shallow weathered bedrock (Model Layer 2).

Figure 4.5.1b shows the drawdown in Model Layer 5 associated with the mining activities at 5-years post-mining. At 5 years into post-closure, drawdown adjacent to the pit remains nearly 100 m below initial water levels. At this point during the filling of ABM Lake, the lake stage is at approximately 1,316 m elevation, which is slightly over half full, with approximately 64 metres to go until it has filled completely. After 5 years, water levels remain 50 m lower than pre-mining conditions on the western side of the pit and between 50 and 120 m lower on the east side. Within 1 km of the pit, the overburden water levels have rebounded to within a few metres of pre-mining conditions as the annual snowmelt saturates the alluvium quickly each year. The underlying drawdown within the low-permeability bedrock requires additional time to re-pressurize however, and will never reach the same hydraulic head as under pre-mining conditions because the pit lake will prevent hydraulic head from rising above 1,380 m.

Fluxes in Table 4.5 suggest that by 25 years post-mining, the hydrological system has reached conditions approaching a new steady-state equilibrium. Figure 4.5.1c shows the simulated water-level elevations associated with the mining activities at 30-years post-mining. The lake has now been full for approximately 14 years at an elevation of 1,380 m. Shallow groundwater flow in the vicinity of the pit is still generally convergent upon the pit, although the water levels are higher than they were at the 5-years post-mining timeframe, and north of the pit shallow groundwater flow is toward Geona Creek, rather than the pit. Beneath Geona Creek water levels are slightly higher in the deeper bedrock than in the shallow weathered bedrock.

Figure 4.5.1d shows the water-table drawdown associated with the mining activities at 30-years post-mining. Water levels are within 10 m of pre-mining conditions at the pit and approximately within 20 m in the low-permeability bedrock east of the pit. In the model, the simulated water table remains approximately 50 m lower than pre-mining conditions. While this seems counter-intuitive, the reason is that the pit lake represents a volume with uniform hydraulic heads from the surface to the bottom of the pit. During pre-mining conditions, hydraulic heads in Model Layer 5 were higher than those at the surface with associated upward flow gradients. Without the presence of the rock, the heads in the immediate vicinity of the pit are therefore lower than under pre-mining conditions. Although there remains a net upward flow gradient near the pit, the gradient is much lower. Flow into the pit continues to occur as deeper groundwater discharges into the pit, but due to the low hydraulic conductivity of the bedrock, this discharge rate is low.

4.5.2 Post-Mining Waste Rock Particle Tracking

Although the mine plan has been developed to minimize the likelihood of a release of mining-related compounds to the groundwater at the Site, part of the determination of the potential impact to the environment involves the evaluation of the simulated path a hypothetical solute might take if released at facilities around the Mine Site. Three different categories of waste rock facilities have been planned as part of the proposed mining operation. Class A and B storage facilities include rock and tailings expected to be potentially acid generating and will be constructed with a low permeability compacted till under-liner. Water collection ponds for the Class A and B storage facilities will have synthetic liners. Class C facilities and non-waste rock stockpiles for overburden and topsoil are not planned for lining, although surface-water interception trenches are planned for diversion of snowmelt and surface run-off around those facilities.

For the purposes of evaluating the potential impact to the environment, it was assumed that the liner could leak beneath each of the storage facilities. Water passing the liner would then shortly contact shallow groundwater beneath the facility and follow the groundwater flow direction until it left the groundwater. The rate of infiltration to groundwater was not evaluated, only the fate of the hypothetical particle released from the footprint of the storage facility.

To identify the path potentially followed by water or waste from the base of each of the facilities, MODPATH was again used to track a set of particles released within the footprint of each facility. Following the initiation of mining, particles were released from the centroids of the model cells which underlie each of the storage facilities, the overburden stockpile and the topsoil stockpiles. The particles were placed in the upper-most saturated Model Layer and allowed to travel with groundwater flow from the start of mining operation, and continuing for 50 years post-closure.

Figure 4.5.2 shows the paths followed by each of the released particles over the 59-year period of time. Each particle follows the flow of groundwater toward the Geona Creek drainage then either flows northward through the shallow alluvium, or discharges directly to Geona Creek. A group of particles originating at the Class C Storage Facility terminate in the pit. This is because for many years after the cessation of mining, the pit continues to fill in from the combined discharge of Fault Creek and groundwater influx. During this time the pit acts as a terminal sink into which nearby groundwater flows. After approximately 16 years the pit fills to its spill elevation at the base of the Geona Creek valley.

4.5.3 Post-Mining Pit-Water Particle Tracking

As noted in the previous section, the pit reaches its spill elevation of 1,380 m after 16 years and begins discharging to the Geona Creek drainage. From this time on, the pit ceases to be a terminal sink for water. Groundwater that discharges to the pit at depth moves upward and either discharges directly into Geona Creek, or due to the high permeability of the overburden sands and gravels, contributes to the shallow groundwater that saturates the overburden. As a result of this new configuration of pit flow, some water that originates in the ABM Lake leaves the pit as shallow groundwater and travels a certain distance through the overburden until it eventually discharges to Geona Creek. A particle tracking simulation was performed to evaluate where water originating at the pit would flow after the pit filled completely. Figure 4.5.3 shows the particle paths traveled as a result of this simulation. In general, particles that originate in the bedrock to the east or west of the pit flow into the pit.

Particles started in, or near the saturated overburden to the north flow away from the pit and parallel to Geona Creek. These particles represent the component of ABM Lake water which rises to saturate the overburden and exits the lake through shallow subsurface flow, rather than through stream flow, although the majority of the discharging lake water does exit as part of the stream flow. Groundwater particles may travel up to approximately 1 km before the upward groundwater gradients present throughout the valley result in the particle discharging into the re-aligned Geona Creek.

5.0 CONCLUSIONS

Based on the groundwater modeling results presented in this report, Tetra Tech EBA arrived at the following conclusions:

1. A drainage trench excavated within the surficial sands and gravels of the valley-fill overburden to the bedrock contact in an orientation parallel to the valley axis and pumped at a rate of 85 to 95 L/s [1,350 to 1,470 USgpm] for six months will be sufficient for the purposes of dewatering in anticipation of Year 1 mining.

2. With the exception of areas of faulting or fracturing, the bedrock appears to be of sufficiently low permeability to permit water seepage management to be conducted by collection of seepage face drainage and horizontal drains as necessary. Depending on the nature of the distribution of fracture sets or other prominent fault conduits intersecting the pit within the bedrock, it may be possible to implement a set of approximately 15 dewatering wells arrayed at 500-metre spacing around the perimeter of the pit. Assuming that groundwater flow occurs through a reasonably isotropic bedrock with interconnected fractures, these wells installed to a depth of 200 to 250 metres may be pumped at rates of 400-800 m^3/d and may be sufficient to dewater the bedrock around the pit to minimize seepage face flow.

3. Fault zones within the pit and underground workings may produce water at higher rates of discharge and require the installation of dewatering wells outside the pit and drilling of horizontal drains to stabilize hydraulic conditions locally. Given the nature of fractured bedrock being sometimes unpredictably connected, it is likely that the need for these wells will not become apparent until pit excavation has begun and the water-producing zones are identified.

4. Groundwater entering the pit primarily comes from recharge along the areas of higher elevation to the west recharging the overburden and shallow bedrock.

5. Although the simulated rates of drainage into the pit or dewatering trenches reflect averaged conditions, since much of the Geona Creek water is derived from snowmelt, the snowmelt period is likely to produce higher rates of infiltration and flow to the trench and pit. This variation is expected to occur seasonally every year, but was not incorporated into the groundwater model. As a result the degree of variation that may occur is uncertain. As a result the degree of variation that may occur is uncertain, but elevated groundwater rates are likely to occur seasonally. A perimeter interceptor channel excavated around the pit on the eastern and western sides to the top of bedrock would likely remove any snowmelt water before it could reach the pit.

6. Following completion of mining and sealing of the underground workings, the pit will begin to refill through the combination of redirected surface water flow from Fault Creek, and groundwater seepage as the drawdown associated with mining begins to subside and groundwater levels begin rising. The pit is expected to have filled to half of its original depth within 4 years, and to fill completely to the spill elevation of 1,380 m after approximately 16 years.

7. After the pit has filled, the pit is expected to act as a lake through which streamflow enters and leaves, and which is augmented by groundwater discharge of approximately 1,225 m^3/d.

8. Tracking of particles sourced at each of the storage facilities flow toward Geona Creek where they either immediately discharge to the stream, or travel through the overburden along the stream valley until they eventually discharge to the stream.

9. Tracking of particles originating at the ABM Lake flow north away from the pit following the upward hydraulic gradients in the bedrock and overburden until they discharge to Geona Creek within approximately 1 km north of the ABM Lake.

6.0 CLOSURE

We trust this report meets your present requirements. If you have any questions or comments, please contact the undersigned.

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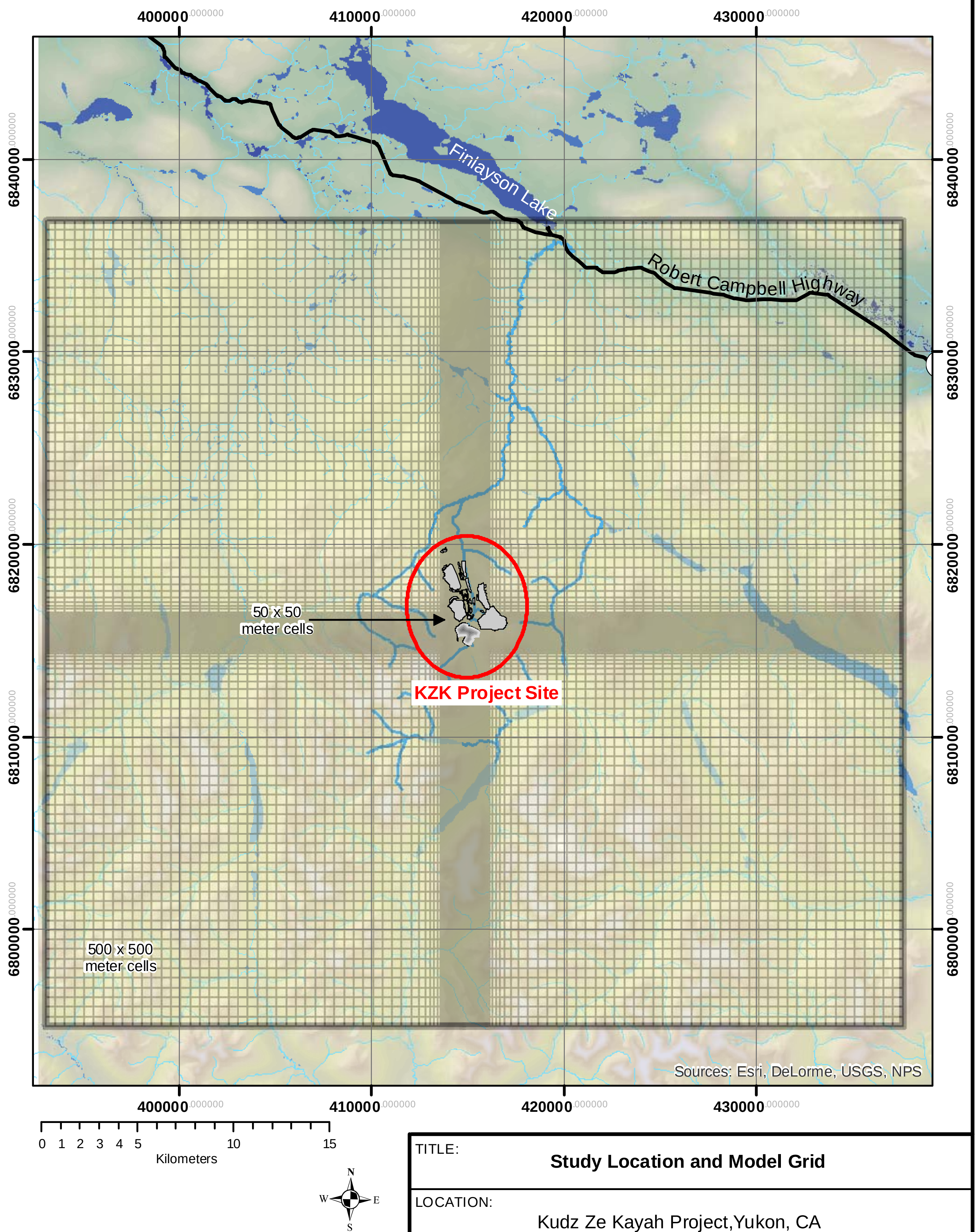
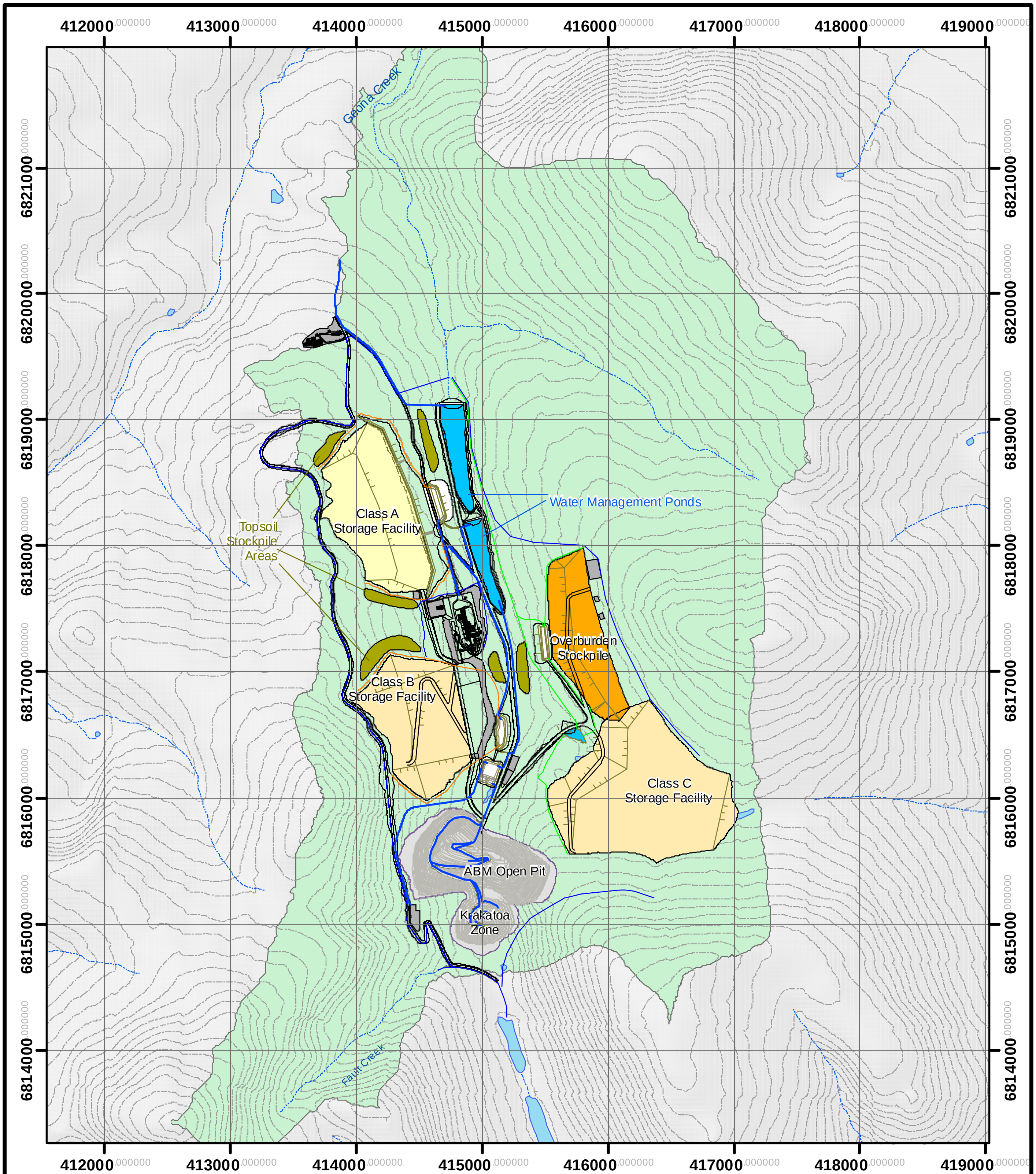


TITLE: **Study Location and Model Grid**

LOCATION: Kudz Ze Kayah Project,Yukon, CA

TETRA TECH

APPROVED	SK	FIGURE
DRAFTED	CKG	1.0
PROJECT#	GWTR03021	
DATE	09-28-16	



Legend

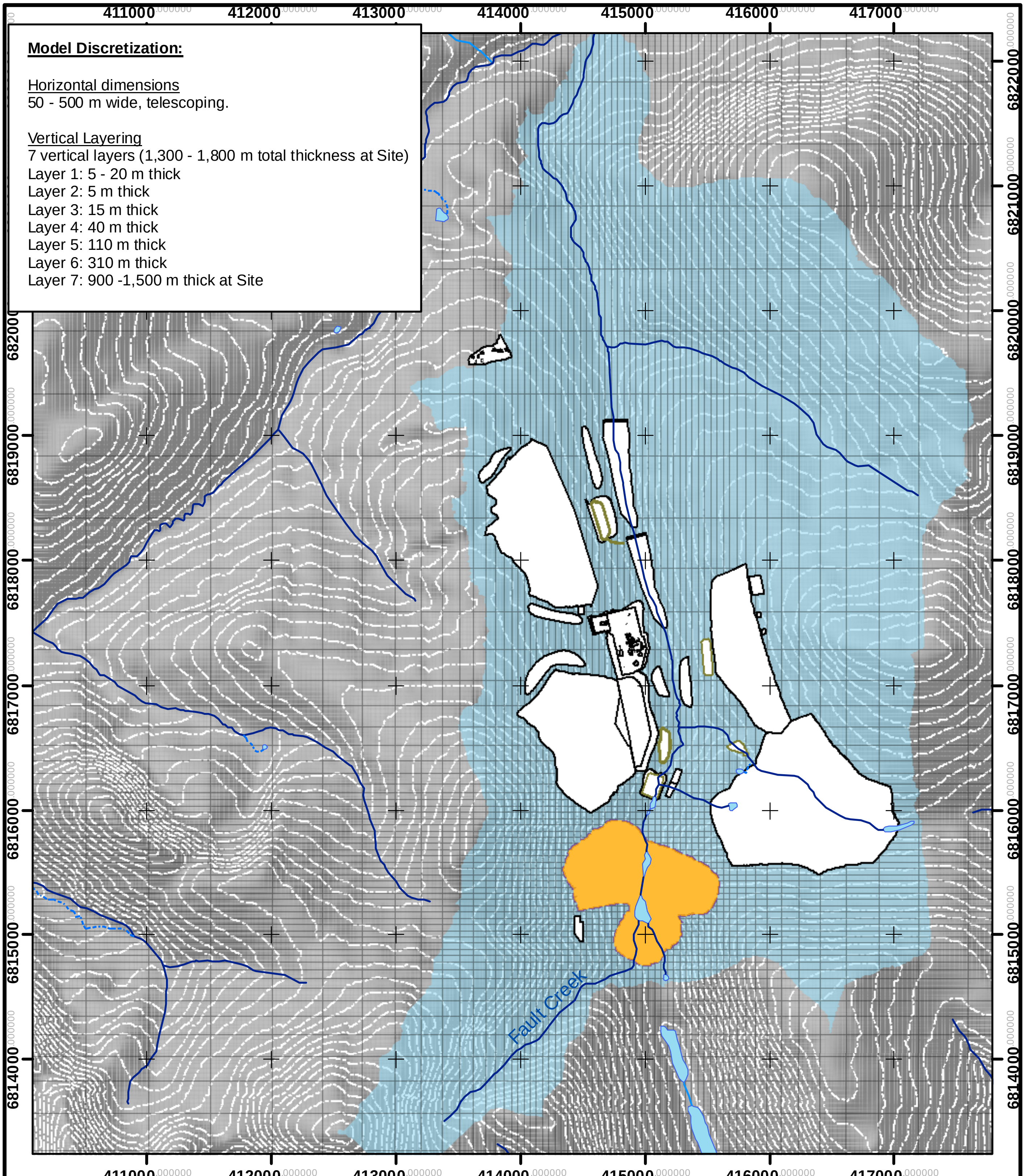
- Streams
- Geona Creek Watershed
- Haul Road
- Class A and B Storage Facility Interceptor Canal
- Storage Facility Drainage
- Surface Water Conveyance

TITLE:
Planned Mine Pit, Storage Facilities, and Structures

LOCATION:
Kudz Ze Kayah Project, Yukon, CA

TETRA TECH

APPROVED	CKG	FIGURE
DRAFTED	CKG	2.0
PROJECT#	GWTR03021	
DATE	05-12-2016	



0 0.5 1 2 3
Kilometers

N W E S

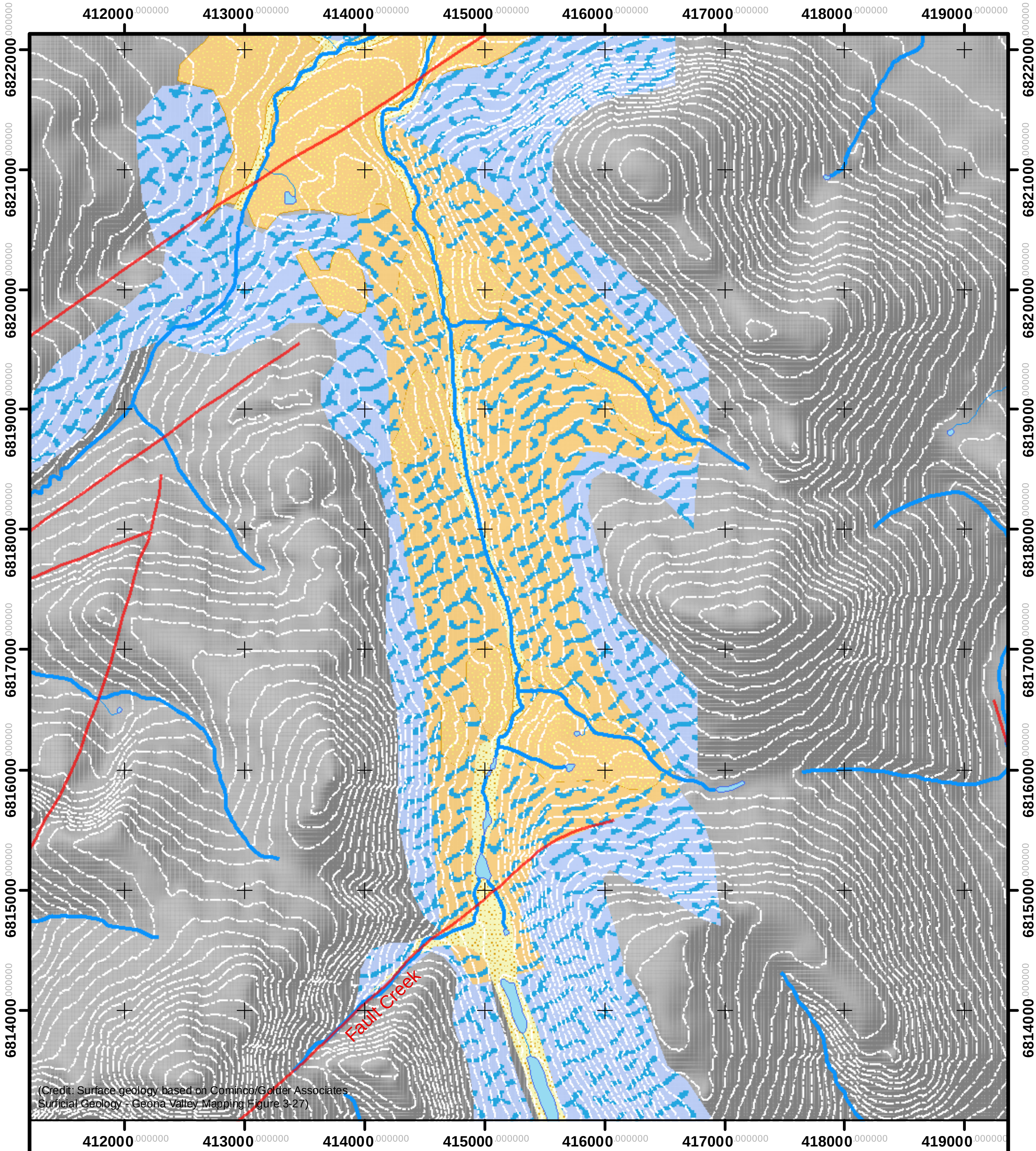
Legend

- Composite Pit
- Model Grid
- Geona Creek Catchment

TITLE:	**Preliminary Mine Plan and Local Model Grid**
LOCATION:	Kudz Ze Kayah Project,Yukon, CA

TETRA TECH

APPROVED	CKG	FIGURE
DRAFTED	CKG	2.2.1
PROJECT#	EBA-KZK	
DATE	10-25-16	



0 0.5 1 2 3
Kilometers

Legend

Overburden Geology

- Alluvium
- Glacio-fluvial Sediments
- Till Apron
- Till
- Faults

N W E S

TITLE:

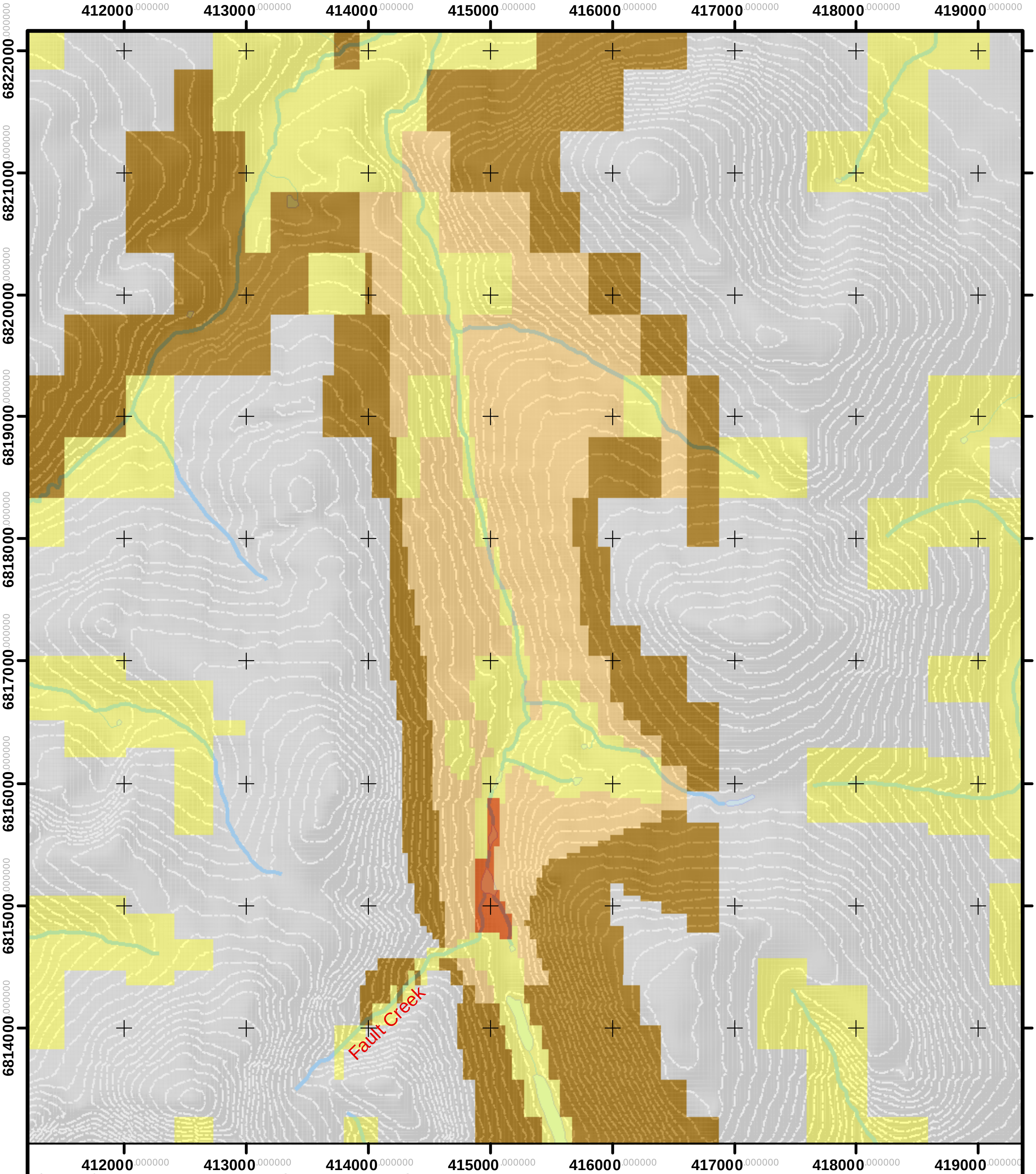
Mapped Surficial Geology

LOCATION:

Kudz Ze Kayah Project,Yukon, CA

TETRA TECH

APPROVED	CKG	FIGURE
DRAFTED	CKG	2.3.1a
PROJECT#	GWTR03021	
DATE	07-25-16	



TITLE:

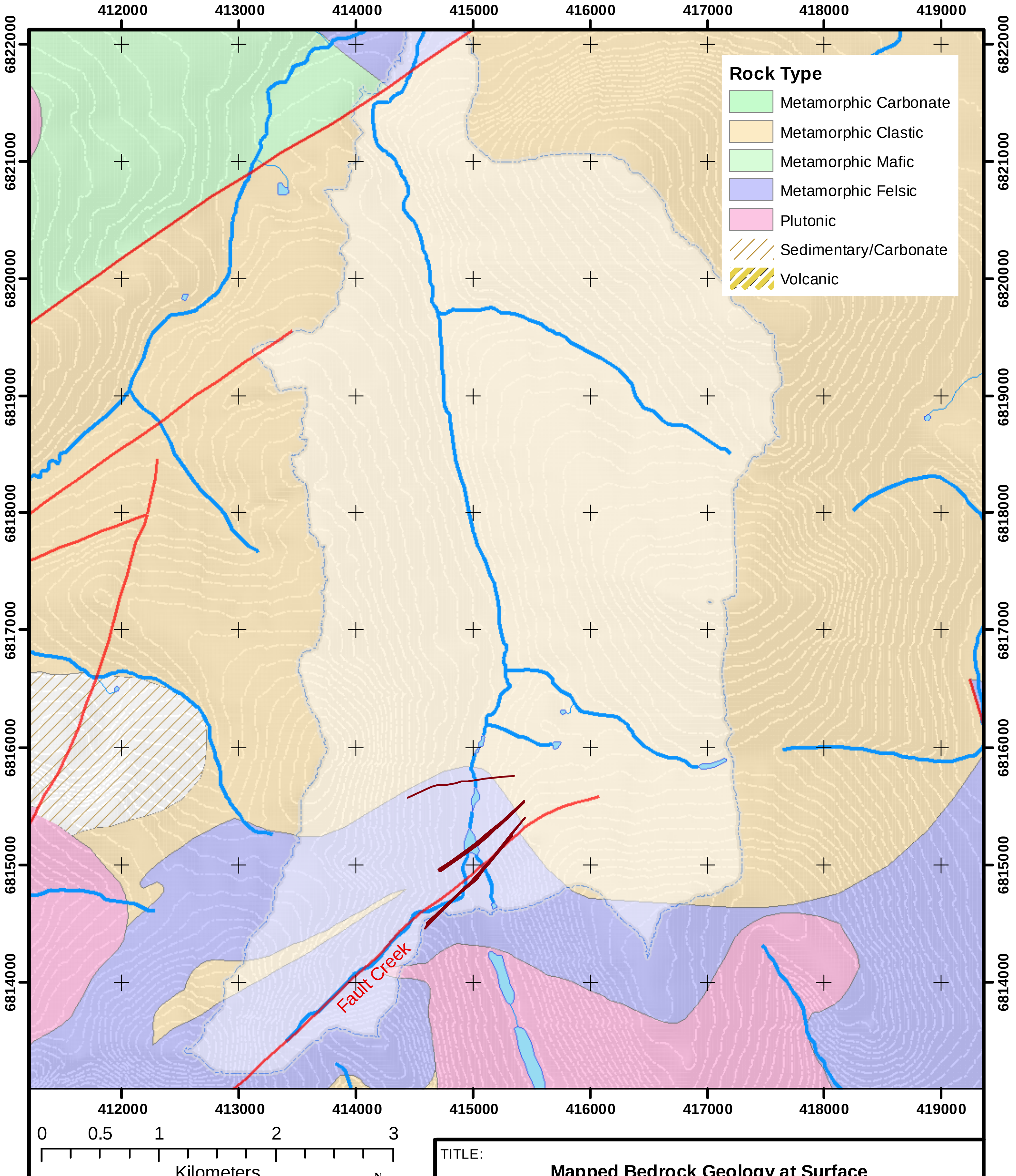
Overburden Hydraulic Conductivity Zonation

LOCATION:

Kudz Ze Kayah Project,Yukon, CA

TETRA TECH

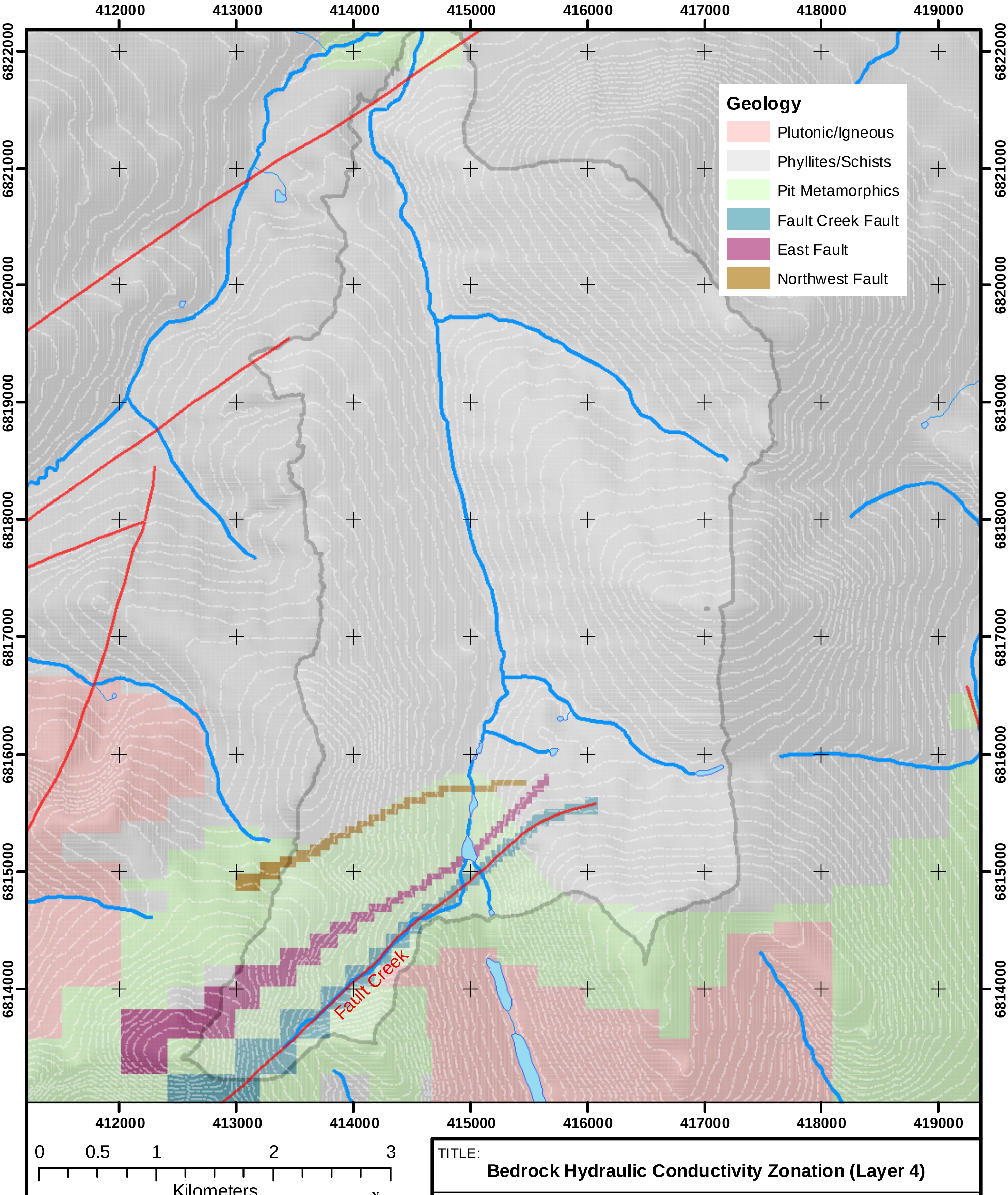
APPROVED	CKG	FIGURE
DRAFTED	CKG	2.3.1b
PROJECT#	EBA-KZK	
DATE	04-05-16	



Legend

- Mapped Faults near Pit (BMC)
- Faults
- Geona Creek Watershed

TITLE: **Mapped Bedrock Geology at Surface**			
LOCATION: Kudz Ze Kayah Project,Yukon, CA			
TETRA TECH	APPROVED	CKG	FIGURE
	DRAFTED	CKG	2.3.2a
	PROJECT#	GWTR03021	
	DATE	04-05-16	

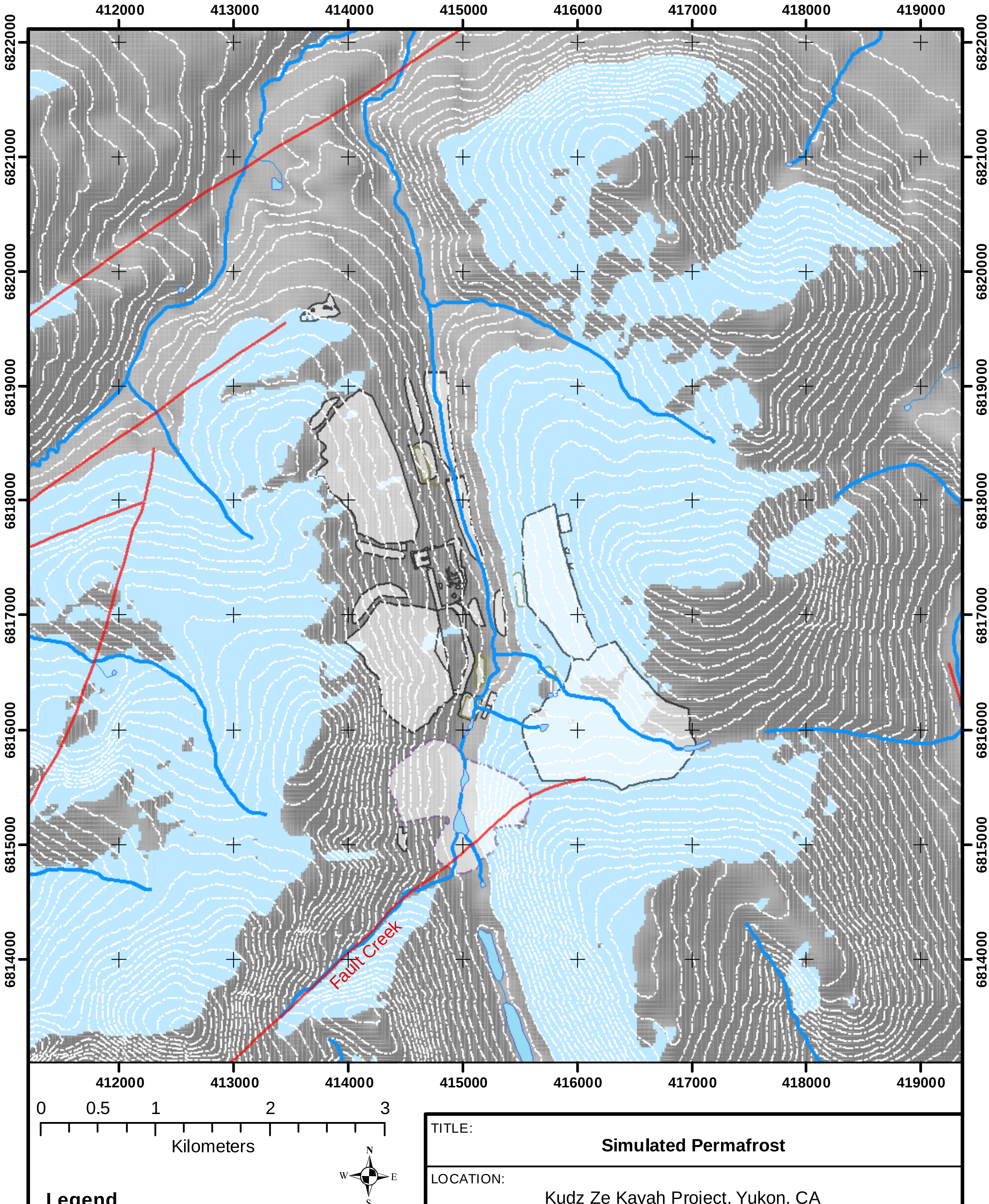


TITLE: **Bedrock Hydraulic Conductivity Zonation (Layer 4)**

LOCATION: Kudz Ze Kayah Project,Yukon, CA

TETRA TECH

APPROVED	CKG	FIGURE
DRAFTED	CKG	2.3.2b
PROJECT#	EBA-KZK	
DATE	04-05-16	



Legend

Faults

Permafrost
(>1,400 m elev., Northern and Western Exposures)

TITLE:

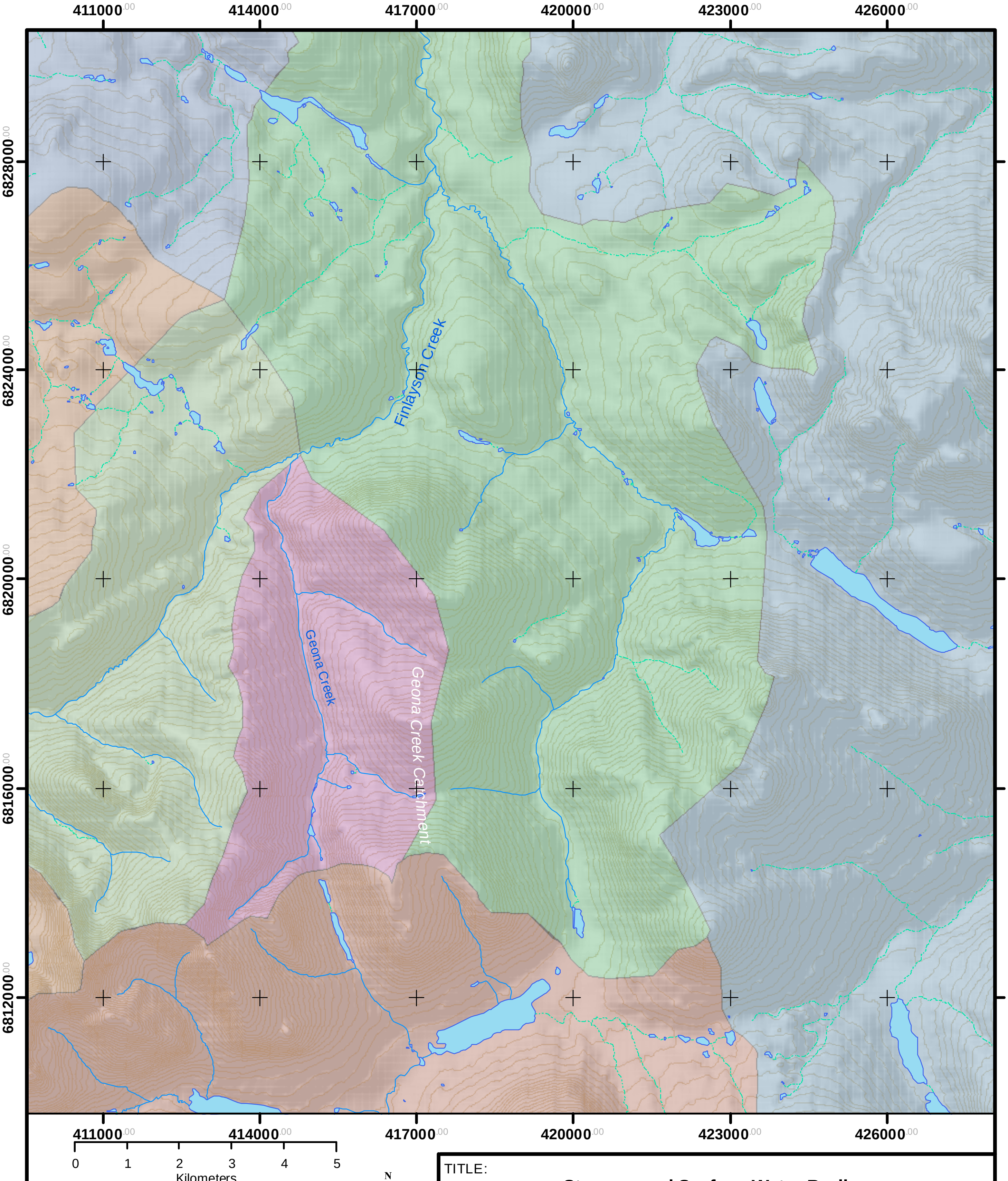
Simulated Permafrost

LOCATION:

Kudz Ze Kayah Project, Yukon, CA

TETRA TECH

APPROVED	CKG	FIGURE
DRAFTED	CKG	
PROJECT#	EBA-KZK	2.4.5
DATE	09-28-16	



Legend

Stream (Close proximity with simulated flow)

Stream (> 5 Km Distance)

Watershed Boundaries

TITLE:

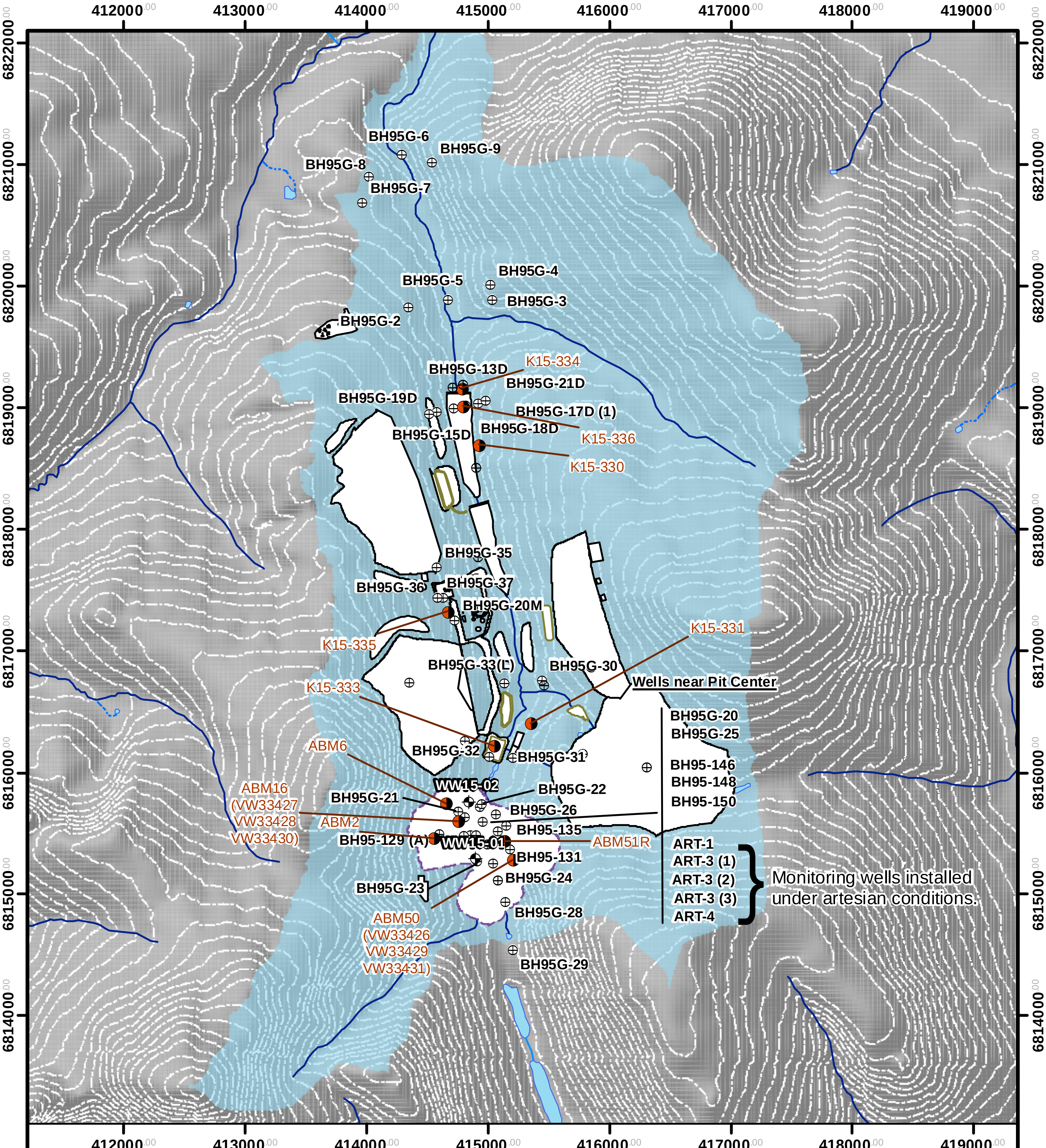
Streams and Surface Water Bodies

LOCATION:

Kudz Ze Kayah Project, Yukon, CA

TETRA TECH

APPROVED	CKG	FIGURE
DRAFTED	CKG	2.5
PROJECT#	GWTR03021	
DATE	04-05-16	



0 0.5 1 2 3

Kilometers

Legend

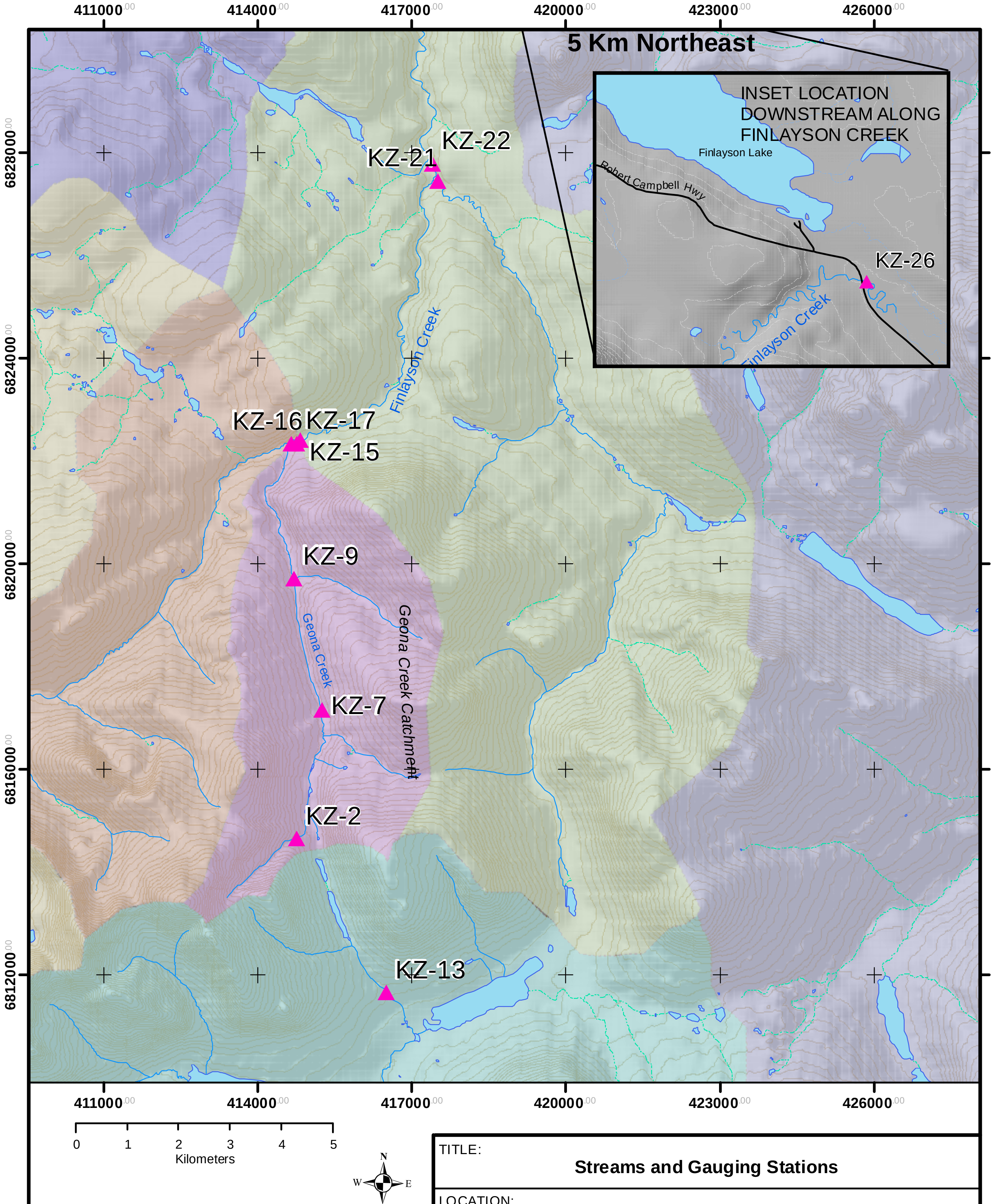
- Packer Test Locations (may have VWPs)
- Pumping Test Wells
- Monitoring Well
- Geona Creek Catchment

N W E S

TITLE:	**Well Locations**
LOCATION:	Kudz Ze Kayah Project, Yukon, CA

TETRA TECH

APPROVED	CKG	FIGURE
DRAFTED	CKG	2.6.3
PROJECT#	EBA-KZK	
DATE	09-28-16	



TITLE:

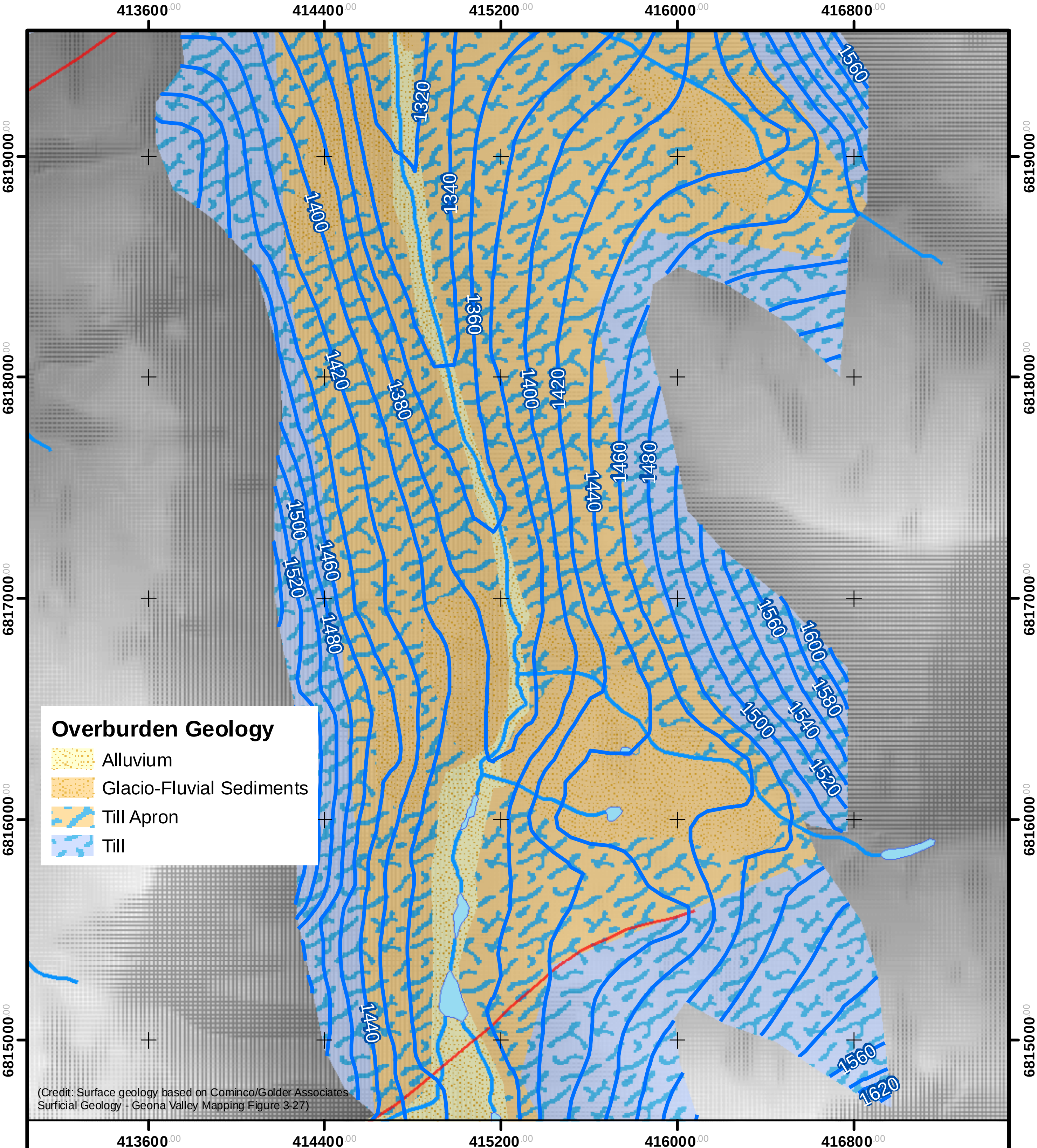
Streams and Gauging Stations

LOCATION:

Kudz Ze Kayah Project, Yukon, CA

TETRA TECH

APPROVED	CKG	FIGURE
DRAFTED	CKG	2.6.4
PROJECT#	GWTR03021	
DATE	04-05-16	



0 0.5 1

Kilometers

N W E S

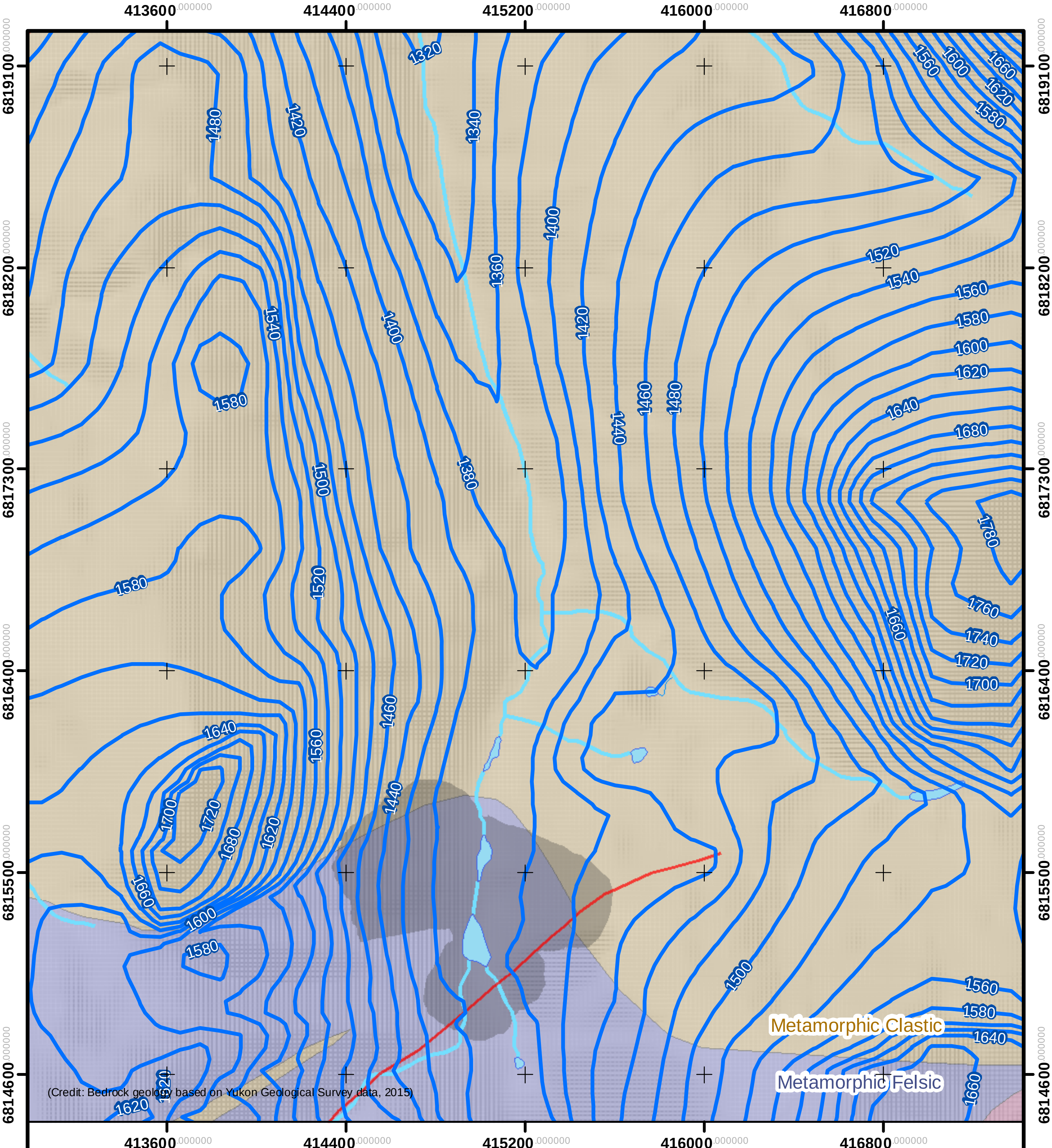
Legend

Pre-Pumping Water-Level Elevation

TITLE:	**Water-Table Elevation Contours in Overburden Footprint**
LOCATION:	Kudz Ze Kayah Project, Yukon, CA

TETRA TECH

APPROVED	CKG	FIGURE
DRAFTED	CKG	3.4.1a
PROJECT#	GWTR03021	
DATE	04-05-16	



0 0.5 1

Kilometers

Legend

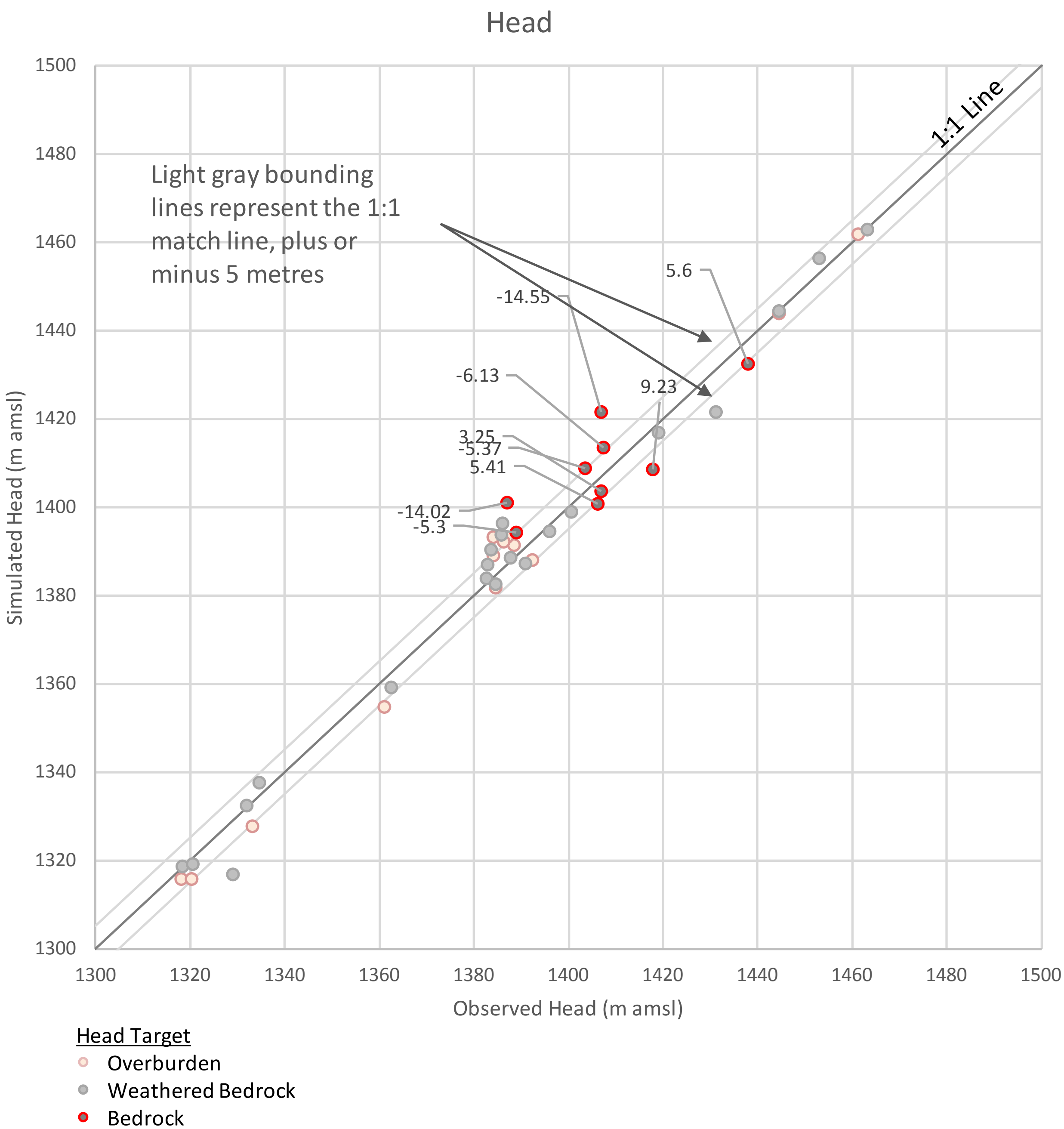
Pre-Pumping Water-Level Elevation

Composite Pit Footprint

N W E S

TITLE:	**Simulated Weathered Bedrock Water-Level Elevation Contours Model Layer 3**
LOCATION:	Kudz Ze Kayah Project, Yukon, CA

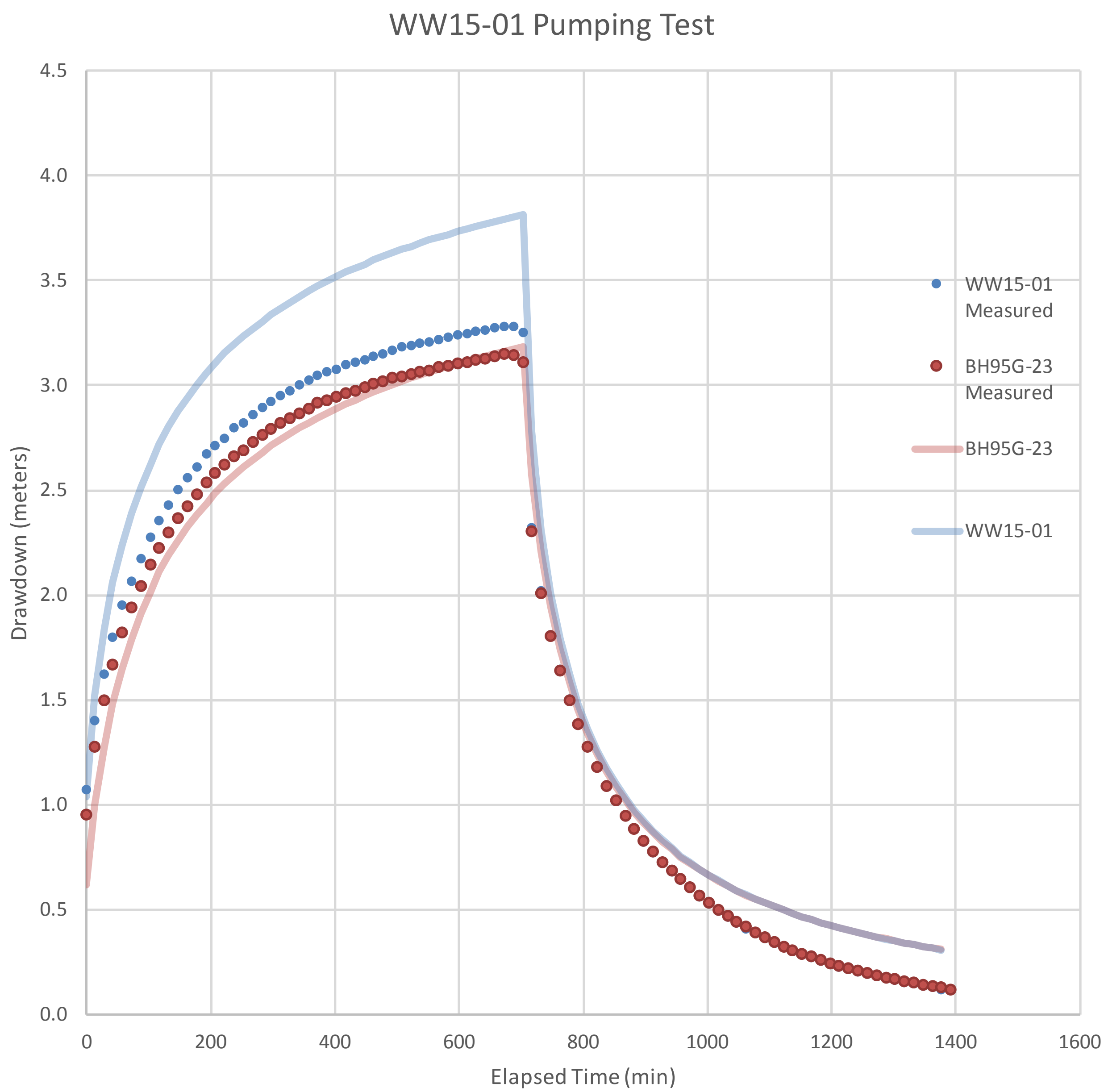
TETRA TECH			FIGURE
	APPROVED	CKG	3.4.1b
	DRAFTED	CKG	
	PROJECT#	EBA-KZK	
	DATE	04-05-16	



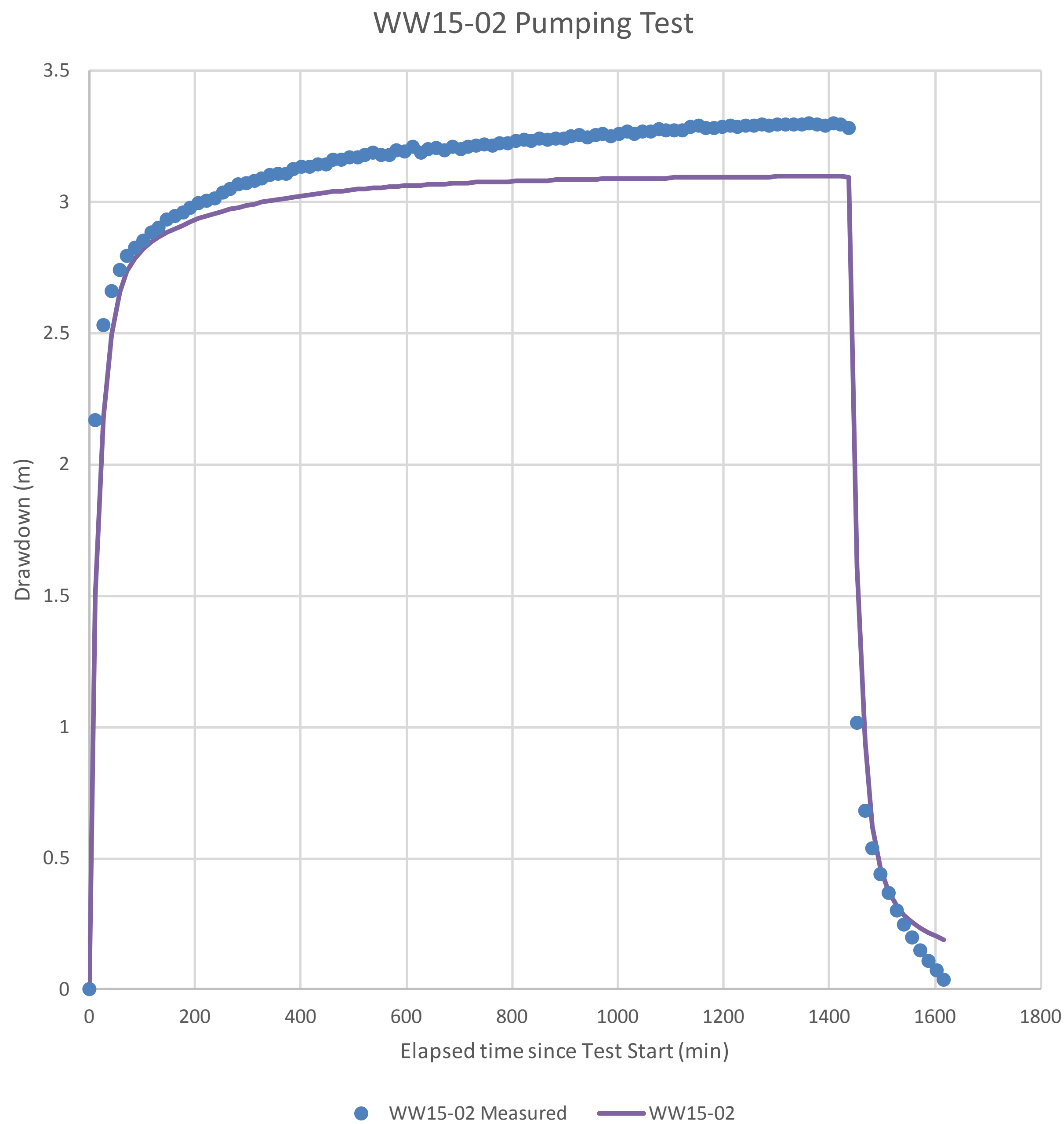
TITLE:	OBSERVED VS SIMULATED HEAD COMPARISON
LOCATION:	Kudz Ze Kayah Mine, Yukon, Canada

TETRA TECH

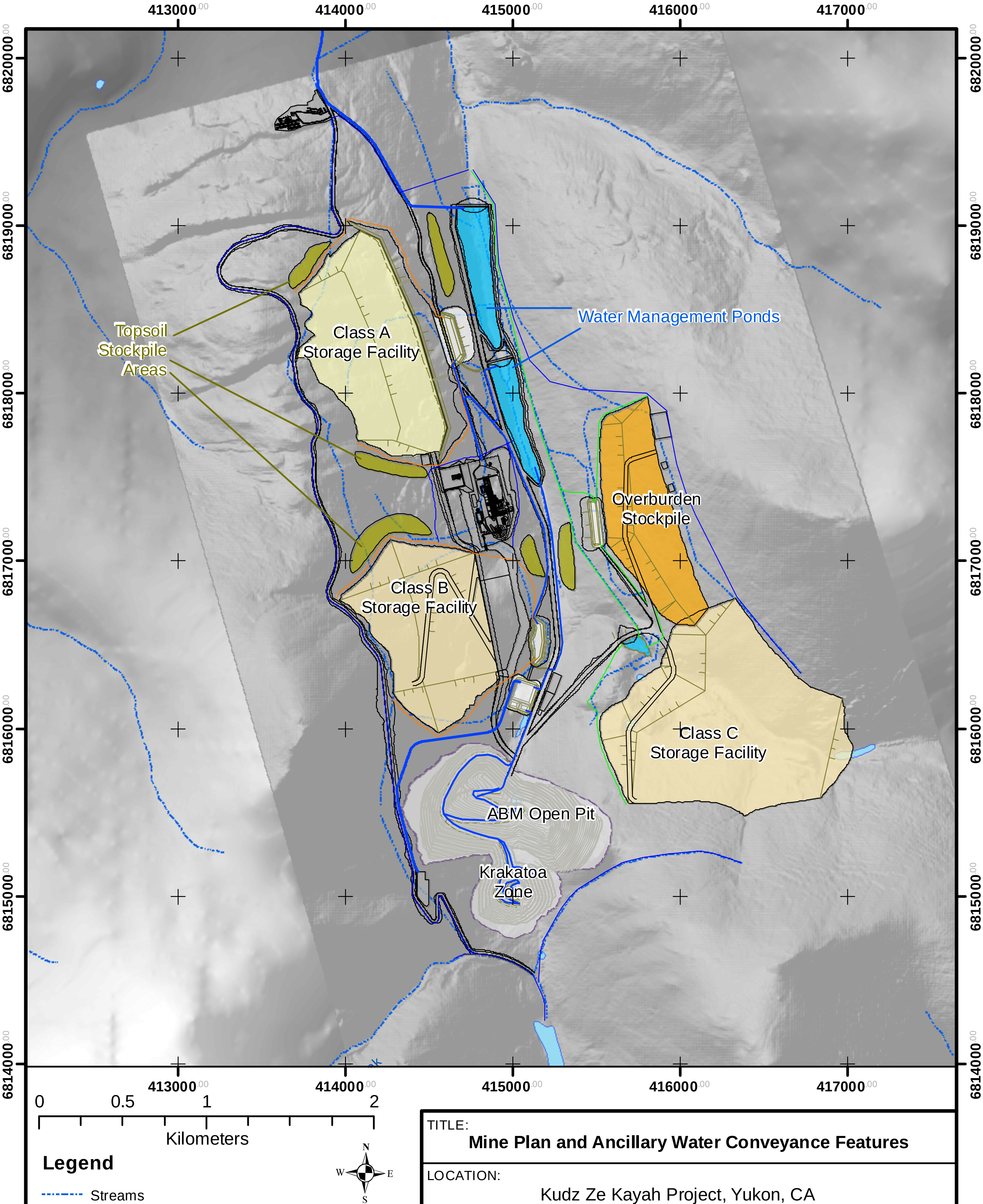
APPROVED	CG	FIGURE
DRAFTED	CG	3.4.2
PROJECT #	117-0513011	
DATE	11-03-2016	



TITLE:	WW15-01 AQUIFER TEST, SIMULATED VS OBSERVED DRAWDOWN		
LOCATION:	Kudz Ze Kayah Mine, Yukon, Canada		
TETRA TECH	APPROVED	CG	FIGURE
	DRAFTED	CG	3.4.3a
	PROJECT #	117-0513011	
	DATE	04-13-2016	



TITLE:	**WW15-02 AQUIFER TEST, SIMULATED VS OBSERVED DRAWDOWN**		
LOCATION:	**Kudz Ze Kayah Mine, Yukon, Canada**		
TETRA TECH	APPROVED	CG	FIGURE
	DRAFTED	CG	**3.4.3b**
	PROJECT #	117-0513011	
	DATE	04-13-2016	



TITLE:

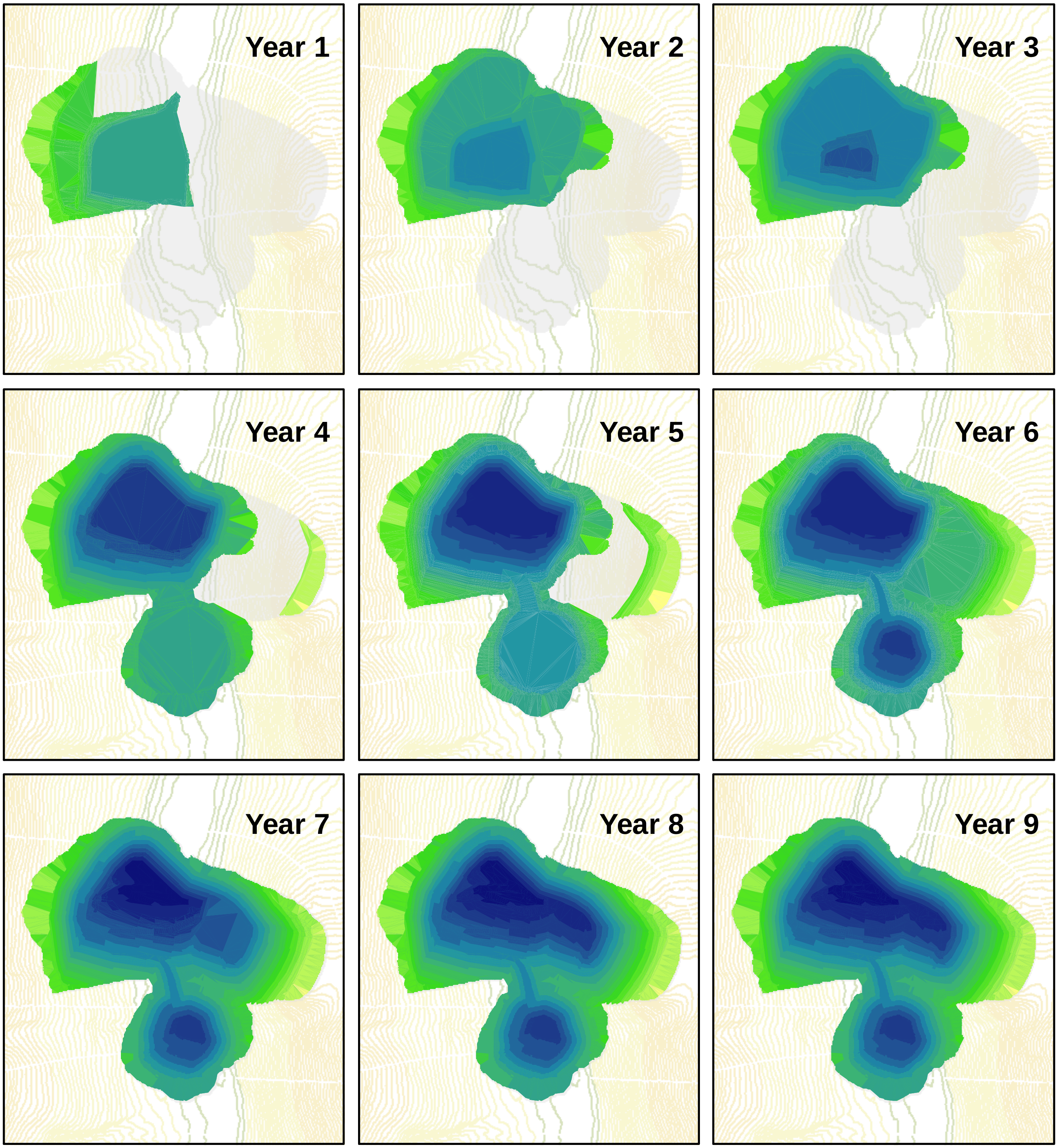
Mine Plan and Ancillary Water Conveyance Features

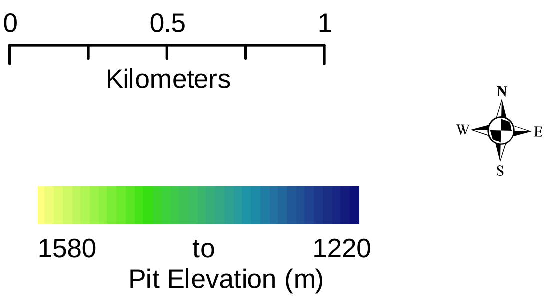
LOCATION:

Kudz Ze Kayah Project, Yukon, CA

TETRA TECH

APPROVED	CKG	FIGURE
DRAFTED	CKG	4.1.1
PROJECT#	GWTR03021	
DATE	10-25-2016	





TITLE:

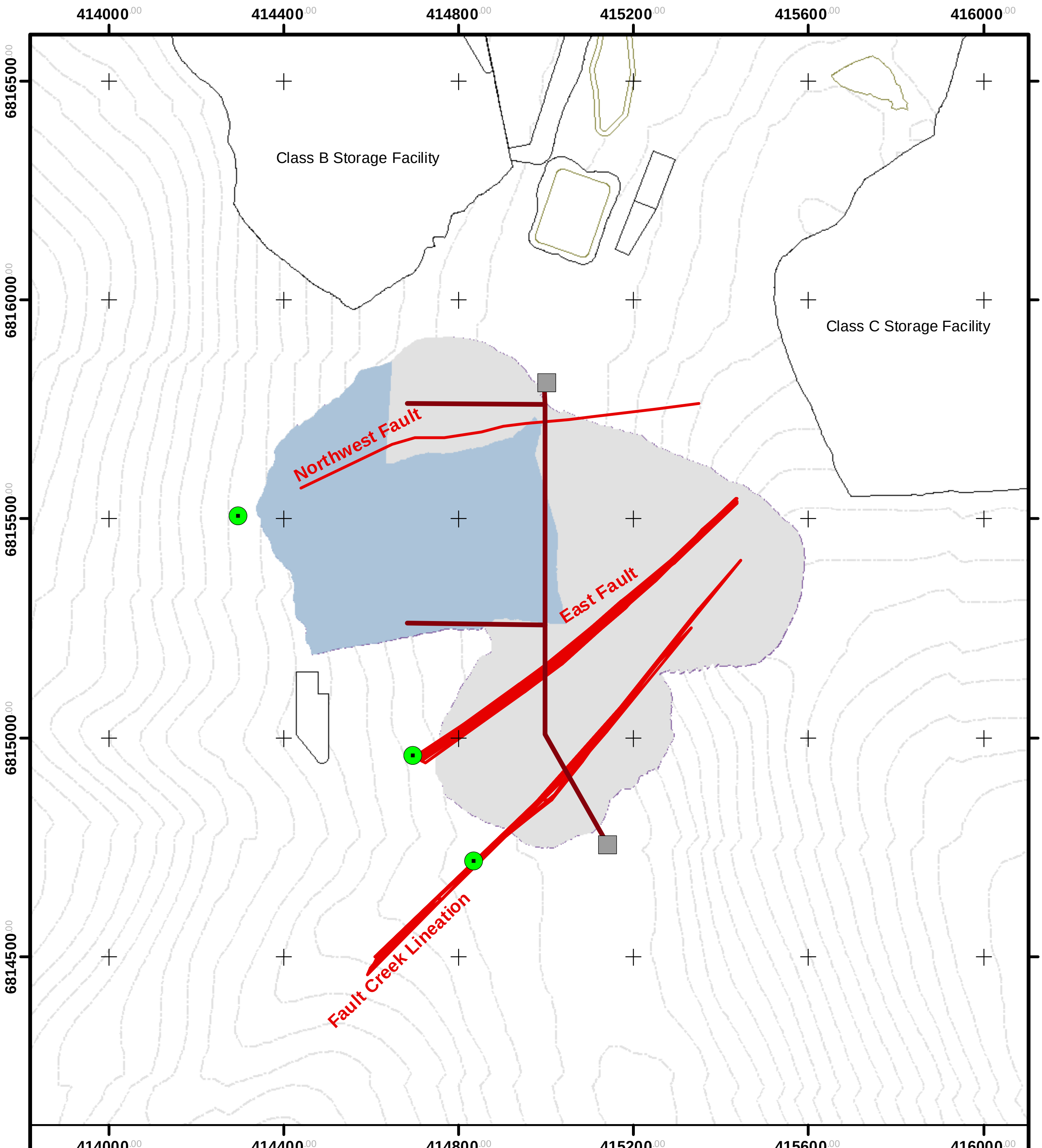
Pit Sequence

LOCATION:

Kudz Ze Kayah Project, Yukon, CA

TETRA TECH

APPROVED	CKG	FIGURE
DRAFTED	CKG	4.1.2
PROJECT#	EBA-KZK	
DATE	05-12-2016	



0 100 200 300 400 500
Meters

Legend

Fault Zone Dewatering Well (Approximate Location)

Dewatering Trench Sump

Dewatering Trench Lineation

Pit Footprint

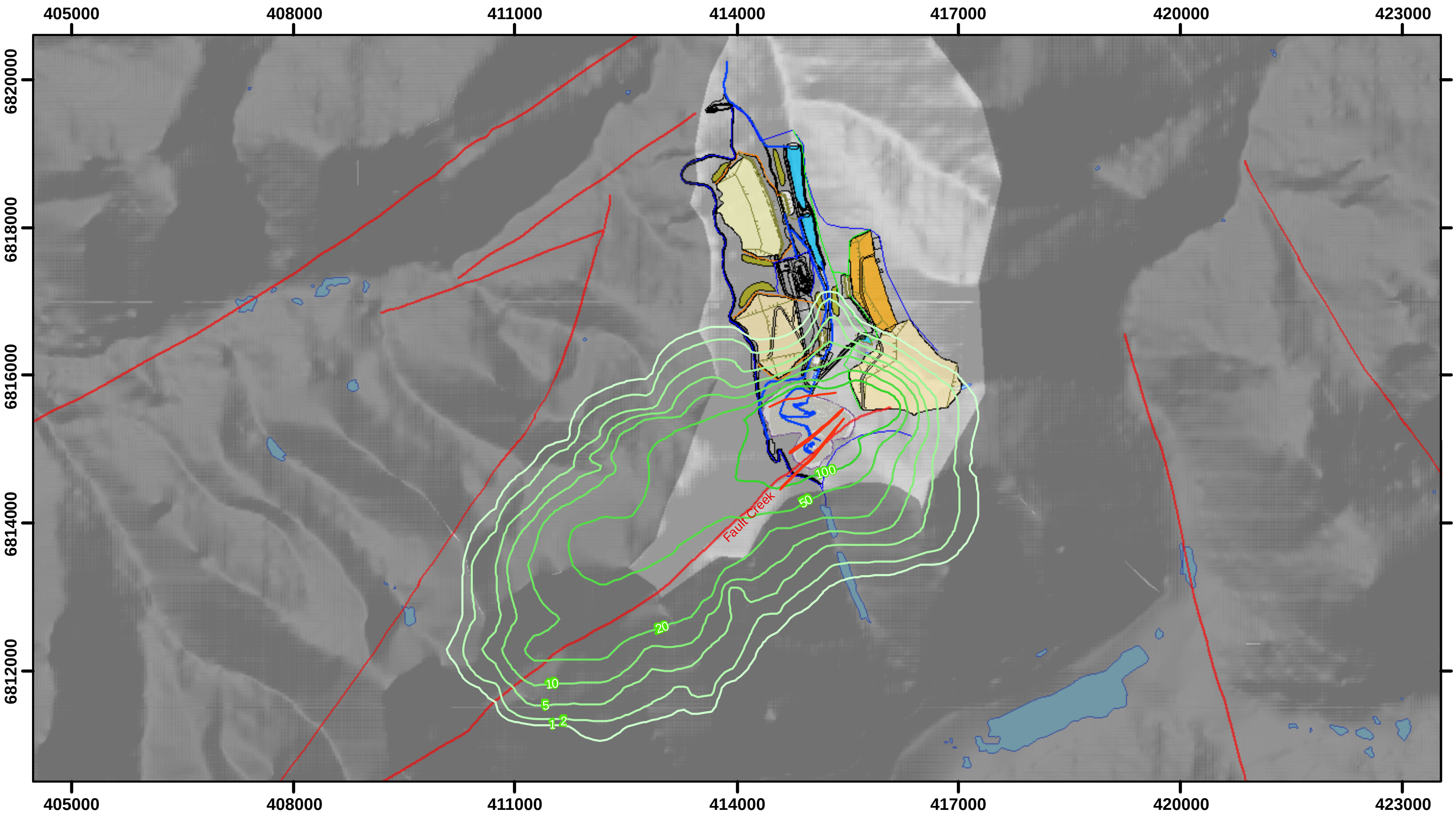
Year 1 Pit Extent

N W E S

TITLE:	**Dewatering Trench Location**
LOCATION:	Kudz Ze Kayah, Yukon, CA

TETRA TECH

APPROVED	CKG	FIGURE
DRAFTED	CKG	4.2.1
PROJECT#	EBA-KZK	
DATE	06-10-2016	



Model Layer 6: Bedrock (320 m depth, approx)

Legend

- Mapped Faults near Pit (BMC)

Drawdown Contours (m)

- 1
- 2
- 5
- 10
- 20
- 50
- 100
- 200

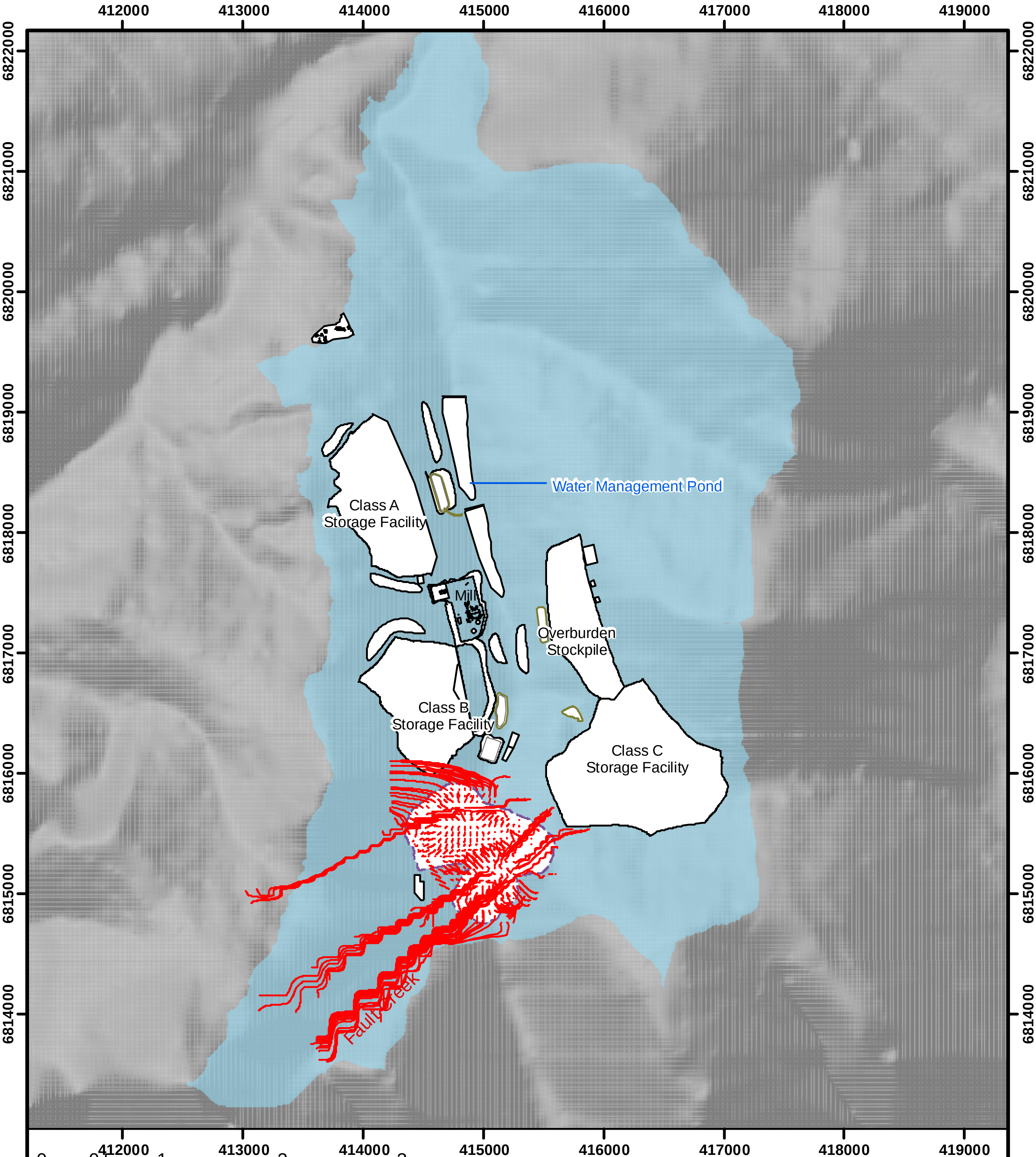
0 0.5 1 2 3 4 Kilometers

N W E S

TITLE:	**Mining Year 9 Drawdown Contours**
LOCATION:	Kudz Ze Kayah Project, Yukon, CA

TETRA TECH

APPROVED	GJCR	FIGURE
DRAFTED	CKG	4.4.1
PROJECT#	WTR.GWTR03021-01	
DATE	11-03-16	



0 0.5 1 2 3
Kilometers

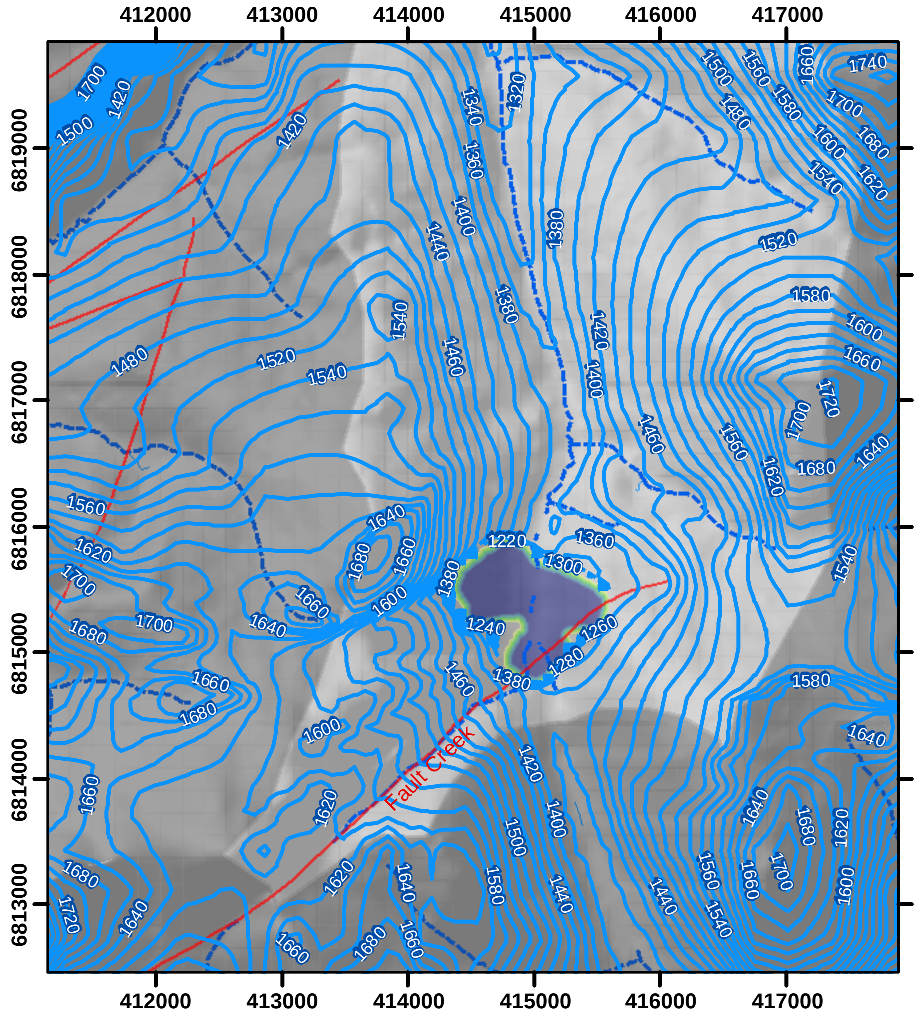
Legend

Influent Particles

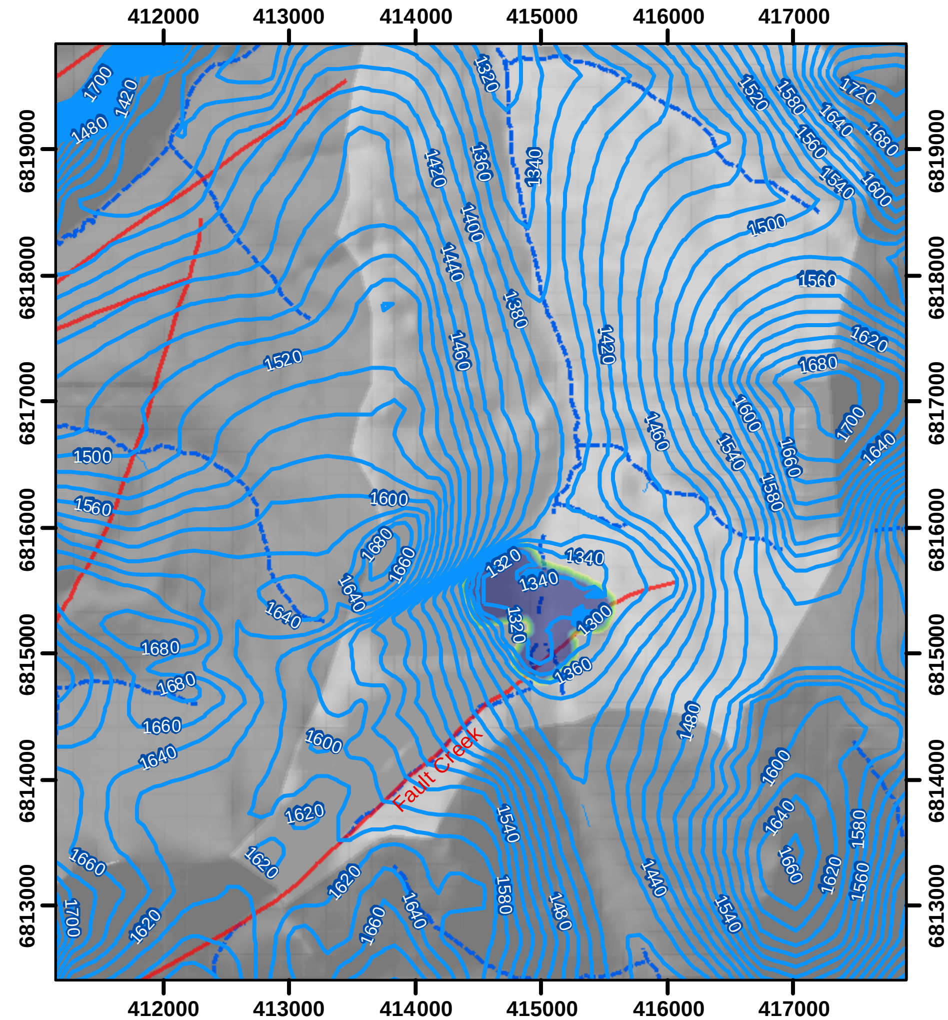
Geona Creek Catchment

N S E W

TITLE: **Influent Pit Water Pathlines**			
LOCATION: Kudz Ze Kayah Project, Yukon, CA			
TETRA TECH	APPROVED	CKG	FIGURE
	DRAFTED	CKG	4.4.2
	PROJECT#	GWTR03021	
	DATE	10-05-2016	



Model Layer 2: Overburden and Shallow Weathered Bedrock

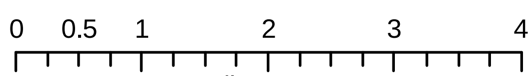


Model Layer 5: Bedrock (200 m depth, approx)

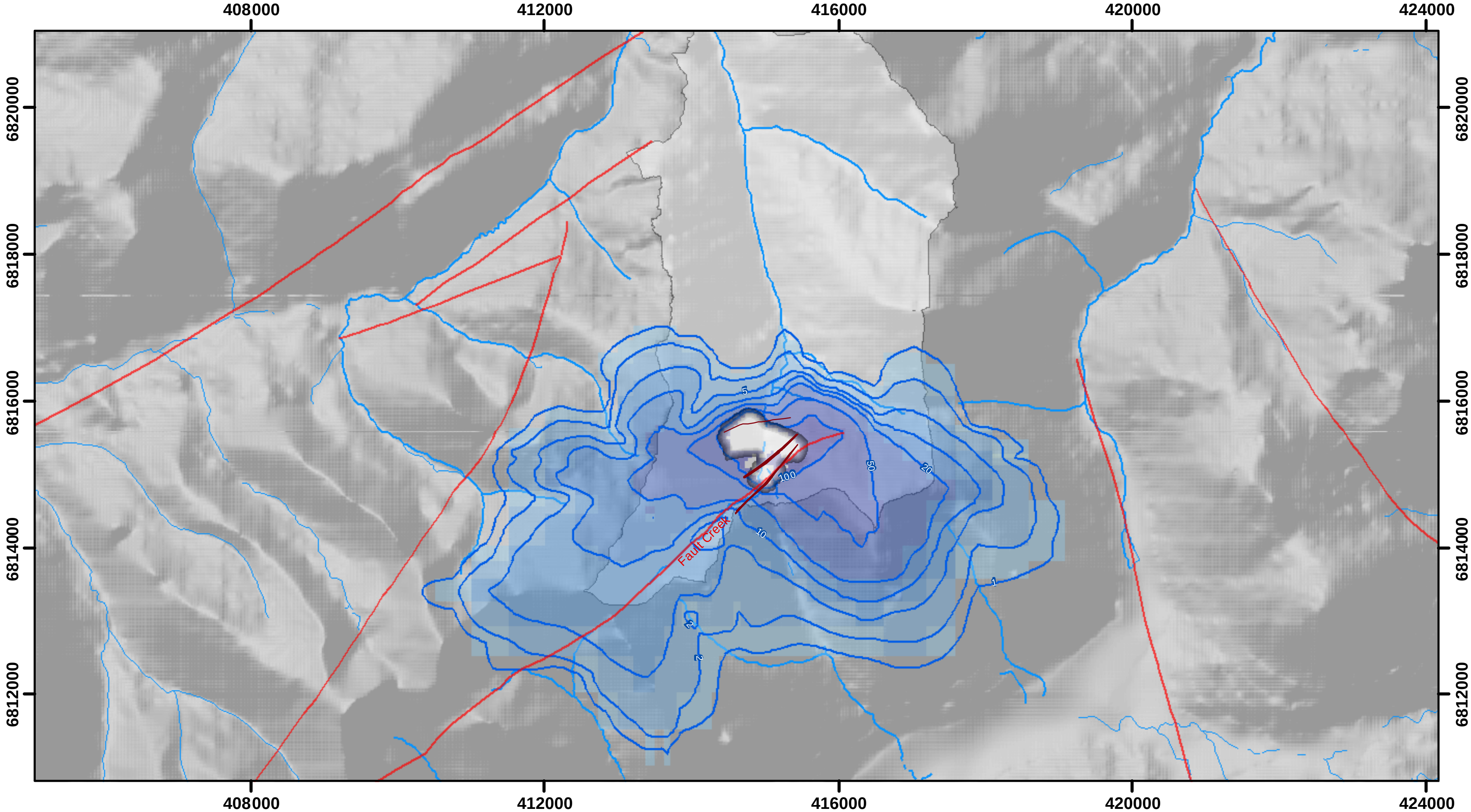
Legend

Water-Level Elevation Contour (m amsl)

Pit Outline



TITLE:	**Post-Mining Year 5** **Water-Level Elevation Contours**		
LOCATION:	Kud-ze-Kayah, Yukon, CA		
TETRA TECH	APPROVED	GJCR	FIGURE
	DRAFTED	CKG	4.5.1a
	PROJECT#	WTR.GWTR03021-01	
	DATE	11-02-16	

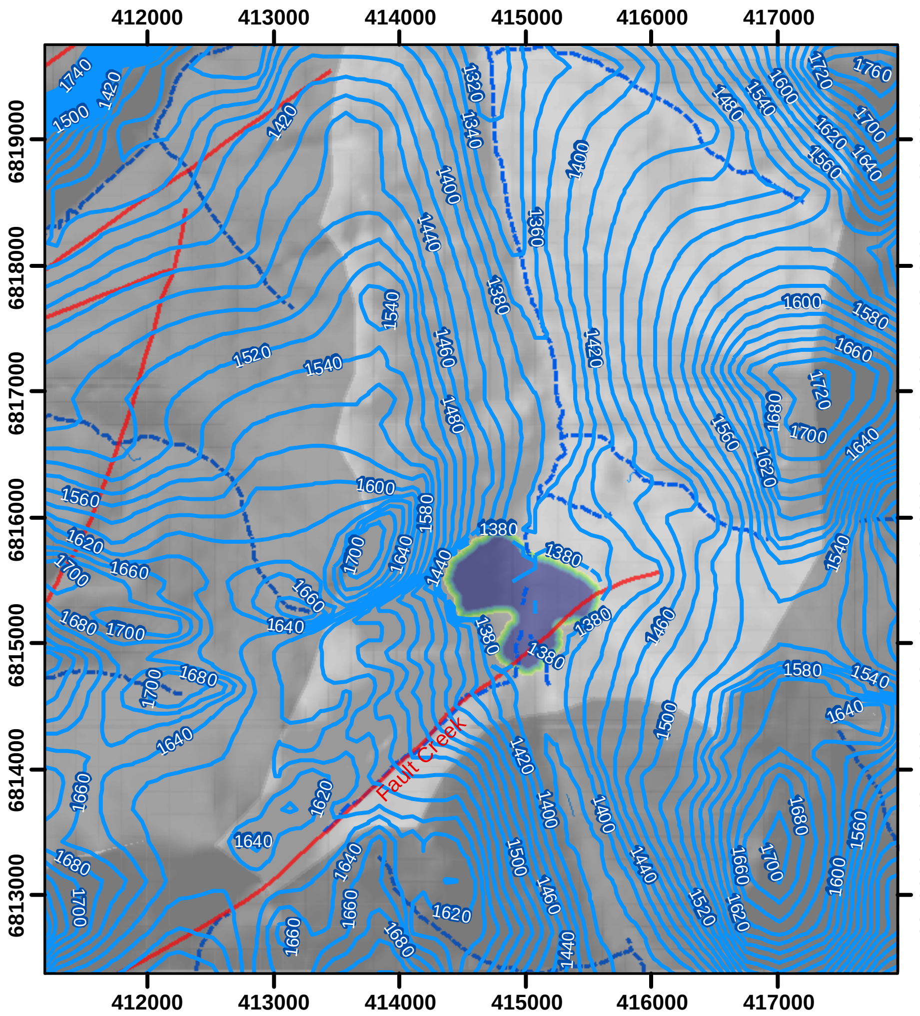


Legend

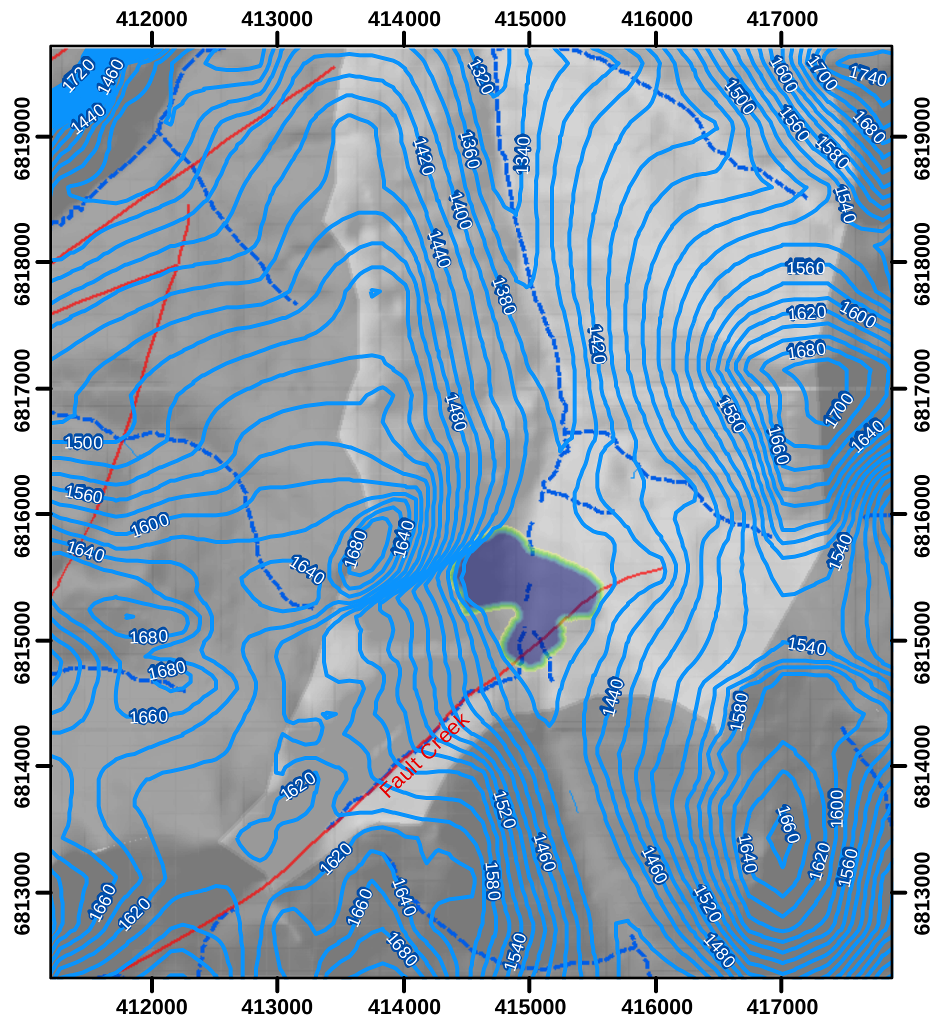
- Faults
- Pit Outline
- Drawdown Contours (m)
- Geona Creek Basin

Note: Drawdown reported for model layer 5.

TITLE:	**5-Year Post-Mining Bedrock Drawdown Contours**		
LOCATION:	Kudz Ze Kayah, Yukon, CA		
TETRA TECH	APPROVED	GJCR	FIGURE
	DRAFTED	CKG	4.5.1b
	PROJECT#	WTR.GWTR03021-01	
	DATE	11-01-16	



Model Layer 2: Overburden and Shallow Weathered Bedrock



Model Layer 5: Bedrock (200 m depth, approx)

Legend

Water-Level Elevation Contour (m amsl)
Pit Outline

N
W E
S

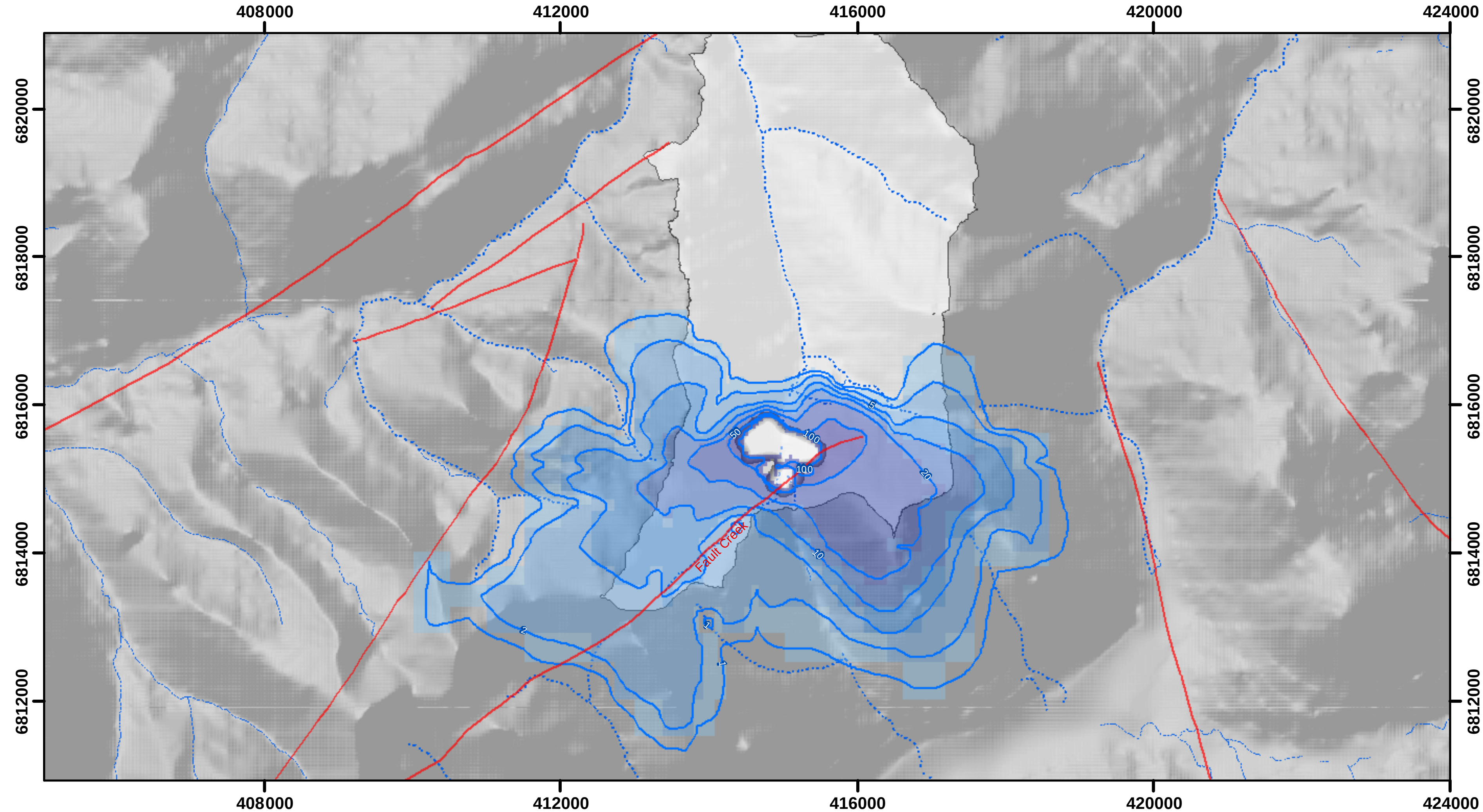
0 0.5 1 2 3 4
Kilometers

TITLE:
Post-Mining Year 30
Water-Level Elevation Contours

LOCATION:
Kudz-ze-Kayah, Yukon, CA

TETRA TECH

APPROVED	GJCR	FIGURE
DRAFTED	CKG	4.5.1c
PROJECT#	WTR.GWTR03021-01	
DATE	11-02-16	



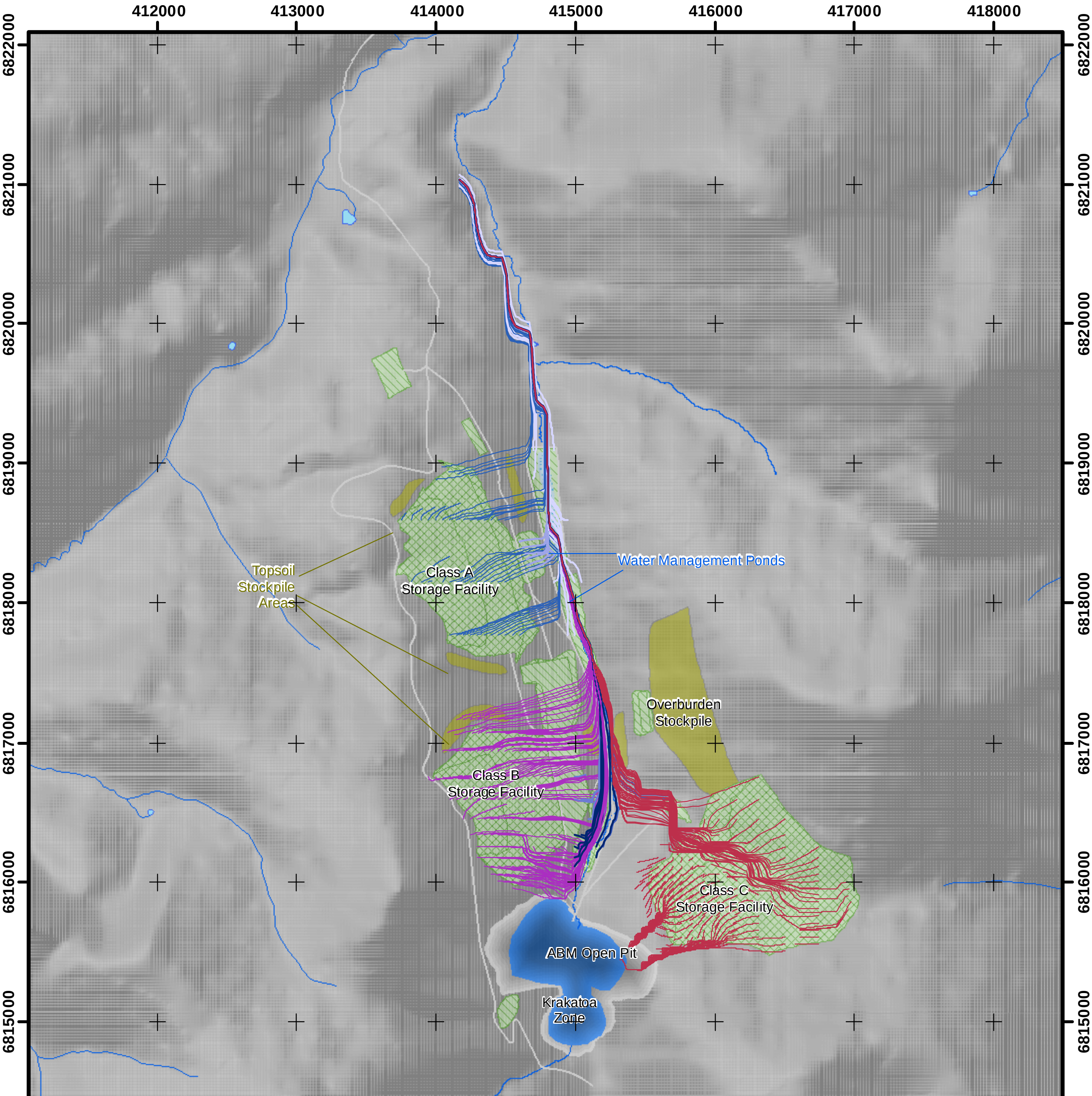
Legend

- Drawdown Contours (m)
- Pit Outline
- Geona Creek Basin

0 0.5 1 2 3 4 5
Kilometers

Note: Results reported for model layer 5.

TITLE:	**30-Year Post-Mining Shallow Bedrock Drawdown Contours**		
LOCATION:	Kudz Ze Kayah, Yukon, CA		
TETRA TECH	APPROVED	GJCR	FIGURE 4.5.1d
	DRAFTED	CKG	
	PROJECT#	WTR.GWTR03021-01	
	DATE	11-02-16	



Legend

Particle Origin

- Water Mgmt Pond
- Class A
- Class B
- Class C
- Class A Water Collection Pond
- Class B Water Collection Pond
- Class C Water Collection Pond
- Pit-Rim Pond

Facilities

- Constructed Wetland
- Engineered Cover
- Covered with Overburden; Revegetated
- Materials used for Reclamation

- Roads
- Watercourses
- ABM Lake
- ABM Open Pit
- Waterbodies

0 0.5 1 2
Kilometers

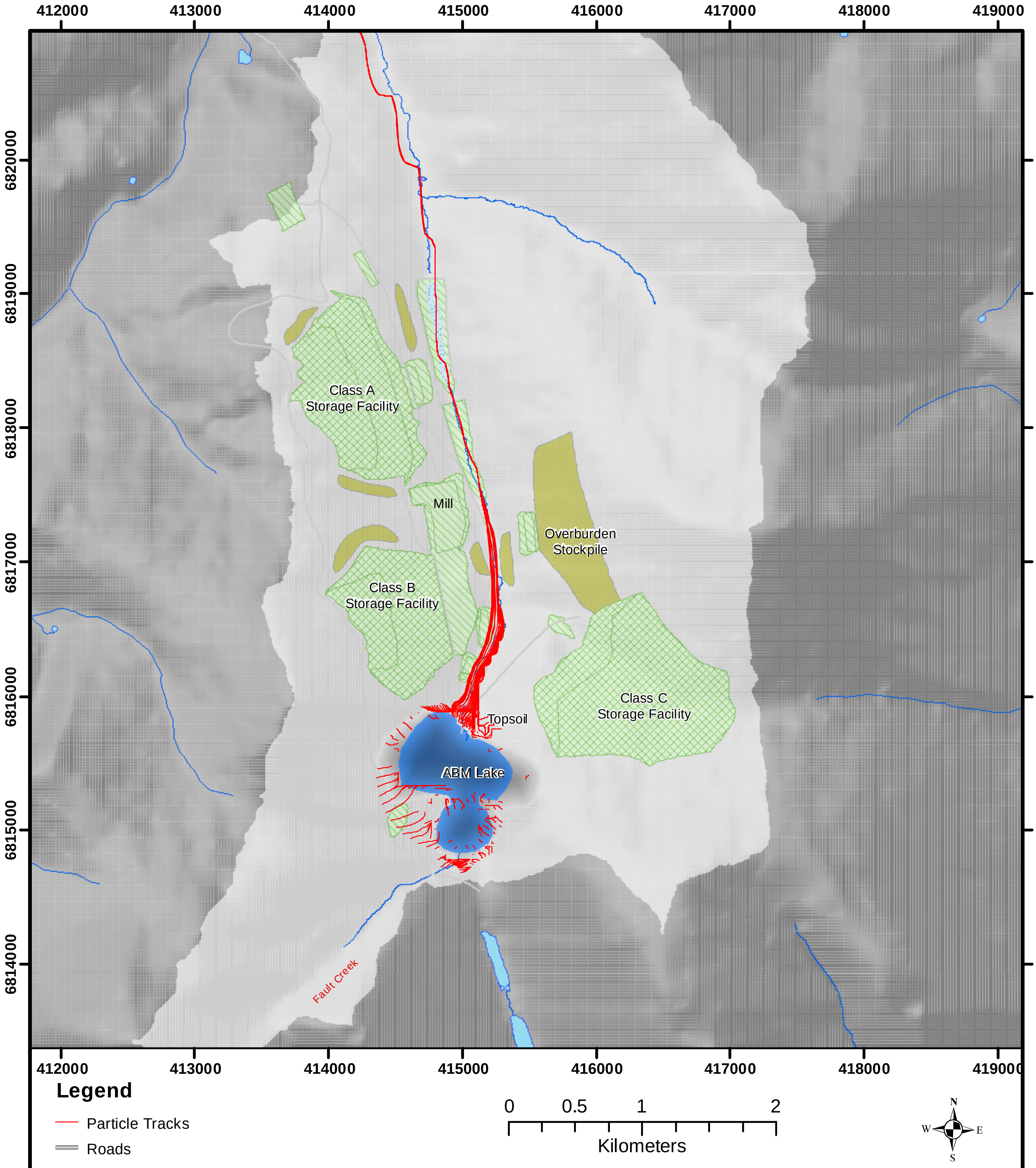
N W E S

TITLE:
Post-Closure Waste Rock Particle Tracking

LOCATION:
Kudz Ze Kayah, Yukon, CA

TETRA TECH

APPROVED	CKG	FIGURE
DRAFTED	CKG	4.5.2
PROJECT#	GWTR03021	
DATE	11-04-2016	



TITLE: Pit-Water Particle Tracking 16 to 50 years Post-Closure	
LOCATION: Kudz Ze Kayah, Yukon, CA	

TETRA TECH			FIGURE
	APPROVED	CKG	4.5.3
	DRAFTED	CKG	
	PROJECT#	GWTR03021	
	DATE	12-14-2016	

APPENDIX A
TETRA TECH'S GENERAL CONDITIONS

GENERAL CONDITIONS

GEOENVIRONMENTAL REPORT

This report incorporates and is subject to these "General Conditions".

1.1 USE OF REPORT AND OWNERSHIP

This report pertains to a specific site, a specific development, and a specific scope of work. It is not applicable to any other sites, nor should it be relied upon for types of development other than those to which it refers. Any variation from the site or proposed development would necessitate a supplementary investigation and assessment.

This report and the assessments and recommendations contained in it are intended for the sole use of TETRA TECH's client. TETRA TECH does not accept any responsibility for the accuracy of any of the data, the analysis or the recommendations contained or referenced in the report when the report is used or relied upon by any party other than TETRA TECH's Client unless otherwise authorized in writing by TETRA TECH. Any unauthorized use of the report is at the sole risk of the user.

This report is subject to copyright and shall not be reproduced either wholly or in part without the prior, written permission of TETRA TECH. Additional copies of the report, if required, may be obtained upon request.

1.2 ALTERNATE REPORT FORMAT

Where TETRA TECH submits both electronic file and hard copy versions of reports, drawings and other project-related documents and deliverables (collectively termed TETRA TECH's instruments of professional service); only the signed and/or sealed versions shall be considered final and legally binding. The original signed and/or sealed version archived by TETRA TECH shall be deemed to be the original for the Project.

Both electronic file and hard copy versions of TETRA TECH's instruments of professional service shall not, under any circumstances, no matter who owns or uses them, be altered by any party except TETRA TECH. The Client warrants that TETRA TECH's instruments of professional service will be used only and exactly as submitted by TETRA TECH.

Electronic files submitted by TETRA TECH have been prepared and submitted using specific software and hardware systems. TETRA TECH makes no representation about the compatibility of these files with the Client's current or future software and hardware systems.

1.3 NOTIFICATION OF AUTHORITIES

In certain instances, the discovery of hazardous substances or conditions and materials may require that regulatory agencies and other persons be informed and the client agrees that notification to such bodies or persons as required may be done by TETRA TECH in its reasonably exercised discretion.

1.4 INFORMATION PROVIDED TO TETRA TECH BY OTHERS

During the performance of the work and the preparation of the report, TETRA TECH may rely on information provided by persons other than the Client. While TETRA TECH endeavours to verify the accuracy of such information when instructed to do so by the Client, TETRA TECH accepts no responsibility for the accuracy or the reliability of such information which may affect the report.