Hydrogeological Model Revision
Kudz Ze Kayah Project, Yukon

PRESENTED TO
BMC Minerals (No. 1) Ltd.

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Tetra Tech EBA Inc.
61 Wasson Place
Whitehorse, YT Y1A 0H7 CANADA
Tel 867.668.3068 Fax 867.668.4349

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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 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. Previously in 2016, Tetra Tech EBA had developed, calibrated and presented the simulated results of a hydrogeological groundwater flow model in support of the hydrogeological baseline and effects assessments for the KZK Project (Tetra Tech, 2016). This model was also used for developing of a preliminary dewatering strategy for the area of the proposed open pit and underground mine. The 2016 groundwater flow model report concluded that the resolution of the model grid in the vicinity of the pit was too coarse to allow the simulation of the faults intersecting the pit to be treated accurately. The fault zones were estimated in the field to be approximately 5 metres wide; however, the model grid cells were 50 metres wide. Additionally, the fault features themselves, in order to retain hydraulic connectivity, were in places simulated using 2 to 3 model cells. While this allowed for the calibration of the model to the available data, the lack of detail in the grid did not allow for as effective a calibration as was performed in the current version of the model. Thus the predictions of groundwater flow associated with the bedrock and faults in the 2016 model reflect this calibration and did not permit as accurate an estimation of the amount of groundwater flow likely to be transmitted to the pit and underground workings.

As a result of these conclusions, BMC requested Tetra Tech to perform a revision and update of the groundwater flow model using significantly smaller model cells to represent the faults intersecting the pit. This report presents the revision of the initial model using a significantly decreased model cell size in the immediate vicinity of the proposed open pit and underground mine.

Geologic zonations, recharge rates, stream and lake data and water level target data were retained from the 2016 groundwater flow model and adapted for use in the new model. New data collected subsequent to the development of the 2016 model was also integrated in development of the 2018 groundwater flow model. These data included permafrost mapping, packer testing data collected in the footprint of the proposed open pit, and aquifer testing of the rock in and around the fault zones.

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. The steady-state model was then 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, a 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 values derived from field observation or professional judgement.

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 to minimize the interaction of deeper groundwater with the pit lake expected to form, followed by the re-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 arrived at the following conclusions:

1. Similarly to the conclusions reached in the 2016 groundwater flow model, pre mining dewatering can be accomplished by excavation of a drainage trench parallel to the valley axis to the top of the bedrock, and pumping out the water that enters the trench. The re-calibration of the model suggests that the hydraulic conductivity of the overburden is less than previously thought, which results in the need for four trenches to be placed and oriented orthogonally to the original trench. Although the initial month of dewatering will produce higher rates of flow (around 8,100 m^3/d, or 94 L/sec), the final month should be reduced to around 2,200 m^3/d.

2. With the exception of areas of faulting or fracturing, the pit bedrock still 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 worthwhile to implement a set of approximately fifteen (15) 100 metre deep dewatering wells arrayed at 500 metre spacing around the perimeter of the pit. Assuming that groundwater flow occurs through a reasonably isotropic weathered bedrock with interconnected fractures, these wells may be sufficient to dewater the weathered bedrock around the pit to minimize seepage face flow.

3. Fault zones within the underground workings may be expected to produce water at higher rates of discharge and require the drilling of horizontal drains to stabilize hydraulic conditions locally, draining a simulated rate of 1,100 m^3/d.

4. 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 approximately 4 years, and to fill completely to the spill elevation of 1,380 m amsl after approximately 16 years.

5. 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 1,400 m^3/d.

6. 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.

7. 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.

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ACRONYMS & ABBREVIATIONS

amsl	above mean sea level
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
LiDAR	Light Detection and Ranging
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 Topographic 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 Project), a volcanic massive sulphide (VMS) deposit within the Finlayson VMS district, South Central Yukon. The ABM deposit hosts zinc-rich polymetallic (zinc-lead-copper-silver-gold) massive-sulphide mineralization. The Project is located in the northern Pelly Mountains, approximately 115 km southeast of Ross River, YT. The Property (the Site) covers 23,000 hectares and is accessible by an all-weather Tote Road from Yukon Highway 4 (Robert Campbell Highway) (Figure 1.0).

The Project 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 Site has an approximate UTM/NAD83 location of 414700 E / 6816200 N in Zone 9Z and lies on National Topographic System (NTS) map sheet 105G/10.

Tetra Tech EBA Inc. (Tetra Tech) was retained by BMC to conduct a hydrogeological baseline and effects assessments for the 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. In support of this effort, Tetra Tech developed, calibrated and presented the simulated results of a hydrogeological groundwater flow model (Tetra Tech, 2016). 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 presenting the results of the groundwater flow model simulations, Tetra Tech concluded that the potential nature of three faults intersecting the planned open pit mine and underground workings was not likely possible to be adequately simulated given the resolution of the model.

BMC subsequently retained Tetra Tech to perform a revision of the groundwater flow model, reducing the size of the cells in the vicinity of the open pit mine to more accurately simulate the effects of the faults.

1.1 Purpose and Objective

The purpose of this effort is to revise the groundwater flow model developed in 2016 using a refined model grid and integrate data collected since the development of the original groundwater flow model. By reducing the grid dimensions in the pit area, the fault zones can be represented more accurately instead of distributing the faults over multiple oversized cells for the purposes of hydraulic connectivity. The revised model is then used to simulate future conditions associated with mining to predict their hydrological impacts.

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 1.2). 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.

A groundwater flow model was previously developed in 2016 by Tetra Tech, and used to predict the hydrological impacts of the proposed mine on future conditions (Tetra Tech, 2016). This model revision relies on the data and mapping presented in the original report, and provides updates as necessary to clarify the changes made as part of the development of the grid refinement and groundwater flow model update.

2.0 MODEL DEVELOPMENT

2.1 Modeling Software

Although the 2016 groundwater flow model was developed using the United States Geological Survey (USGS) software package MODFLOW-NWT (Niswonger et al., 2011), a change was made for the purposes of simulating contrasting conditions of higher hydraulic conductivity such as the fault zones. Development and calibration of the revised groundwater flow model was conducted using the framework for the software package MODFLOW-SURFACT v4.01 (HydroGeoLogic, Inc, 2017). MODFLOW-SURFACT is a 3D finite-difference modeling code like MODFLOW-NWT; however, it has the capability to modify the length of the numerical time steps used for a solution, reducing the length of the time step when convergence is not reached within a specified number of iterations, and lengthening it when a solution is quickly reached. In general, MODFLOW-SURFACT is applicable to the problem of simulating the life of a mine as it is intended for solving problems involving drying and rewetting nonlinearities of the unconfined groundwater-flow equation. 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).

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 Project Site is centrally located, and extends as far north as stream gauge KZ-22 on Finlayson Creek, a distance of approximately 12.5 km north. The model was then extended approximately to the boundaries of the watersheds adjacent on each side to the Geona Creek watershed, an extent judged sufficient to capture the probable extent of drawdown from mining-related activities based on the results from the 2016 model (Figure 1.0).

2.2.1 Model Grid

The original 2016 groundwater model developed for the Project telescoped to a locally refined resolution of 50 m by 50 m cells. This was subsequently determined to be too coarse to represent the fault zones mapped near the pit, resulting in a reduced confidence in the model predictions for pit inflow rates. As a result, during the model revision, the model grid in the vicinity of the planned pit was reduced. 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 Project Site to model cells with dimensions of 5 m by 5 m (see Figure 1.0). The resulting grid consists of 311 model rows and 332 model columns, covering a geographic area of approximately 508 square kilometres. Model cells associated with catchment basins outside of the immediately adjacent basins were deactivated (set to a status of no-flow) to reduce the number of cells for the purposes of speeding up model run times. As a result, the active geographic area is approximately 301 square kilometres. The grid is oriented in a north-south orientation (no angular rotation), with model coordinates at the lower left corner of 402,920 E / 6,806,328 N in Zone 9Z of UTM/NAD83. The model grid in the area of the Site is shown along with the mine features on Figure 2.2.1.

Vertically, the model grid was established using nine (9) model layers which range in thickness from approximately 1 m to 1,150 m in the vicinity of the mine. The upper three model layers generally represent the overburden and weathered bedrock, and are based on a combination of overburden thickness near the pit and depth below land surface away from the pit. Layers 4 and 5 represent a transition zone between Layers 3 and 6. Layers 6 through 8 represent 30 – 35 meter thick, near-horizontal layers whose elevations coincide with the upper, middle and lower third intervals associated with the underground workings. Layer 9 extends from the bottom of layer 8 around 1,100 to 1,165 metres to the bottom of the model at 0 metres of elevation. The layer thicknesses are summarized in Table 2.2.1 below.

Table 2.2.1: Model Vertical Discretization

Numerical Layer	Geology	Model Thickness
Layer 1	Overburden and Weathered Bedrock	1 – 30 m
Layer 2	Weathered Bedrock / Overburden in vicinity of WW15-01	1 - 15 m
Layer 3	Weathered Bedrock	15 m
Layer 4	Bedrock	45 - 165 m
Layer 5	Bedrock	45 - 165 m
Layer 6	Bedrock	30 m
Layer 7	Bedrock	35 m
Layer 8	Bedrock	35 m
Layer 9	Bedrock	1,150 m

2.2.2 Time Discretization

The groundwater model was developed and calibrated using seven 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 (days)	Time Steps
1	Steady-State Conditions	0	1
2	Quiescent transient period	1,000	60
3	Simulate WW15-01 Pumping Test	0.5	60
4	WW15-01 recovery evaluation	0.5	60
5	Period between testing	12	30
6	Simulate WW15-02 Pumping Test	1	120
7	WW15-02 recovery evaluation	0.15	16

2.3 Implementation of Geology

The geology associated with each of the model layers is based on the 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 Geology

The spatial distributions of surficial and bedrock geologic zones were assigned based on that used in development of the 2016 groundwater flow model. The implementation of the surficial geology is shown in Figure 2.3.1, and the bedrock geology in Figure 2.3.2.

2.3.2 Faults

Based on development and calibration of the 2016 groundwater flow model, three pit area faults were simulated in the revised groundwater flow model. Additionally, the southwest-northeast structural block bounding fault at the north end of Geona Creek was implemented in the model, although its role in the hydrogeology is uncertain, and did not significantly factor into the model development or calibration. The locations of the three faults in the vicinity of the proposed pit are shown on Figure 2.3.2. The only significant difference from the 2016 model is that the width of the three faults (which intersect the planned open-pit mine) are now represented with much thinner fault zones of only 5-10 metres width.

2.4 Precipitation and Climate

Climate and precipitation impact the groundwater flow model in several ways. The northerly nature of the location of the Site is such that at many areas a layer of permafrost is present. The permafrost acts as both a barrier to groundwater flow and a restrictor on water infiltration. The precipitation which falls partly as snow and partly as rain has been recorded and estimates of resulting basin-scale recharge have been derived. These factors were used during development of the 2016 groundwater flow model. The calibrated basin-wide recharge rate applied for the permafrost and non-permafrost zones in the 2016 groundwater flow model were again applied for the purposes of calibration of the 2018 groundwater flow model revision.

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 groundwater elevation or surface water from year to year and therefore negligible change watershed storage from year to year.

2.4.2 Permafrost

During field activities, the presence of permafrost in some areas was confirmed above the valley floor along the eastern hillside. In 2017 the extent of permafrost within the Geona Creek basin was thoroughly mapped within a 100 m buffer of all proposed mine infrastructure footprints and the Tote Road centre line (Coregeo and Associates, 2017) and integrated into a memorandum on the permafrost distribution (Coregeo and Associates, Palmer Environmental Consulting Group, 2017). For the purposes of the 2018 revised groundwater flow model development, permafrost is assumed to be present in the zone categorized as “probable” as well as “confirmed.” This investigation generally supported the following assumptions used in assigning an extent of permafrost during model development. First, permafrost tends to be present in areas at elevations greater than 1,400 m above mean sea level (amsl). 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.

The permafrost distribution previously used to develop the 2016 groundwater flow model was modified for consistency with the findings of the 2017 mapping effort. Permafrost is estimated to cover 52% of the Geona Creek catchment based on this analysis, which is a slight increase over the previous 2016 estimate of 45% (Figure 2.4.5).

2.4.3 Groundwater Recharge

The distribution of groundwater recharge from precipitation was implemented as it was in the 2016 groundwater model on the basis of the presence or absence of permafrost. For the purposes of groundwater modeling, it was assumed that the mapping of “confirmed” or “probable” permafrost would best be represented hydrologically as a zone of reduced-permeability with a corresponding reduction in recharge. 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. The revised distribution of permafrost (Coregeo and Associates, Palmer Environmental Consulting Group, 2017) resulted in a revised recharge distribution dataset, but in which the rates assigned to each zone (permafrost vs non-permafrost) remained the same as implemented during calibration of the 2016 groundwater flow model. During 2016 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.

2.4.4 Run-off

The annual run-off rates were assigned consistent with that used in development of the 2016 groundwater flow model. These annual rates were calculated on the basis of run-off rates and contributing catchment area above a particular stream segment.

2.4.5 Evapotranspiration

The assumptions used for evapotranspiration during development of the 2016 groundwater flow model were also used during development and calibration of the 2018 revised groundwater flow model. Run-off rates were assigned consistent with that used in development of the 2016 groundwater flow model. Annual evapotranspiration (estimated at 88 mm/yr based the annual precipitation, run-off and recharge estimates above) was not explicitly simulated in the model, but rather subtracted off from the water budget before recharge is applied.

2.5 Surface Water Features

Consistent with the development of the 2016 groundwater flow model, streams and lakes were incorporated into the groundwater flow model using three separate MODFLOW packages. A variation was required with regard to the lake package because of stability problems that occurred when attempting to use the LAK3 package within MODFLOW-SURFACT. Instead the modeling packages used in the 2018 groundwater flow model revision included the streamflow routing package (SFR2), the lake package (LAK2), and the drain package (DRN). Implementation of these packages is described in the following sections.

2.5.1 Streams

Geona Creek and the streams in the immediately adjacent drainages to the east, west and south were simulated similarly to the form used in the 2016 groundwater flow model using the Streamflow Routing (SFR2) package to drain groundwater and interact with the lakes within the drainages. At a few locations, the drainage network was represented using the MODFLOW Drain package (DRN). This package has the advantage of being more numerically efficient for the numerical model solver, but does not allow for streamflow gauging to be simulated. Since all, or nearly all of the stream reaches are expected to be gaining reaches outside of the Geona Creek watershed area or adjacent watersheds this representation is expected to be appropriate. These locations were generally on the very farthest south of the southern adjoining drainage, and north of the structural bounding fault where streams wouldn't contribute to the gauged flows along Finlayson Creek (see Figure 2.5).

Stream elevations were assigned using the best available digital elevation data for an area. Near the Site, elevations were derived from the Light Detection and Ranging (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 (LAK2). Each of the ponds along the Geona Creek catchment were included as part of the model development.

2.6 Implementation of Wells

During modeling, the groundwater pumping wells, WW15-01 and WW15-02 (see Figure 2.6), were simulated using the MODFLOW well package (WEL). Unlike the implementation of the 2016 groundwater flow model, since MODFLOW-SURFACT is incompatible with the MNW (Multi-Node Well) package, the 2018 model revision uses a different package for pumping. Since the cell size has diminished at the pumping well from 50 metres to 5 metres, the error associated with using a non-analytic element solution is also reduced, making the WEL package a viable solution for the purpose. The addition of two more vertical layers also provides further increase in simulation accuracy since the model was more capable of representing the wells in the correct depth intervals than they had previously been in the 2016 model. Since pumping is entirely prescriptive in the WEL package, the complexity of the solution is also reduced, allowing model run times to be reduced.

2.7 Observation Datasets

Observation datasets or targets used for model calibration included the same water levels recorded in wells and piezometers, streamflow discharge measurements as the 2016 groundwater flow model used, with the exception of the most downstream streamflow gauge at KZ-26, which was outside of the active model domain. As with the 2016 flow model, by using three different types of calibration targets, including head observations, drawdown response observations and streamflow observations, 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.

2.7.1 Water-Level and Drawdown Measurements

With the exception of the reassignment of the water-level observations to different numerical model layers where necessary to account for the change in vertical discretization of the model, the same water-level observations and drawdown observations were used in developing and calibrating the 2018 groundwater flow model revision as was used to calibrate the 2016 groundwater flow model. 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). Simulation of the pumping tests performed at alluvial well WW15-01 and shallow-bedrock well WW15-02 were used to calibrate the aquifer parameters for the overburden and for the weathered pit bedrock, respectively.

2.7.2 Streamflow Discharge

Although stream gauging stations constructed on Geona Creek and Finlayson Creek were used for model calibration (see Figure 2.7), since a large proportion of the flows were judged to be associated with surface runoff rather than direct groundwater discharge, for the purposes of calibration, the discharge observations were used with a reduced weight. The method used for determining the rate of run-off for each stream segment was unchanged from the 2016 groundwater model.

2.7.3 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 allows 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 during the pumping phase in WW15-01 (the pumped well) during the WW15-01 aquifer test were reduced due to uncertainty associated with the results (see Section 2.6.3). Similarly, the weights for drawdown in WW15-02 during the pumping portion of the aquifer test for WW15-02 were reduced, although the recovery observation data were used for calibration.

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 MODEL CALIBRATION

Model calibration was performed with a specific set of goals or objectives. 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 wells in the vicinity of the Site;
2. Visually matching observed drawdown behavior in monitoring wells during the pumping portion of the two aquifer pumping tests, and all wells during the recovery portion of the 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. Typically, the model was initially run to determine if it accurately matched observed water levels. PEST was then used to revise the estimates for hydrogeologic parameters with a goal of minimizing the objective function and optimizing the model solution relative to the observed data. The resulting solution was then examined and if modifications to the configuration were judged appropriate to implement with the goal of better defining the problem and improving the simulated match, this was performed and the process repeated.

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 outcrops 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 aquifer 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. A specific yield of 20% for the overburden and 0.1% for the bedrock was selected as appropriate, initially based on professional judgement, then confirmed during calibration to be representative. Specific storage was identified as being a relatively insensitive parameter during calibration since neither of the constant-rate pumping tests were conducted in the deeper bedrock which was likely to be strongly dependent on confined conditions. Specific storage was therefore assumed to be $1x10^{-6}$ m^{-1} based on professional judgement.

Table 3.2: Zoned Aquifer Hydraulic Properties

Geology	Model Zone	Aquifer Test K	Kx	Kz	Sy	Ss
		m/s	m/s	m/s		1/m
Fluvial/ Glaciofluvial	Zone 1	1.10E-04	1.33E-04	3.83E-07	0.20	6.00E-04
Confining Layer by Pit	Zone 9	-	6.16E-06	6.54E-08	0.20	6.00E-04
Till Apron	Zone 10	-	1.97E-06	3.47E-07	0.20	6.00E-04
Glacial Till	Zone 4	-	1.16E-07	1.16E-07	0.20	6.00E-04
Weathered Bedrock	Zone 2	1.0E-07 - 4.1E-05	1.10E-06	2.75E-07	0.001	1.00E-05
Metamorphics Bedrock	Zone 6	-	7.96E-09	3.21E-07	0.001	1.00E-06
Weathered Pit Bedrock	Zone 13	3.5E-09 - 1.7E-06	1.75E-06	2.86E-07	0.001	6.00E-04
Pit Bedrock	Zone 7	1.1E-13 - 1.2E-07	6.71E-09	2.86E-07	0.001	1.00E-06
Plutonics	Zone 3	-	1.16E-08	1.16E-08	0.001	1.00E-06
Permafrost	Zone 5	-	1.16E-08	1.16E-08	0.001	1.00E-05
Fault Creek Zone	Zone 8	3.5E-06	3.50E-06	3.50E-06	0.001	1.00E-05
East Fault Zone	Zone 11	-	8.18E-09	4.58E-07	0.001	1.00E-05
Northwest Fault	Zone 12	-	8.29E-09	4.64E-07	0.001	1.00E-05

Overburden

Bedrock

Kx and Kz = horizontal and vertical hydraulic conductivity

Sy and Ss = specific yield and specific storage

Aquifer-Test hydraulic conductivity values for the Fluvial/Glaciofluviial are from constant-rate pumping test for WW15-01. Those for the bedrock represent a combination of constant-rate test and packer-test values. The value for the Fault Creek Zone is the result of analysis of a packer test believed to have been conducted over the fault zone.

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 valley fill overburden and the streams would likely be similar to that of the surrounding overburden itself since the streambed is likely composed of reworked overburden material. The streambed hydraulic conductivity was assigned based in part on approximate slope of a stream reach. Steeper stream reaches (gradients over 0.01 m/m) were assumed to have a minimal streambed thickness of 0.1 m and a vertical hydraulic conductivity of 1.2×10^{-6} m/s. Moderately sloped reaches (gradients between 0.05 and 0.1 m/m) were assumed to have a streambed thickness of 0.5 m, and a vertical hydraulic conductivity of 1.2×10^{-5} m/s, and the flattest reaches, generally located in the bottoms of the fluvial deposit-filled channels were assigned a streambed thickness of 0.5 m and a vertical hydraulic conductivity of 2.4×10^{-5} m/s. Since the streambed conductivity values are consistently higher than that of the vertical hydraulic conductivity of the valley alluvium (3.83×10^{-7} m/s), the streambed itself thus does not act as a barrier to flow entering the stream channel.

3.2.2 Fault Conductance

Although the major (believed to be unnamed) northeast/southwest trending fault present at the northern end of Geona Creek Watershed (Figure 2.3.2) was simulated using the Horizontal Flow Barrier (HFB) package and evaluated as a possible barrier to flow as part of the calibration effort, unlike in the 2016 groundwater model, this fault as a barrier was judged to be inconsequential to the current model. Although it was included in the model, it was implemented using a relatively high conductance as none of the observations appeared affected by it. The basis for it in the 2016 model revolved around observed higher than expected heads in one well (BH95-G9) near the northern end of Geona Creek, and the observation that flow in the downstream end of Geona Creek was not confined to a single channel, but occurred throughout the valley, making stream gauging a challenge for field efforts. During calibration, it was determined that while this fault, when implemented as a barrier, could cause groundwater to be pushed to the surface with additional associated surface flow, it also resulted in a more complex numerical solution and increased the difficulty in reaching convergence. Since the model domain had been restricted to simplify an already difficult solution process, the fault as a barrier was judged to be causing more problems than it solved. The fault was therefore not implemented as a hydraulic barrier in the 2018 model.

As noted in Section 2.3.2, three faults have been mapped in the vicinity of the proposed pit area. Each of these 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 model cells or 5 - 10 m to ensure hydraulic connection along the feature where the model grid was oriented at an angle compared to the fault. The northern two faults were not believed to have been intercepted by any of the aquifer testing performed during investigation of the pit area. The southern-most fault, that aligned with Fault Creek, was believed to have been evaluated by packer test which determined the hydraulic conductivity to be $3.5\text{x}10^{-6}$ m/s. During calibration, the hydraulic conductivity for the Fault Creek zone was assigned to be $3.5\text{x}10^{-6}$ m/s. The calibration process suggested that some increased flow was likely associated with the mapped fault zones. The calibrated hydraulic conductivity of the two northern fault zones was determined to be lower than that of the surrounding weathered bedrock zone, and slightly more conductive than the surrounding unweathered bedrock zone.

3.2.3 Recharge Zones

The applied non-permafrost recharge rate in the calibrated 2016 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 2016 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 net surface water 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. 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 flow equations were accurately solved.

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	7,722.9	-7,722.9
Recharge	81,266.7	0	81,266.7
Stream Leakage	44,743.2	117,363.5	-72,620.3
Lake Seepage	30.3	956.6	-926.3
Total	**126,040.2**	**126,043.1**	**-2.9**

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.

The simulated recharge from precipitation is 81,266.7 m^3/d or an average of approximately 99 mm/yr. Discharge out of the model is primarily through the stream channels simulated by streams. Lesser fluxes occur through lakes and the smaller network of streams simulated explicitly using the drain package and appearing as “Drains”. 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.

Geona Creek Catchment Mass Balance

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 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 5,229.4 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 3,212. m^3/d. The flux in component of water (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	1,771.0	3,232.3	-1,461.3
Drains	0	0	0
Recharge	5,229.4	0	5,229.4
Stream Leakage	13,327	16,639	-3,312.0
Lake Seepage	30.2	485.5	-455.3
Total	**20,357.6**	**20,356.7**	**0.9**

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 and 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 the water table (Overburden and weathered bedrock at surface). This represents 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 assume 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, if these changes have only local effects on water levels and discharge rates. Thus, the small changes in water levels 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. 80% 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 68% were within 4 m of their observed values. In the deeper bedrock, over half of the simulated hydraulic heads were within 1 m of their observed values.

3.4.3 Simulation of Aquifer Tests

As discussed in Section 2.2.2, 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.

WW15-01

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 3 to 3.5 m, likely because of the construction of the well itself. The cause for this is uncertain; however, 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. Simulated drawdown does not precisely follow the observed data because the pumping test is likely functioning under partially confining conditions.

WW15-02

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
MWR	0.90 m
WRSD	3.90 m
AWRM	2.90 m
RMSWE	3.94 m
Observation Count	44
Range	163.34 m
Norm. MWR	0.55%
Norm.W RSD	2.39%
Norm. RMSWE	2.41%

Notes:
W – Weighted; Norm - Normalized

For the total model, the MR (Equation 3.5.1) is 0.90 m and the RSD (Equation 3.5.2) is 3.90 m. ARM for the model (Equation 3.5.3) is 2.90 m indicating that in combination with MR, 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 3.90 m. These values should be compared with the overall range in measured water levels of 163 m. The MR and RSD are approximately 0.55 and 2.39% of this range, respectively. The RMSE is approximately 2.39% 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 0.97 indicating a very high degree of correlation.

3.5.2 Drawdown

As discussed in Section 3.4.3 modification of the weighting for a subset of the observed drawdown observations in calibration was conducted 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
MWR	-0.11
WRSD	0.36
AWRM	0.16
RMSWE	1.07
Observation Count	512
Range	3.30
Norm. MWR	-3.21%
Norm. WRSD	10.87%
Norm. RMSWE	32.32%

An evaluation of the residuals of drawdowns associated with simulation of the two pumping tests shows that the MR is -0.11 m and the RSD is 0.36 m. The ARM is 0.16 m and the RMSE is 1.07 m. These values should be compared with the overall range in adjusted observed water levels of 3.30 m. The MR and RSD are approximately 3.2 and 10.9% of this range, respectively. The RMSE is approximately 32.3% of this range. The correlation coefficient (R^2) for the simulated versus observed drawdown data across all layers in the model is 0.90. This correlation coefficient is misleading because it includes all drawdown data without regard to weighting of observations. If zero-weighted observations of drawdown are removed, the correlation coefficient increases to 0.98.

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	2,631.3	204.2
KZ-7	8,976.2	7,772.6	(1,203.6)
KZ-9	22,572.0	16,938.0	(5,634.0)
KZ-13	8,427.6	4,954.7	(3,472.9)
KZ-15	55,374.5	65,854.0	10,479.5
KZ-16	32,532.5	35,579.0	3,046.5
KZ-17	35,763.1	65,368.0	29,604.9
KZ-21	60,889.5	55,707.0	(5,182.5)
KZ-22	119,296.1	150,860.0	31,563.9

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 the calibration process. The observed uncertainties are as follows:

1. Degree of variation in hydraulic conductivity and depth of weathered/fractured near-surface bedrock;
2. 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; and
3. 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 facilities does not interact with groundwater since it is collected and routed for water quality treatment as necessary prior to being discharged to Geona Creek and/or Finlayson 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 mine access tunnels was assumed to entirely occur during the initial year of underground excavation. Implementation of the underground workings was assumed to occur at a rate of 20 m vertically 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 through 9. 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-SURFACT. After establishing steady-state conditions based on the calibrated model parameterization, a single stress-period of 182 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 development, overburden dewatering 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 is anticipated to 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 zone.

To more efficiently dewater the overburden between the footprint of the Year 1 pit and Geona Creek, four 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. The hydraulic conductivity as determined by the model calibration process suggests that the bulk bedrock is low permeability enough that dewatering wells could be effective, but that they would need to be spaced even more closely than the originally estimated 500 metre spacing simulated during the development of the 2016 groundwater model. A pit dewatering strategy might be best selected using wells to dewater the upper-most 50 to 100 metres of bedrock, and pumping the pit-seepage from sumps situated in the bottom of the pit. Since the wells would address the higher permeability materials of the weathered bedrock, these could probably still use approximately 500 metre spacing.

Simulation of the underground workings suggests that about half of the water enters through the locations where the workings intercept the fault associated with Fault Creek, where aquifer testing suggests that the fault zone is a likely conduit for flow. With enough exploration to define the nature and orientation of the fault zone, dewatering wells could be placed in the fault zone with long screened intervals, likely to a depth of 200 metres. An alternative approach might be to determine where the underground workings actually intercept the fault zone, and drill horizontal drain borings into the zone, routing the resulting drained water into tanks from which it could then be pumped to the surface. Based on the results of the mining simulations, it is likely that drainage from the fault zone would produce approximately 1,100 m^3/d.

The decision on selecting the strategy of a combined system of dewatering wells and horizontal drains 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 a 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 water 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 for the pit excavation, 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.

4.2.3 Underground Workings Dewatering

Similarly to the strategy for in-pit dewatering, the dewatering strategy for the underground workings may involve either dewatering wells, horizontal seepage drains or a combination of the two. Depending on the nature of the faults, as experienced during mine development, dewatering wells targeting the fault zones may prove important for managing water. Horizontal drains, where implemented within the underground workings, should be designed such that shallow drainage will be conducted to a local tank or containment structure to be pumped to the surface.

Deeper drains will need to be constructed such that drainage will be conveyed to a series of sumps to be located at the deepest level of the workings. Collected water will be pumped from the sumps and/or tanks to the surface where it can be routed to the water treatment or water storage facilities. It is anticipated that due to the likely nature of the faults to serve as hydraulic conduits connecting the workings to the recharge zones higher in the surrounding area, sustained water flow will occur. Whether this is best managed using in-working drains or perimeter dewatering wells is likely a decision that will have to be reached at the detailed design phase of the Project.

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 the first and last months of each of the nine years of mining in units of m^3/d are presented in Table 4.3.1.

Simulated flow rates immediately 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 the interest of presenting a more realistic evaluation of the scope of the initial required dewatering rates, the simulated results for the first and last months are presented to illustrate the range likely to be necessary for each year. The average dewatering rate likely falls approximately halfway between these rates.

An evaluation of the distribution of simulated drain flux is also presented in Table 4.3.1. The fluxes reported by zones represent the simulated flow of water into the drain cell through the particular zone. During the pre-mining period of trench dewatering, all of the flow comes from the overburden draining into the trenches as the overburden drains. Mining occurs exclusively in the pit for the first 2 years. Flow continues to occur from the overburden as water from the surrounding watershed flows into the overburden and enters the pit area on the north and south. Flow from the shallow bedrock into the pit ranges from 500 to 1,700 cubic metres per day during these first two years. During mining in years 3 through 9, the pit progresses deeper and the underground workings are implemented. Since the fault zone associated with Fault Creek intercepts the underground workings, this results in sustained flow rates of around 1,100 cubic metres per day throughout the mining period. Flow into the pit and workings through the non-fault bedrock is high during years 3 and 4, and reduces to a more sustained flow rate during years 5 through 9. Flow associated with the northern two faults, determined to be less significant through calibration, remains low at 10-20 cubic metres per day.

Table 4.3.1: Annual Dewatering Rates by Zone (m^3/d)

Time Period		Overburden	Pit Bedrock	Pit Fault Zone	Workings Bedrock	Workings Fault Zone	Flow from South Creek watershed*
Pre-Mining	First Month	8,100	-	-	-	-	160
	Last Month	2,200	-	-	-	-	240
Year 1	First Month	-	1,200	-	-	-	180
	Last Month	700	500	-	-	-	(130)
Year 2	First Month	600	1,600	-	-	-	(140)
	Last Month	600	1,000	-	-	-	(190)
Year 3	First Month	300	2,500	40	2,800	1,000	(30)
	Last Month	<100	1,700	10	2,200	800	140
Year 4	First Month	1,000	1,000	10	2,100	1,700	240
	Last Month	500	600	10	900	1,200	260
Year 5	First Month	600	700	10	800	1,200	270
	Last Month	400	700	10	600	1,100	300
Year 6	First Month	400	1,200	20	600	1,100	270
	Last Month	400	700	10	600	1,100	300
Year 7	First Month	400	600	10	600	1,100	260
	Last Month	400	600	10	600	1,100	300
Year 8	First Month	400	600	10	600	1,100	250
	Last Month	400	600	10	600	1,100	300
Year 9	First Month	400	600	10	600	1,100	250
	Last Month	400	600	10	500	1,100	200

Note: * Prior to dewatering, net flow from South was -400 m^3/d (400 m3/d out of Geona Creek watershed.)

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 resumes flowing 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 of the water table. Although additional drawdown at the outer edges of the affected area is likely to occur following the completion of mining as the hydraulic stresses propogate, they will begin to recover at the mine almost immediately after dewatering ceases.

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 much as 2,400 metres), 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 up to 500-600 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. At this point, the entrance to the underground workings will be closed to prevent flow from occurring between the pit and the 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. Filling of the pit is therefore simulated by removal of drain structures from the pit and underground workings areas, and replacement of the pit with a set of high hydraulic conductivity, high specific yield cells in the model. These modified cells allow the pit to function as a reservoir with nearly unrestricted flow and storage volume equivalent to open air. Simulation of this format allows groundwater to flow into the “Lake”, and streamflow and precipitation to be introduced in the form of prescribed water additions. The water levels in the “Lake” are monitored as they rise and return to a final post-mining configuration. Upon filling to capacity (elevation of 1,380 m amsl) the pit lake 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 ABM Lake volume, and that evaporation increases over time as a function of the lake surface area. Due to complications related to numerical convergence associated with the calculation of storage for the cells representing ABM Lake, lake stages were calculated using the model-calculated groundwater fluxes, the surface water contributions, precipitation and evaporation to determine the volume of water entering the pit each year. This volume was then compared to the stage-volume relationship for mining year 9 to determine the water level in the pit. If discrepancies exist between the model-predicted water level and that of the volume-stage relationship calculation, the modeled lake stage was adjusted. This method ensured that the relationship between the influent groundwater and the lake stage was best simulated for the purposes of predicting the development of ABM Lake.

During ABM Lake formation, a significant portion of the water entering the lake comes from the redirected Fault Creek and snowmelt runoff from the area surrounding the lake. Based on a combination of the stream-gauging data set for Fault Creek, information from Alexco Environmental Group, and the areal extent of the drainage with potential to flow into the lake, the surface water flow into the lake was assumed to be a combined 3,600 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.

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 approximate equilibrium after 50 years, the overall net water balance for the lake includes a simulated positive flow of groundwater into the lake of approximately 1,410 m^3/d, which when combined with precipitation and evaporation, results in a slightly higher rate of surface water flow into the Geona Creek drainage (5,170 m^3/d) relative to the rate at which it enters the lake (3,600 m^3/d).

Table 4.5: ABM Lake Formation and Water Budget (m^3/d)

Year	Direct Precipitation	Watershed Runoff	Net GW Inflow	Evaporation	Geona Creek Streamflow	Lake Stage	Interbasin Flow	Flow North from Lake
Year 1 (first 90 days)	700	3,600	1,520	10	0	1,250	190	0
Year 1	700	3,600	1,680	40	0	1,279	140	0
Year 2	700	3,600	1,720	60	0	1,290	130	0
Year 3	700	3,600	1,720	70	0	1,301	130	0
Year 4	700	3,600	1,720	80	0	1,309	130	0
Year 5	700	3,600	1,700	90	0	1,319	120	0
Year 6	700	3,600	1,680	100	0	1,327	120	0
Year 7	700	3,600	1,660	110	0	1,335	120	0
Year 8	700	3,600	1,640	120	0	1,342	120	0
Year 9	700	3,600	1,620	130	0	1,346	120	0
Year 10	700	3,600	1,610	140	0	1,352	120	0
Year 11	700	3,600	1,570	150	0	1,357	110	0
Year 12	700	3,600	1,520	160	0	1,362	110	0

Year 13	700	3,600	1,480	160	0	1,367	110	0
Year 14	700	3,600	1,350	170	0	1,371	100	20
Year 15	700	3,600	1,310	180	0	1,375	80	90
Year 16	700	3,600	1,240	180	1,560	1,380	30	210
Year 17	700	3,600	1,350	180	3,790	1,380	30	150
Year 20	700	3,600	1,400	180	4,860	1,380	40	150
Year 30	700	3,600	1,410	180	5,170	1,380	40	150
Year 50	700	3,600	1,410	180	5,270	1,380	40	150
Year 100	700	3,600	1,410	180	5,310	1,380	40	150

Notes:

All fluxes are reported in cubic metres per day; Lake stage is reported in metres above mean sea level
Interbasin Flow: Flux crossing the topographic divide between Geona Creek watershed and South Creek watershed. Positive is north.

Flow North from Lake: Flux leaving pit through overburden flowing north. Positive is north.

Assumptions:
493 mm/yr annual precipitation rate
130 mm/yr annual lake evaporation rate

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 at 5 years and 30 years after the end of mining. Figure 4.5.1a shows the simulated water table at 5 years post-mining with the locations of the tailings storage facilities for context. Shallow groundwater flow in the vicinity of the pit is convergent upon the pit. North of the pit groundwater flows toward the center of the channel where it discharges and contributes to the post-mining realignment of Geona Creek.

Figure 4.5.1b shows the water table drawdown associated with the mining activities at 5 years post-mining. At this point, 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 100 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 it will never reach the same hydraulic head as under pre-mining conditions because ABM Lake will prevent hydraulic head from rising above 1,380 m.

Fluxes in Table 4.5 suggest that by 30 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 counterintuitive, the reason is that ABM 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 synthetic liner and cover. Water collection ponds for the Class A and B storage facilities will have also synthetic liners. The Class C facility 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 a hypothetical particle released from the footprint of a 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 100 years post-closure. 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 approximately 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 was finished filling completely. Particles were released from the outer most cells of the

Lake and their progress tracked. 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 of the pit 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 60 to 94 L/s [5,200 to 8,100 m^3/d] 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 weathered bedrock with interconnected fractures, these wells installed to a depth of 100 metres may be sufficient to dewater the weathered bedrock around the pit to minimize seepage face flow.

3. Fault and fracture zones within the pit and underground workings can be expected to produce water at higher rates of discharge. These may require the installation of dewatering wells outside the pit and drilling of horizontal drains to stabilize hydraulic conditions locally. Flow through the fault associated with Fault Creek can be expected to be approximately 1,100 m^3/d based on aquifer testing results and subsequent simulations. Given the nature of fractured bedrock being sometimes unpredictably connected, it is likely that the need for these wells will not become certain 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, but elevated groundwater rates are likely to occur during and following freshet each year. A perimeter interceptor channel excavated around the pit on the eastern and western sides to the top of bedrock would likely remove most surface overland flow associated with snowmelt water before it could reach the pit. Some flow into the pit due to snow melt flow into the alluvium on the north and south sides of the pit is still likely to occur.

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 1,400 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.

Respectfully submitted,
Tetra Tech Inc.

[Signature Redacted]

[Signature Redacted]

Prepared by:
[Name Redacted]
Senior Hydrogeologist
Direct Line: [Phone Number Redacted]
[Email Redacted]

Reviewed by:
[Name Redacted]
Associate Engineer
Direct Line: [Phone Number Redacted]
[Email Redacted]

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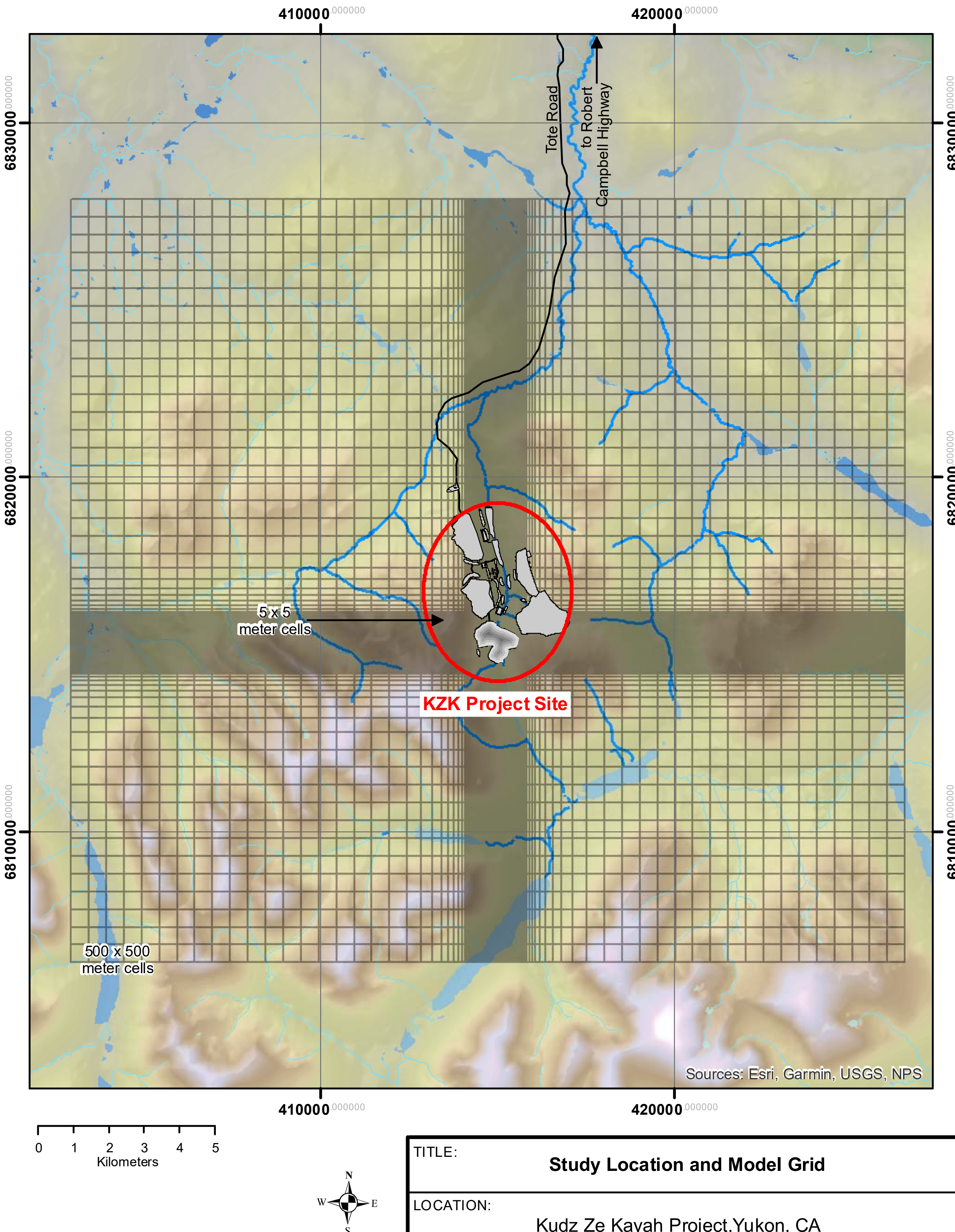
FIGURES

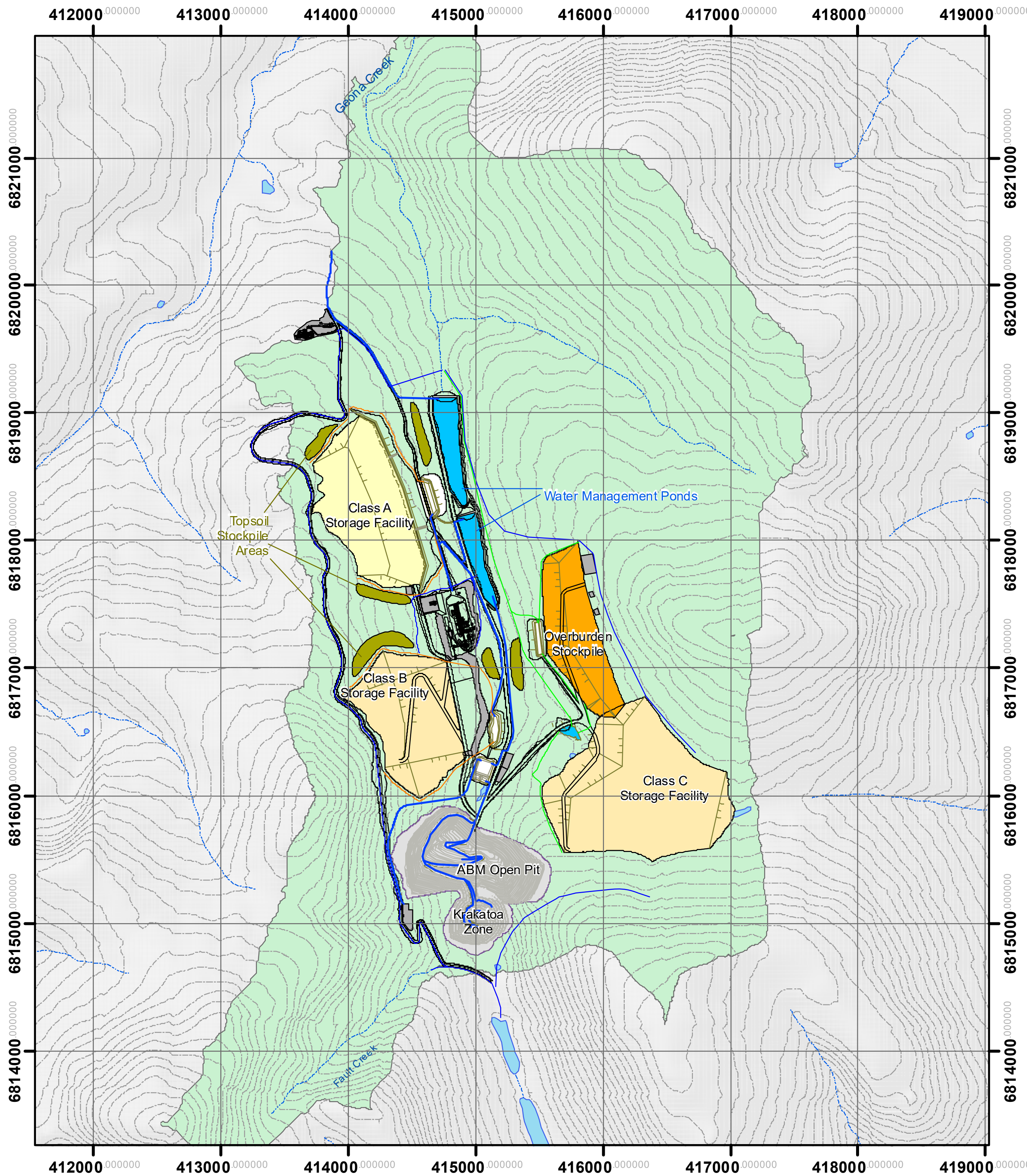


TITLE: **Study Location and Model Grid**

LOCATION: Kudz Ze Kayah Project,Yukon, CA

TETRA TECH

APPROVED	GR	FIGURE
DRAFTED	CKG	1.0
PROJECT#	WENW03070	
DATE	07-30-2018	



0 0.5 1 2 3

Kilometers

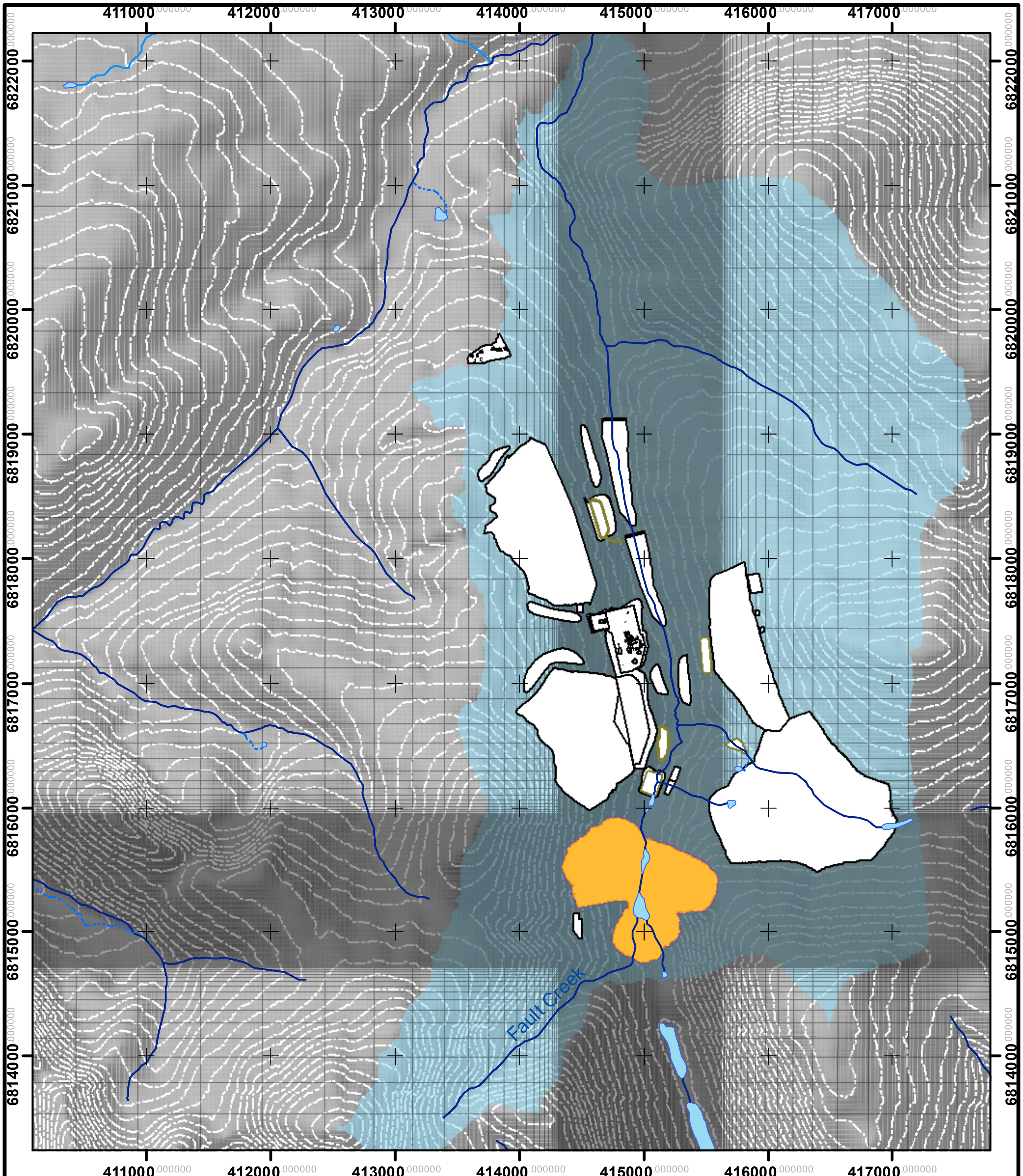
N W E S

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	GR	FIGURE
	DRAFTED	CKG	1.2
	PROJECT#	WENW03070	
	DATE	08-30-2018	



0 0.5 1 2 3
Kilometers

Legend

Composite Pit

Model Grid

Geona Creek Catchment

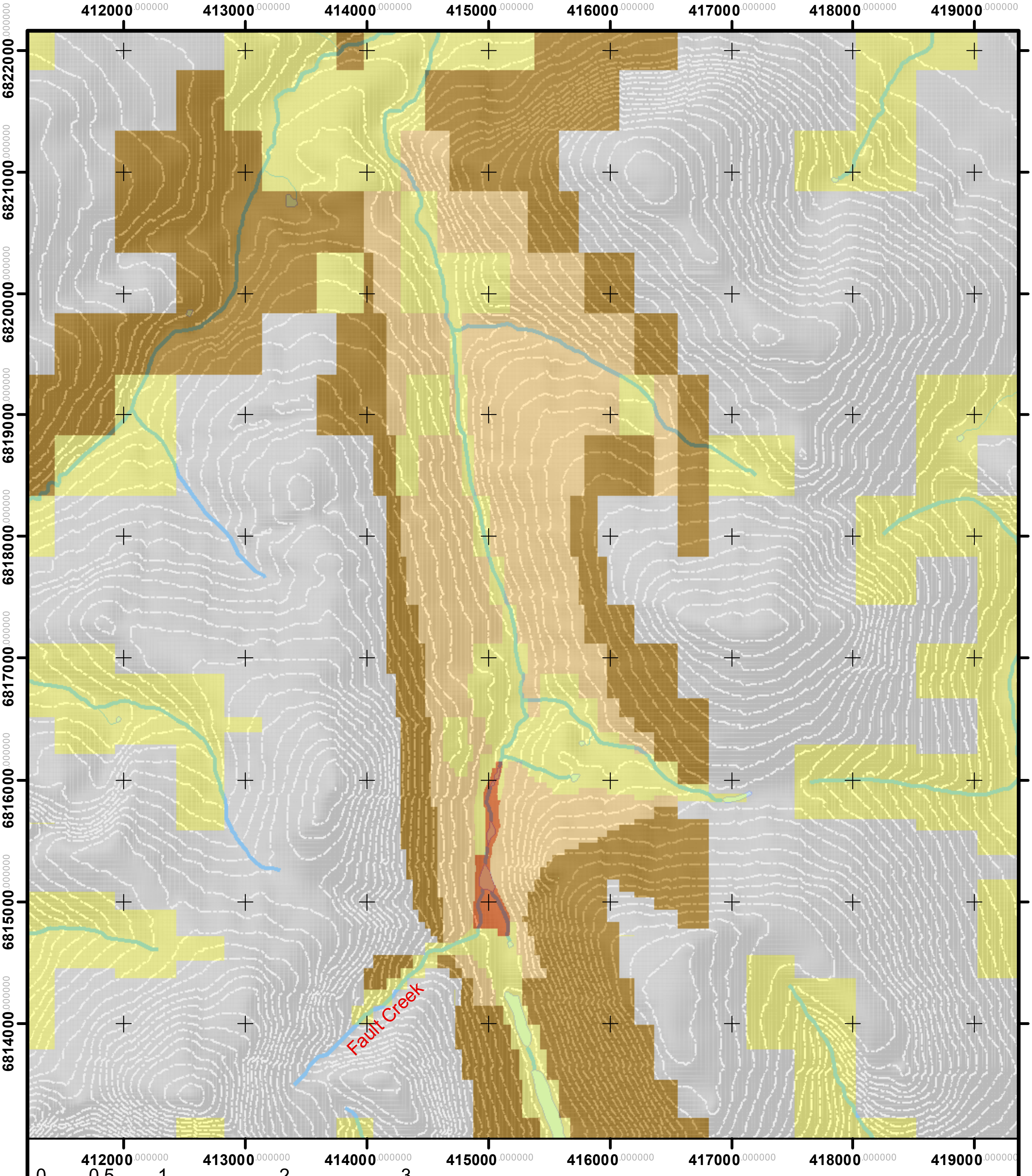
N W E S

TITLE:
Preliminary Mine Plan and Local Model Grid

LOCATION:
Kudz Ze Kayah Project,Yukon, CA

TETRA TECH

APPROVED	GR	FIGURE
DRAFTED	CKG	2.2.1
PROJECT#	WENW03070	
DATE	06-07-18	



Legend

Conductivity Zones

- Glacio-fluvial/Alluvial
- Weathered Bedrock
- Glacial Till
- Silt (local to pit)
- Till Apron

TITLE:

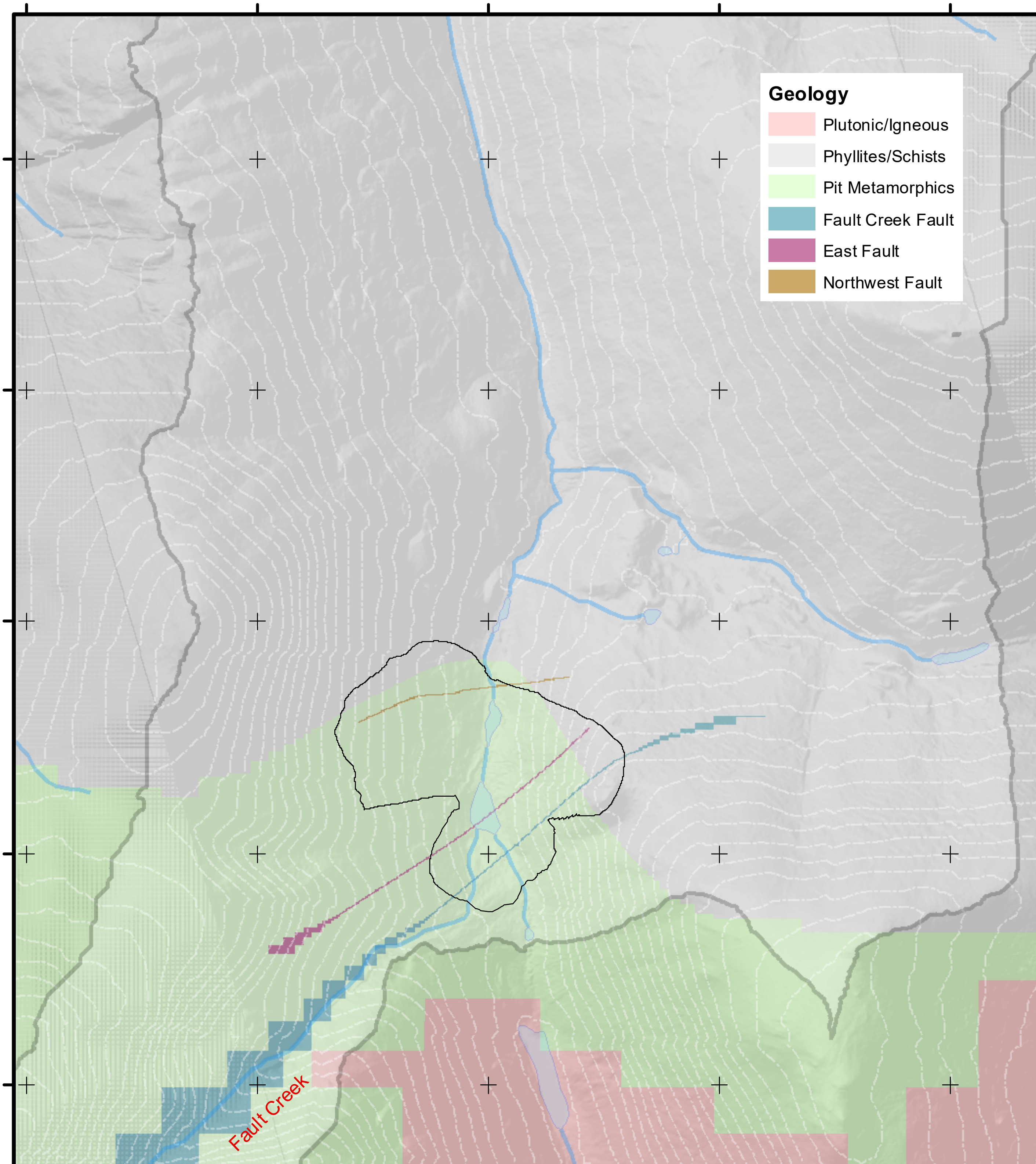
Overburden Hydraulic Conductivity Zonation

LOCATION:

Kudz Ze Kayah Project,Yukon, CA

TETRA TECH

APPROVED	GR	FIGURE
DRAFTED	CKG	2.3.1
PROJECT#	WENW03070	
DATE	06-07-18	



0 0.5 1

Kilometers

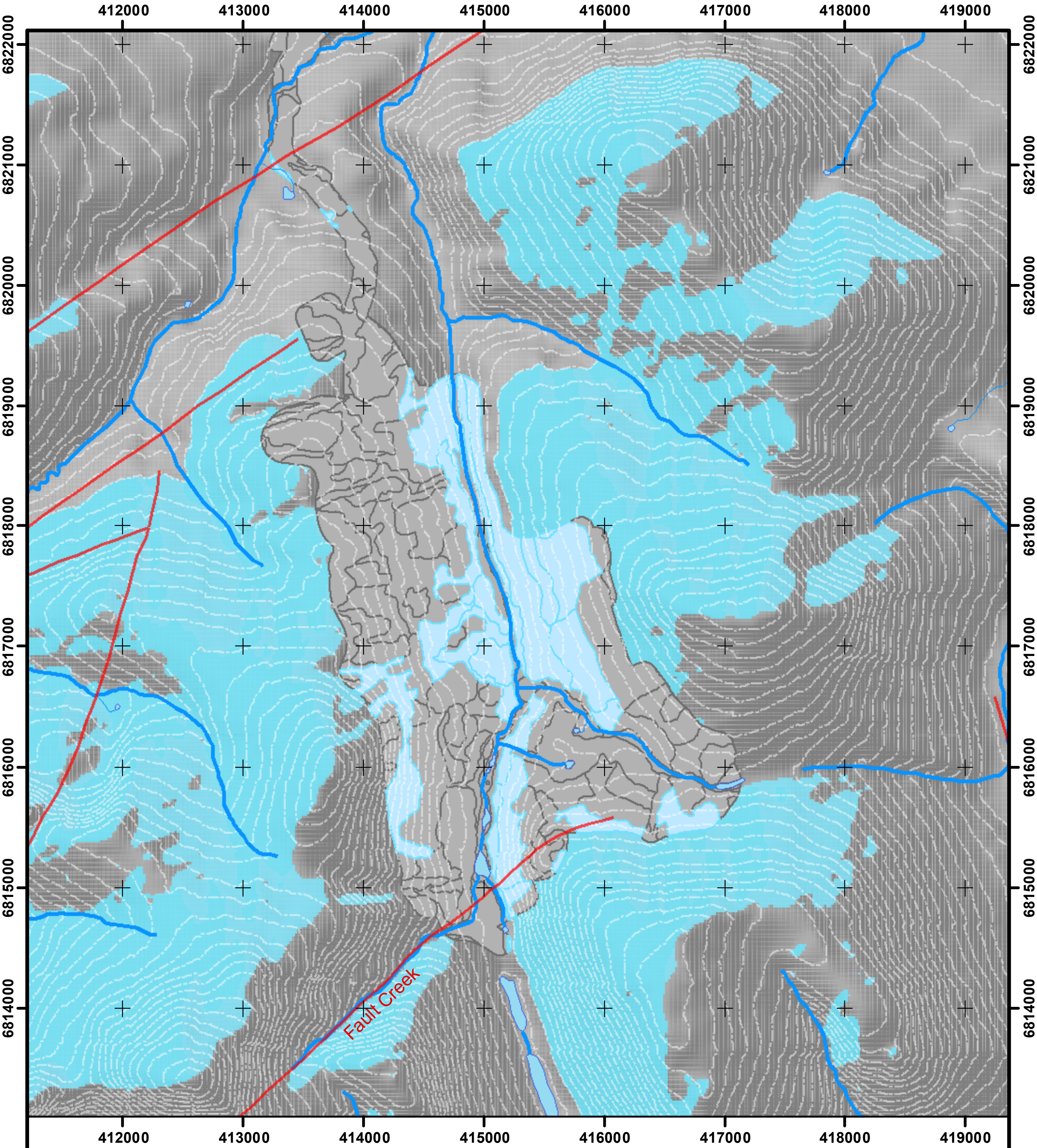
Legend

Pit_outline

Geona Creek Watershed

N W E S

TITLE: **Bedrock Hydraulic Conductivity Zonation (Layer 4)**			
LOCATION: Kudz Ze Kayah Project,Yukon, CA			
TETRA TECH	APPROVED	GR	FIGURE 2.3.2
	DRAFTED	CKG	
	PROJECT#	WENW03070	
	DATE	06-07-18	



0 0.5 1 2 3

Kilometers

Legend

- Faults
- Mapped Permafrost (2017)
- Permafrost free (2017)
- Permafrost (>1,400 m elev., Northern and Western Exposures)

N W E S

TITLE:

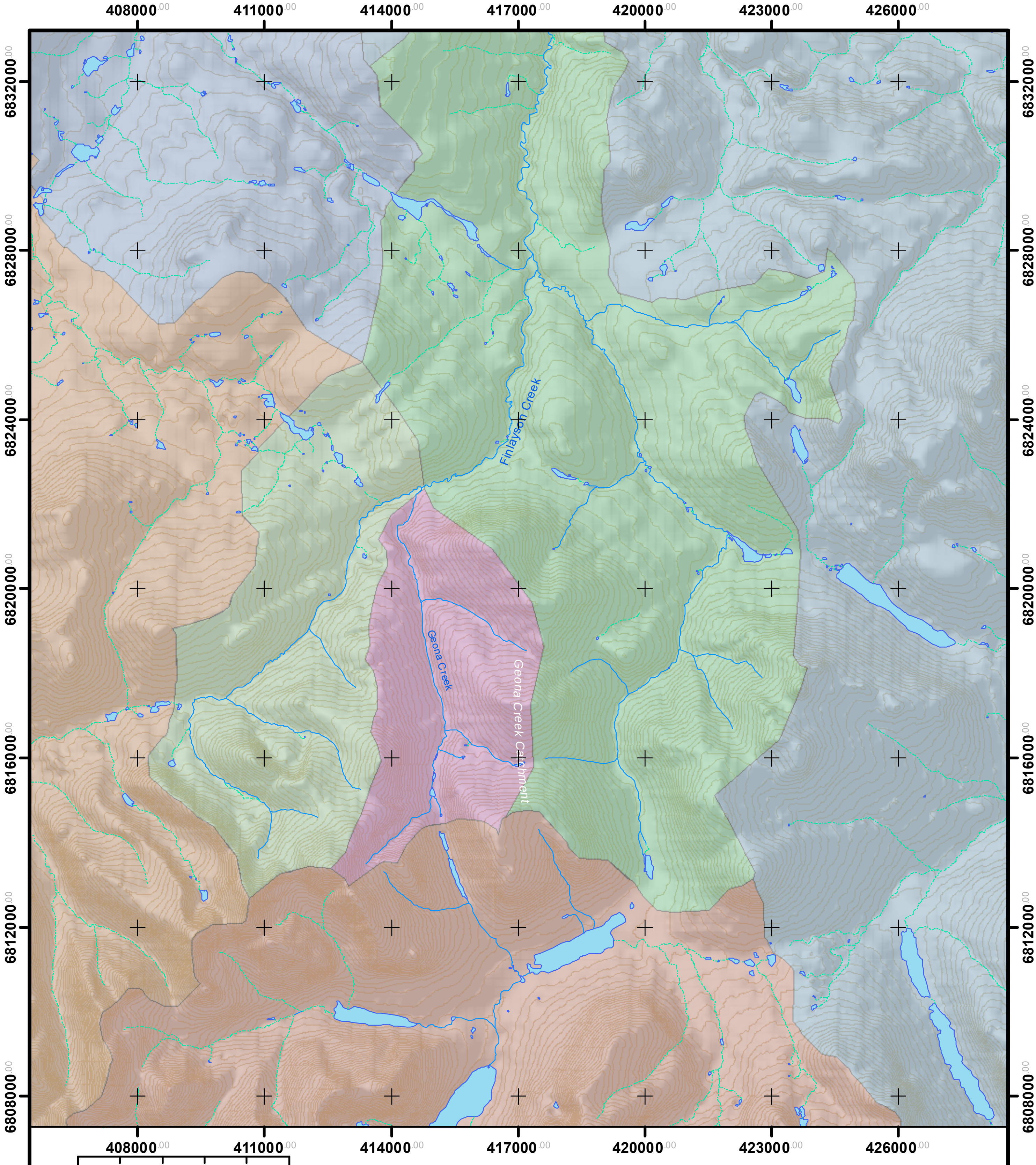
Simulated Permafrost

LOCATION:

Kudz Ze Kayah Project, Yukon, CA

TETRA TECH

APPROVED	GR	FIGURE
DRAFTED	CKG	2.4.5
PROJECT#	WENW03070	
DATE	5-06-18	



0 1 2 3 4 5
Kilometers

N W E S

Legend

- Stream (Close proximity with simulated flow)
- Stream (> 5 Km Distance)
- Watershed Boundaries

TITLE:

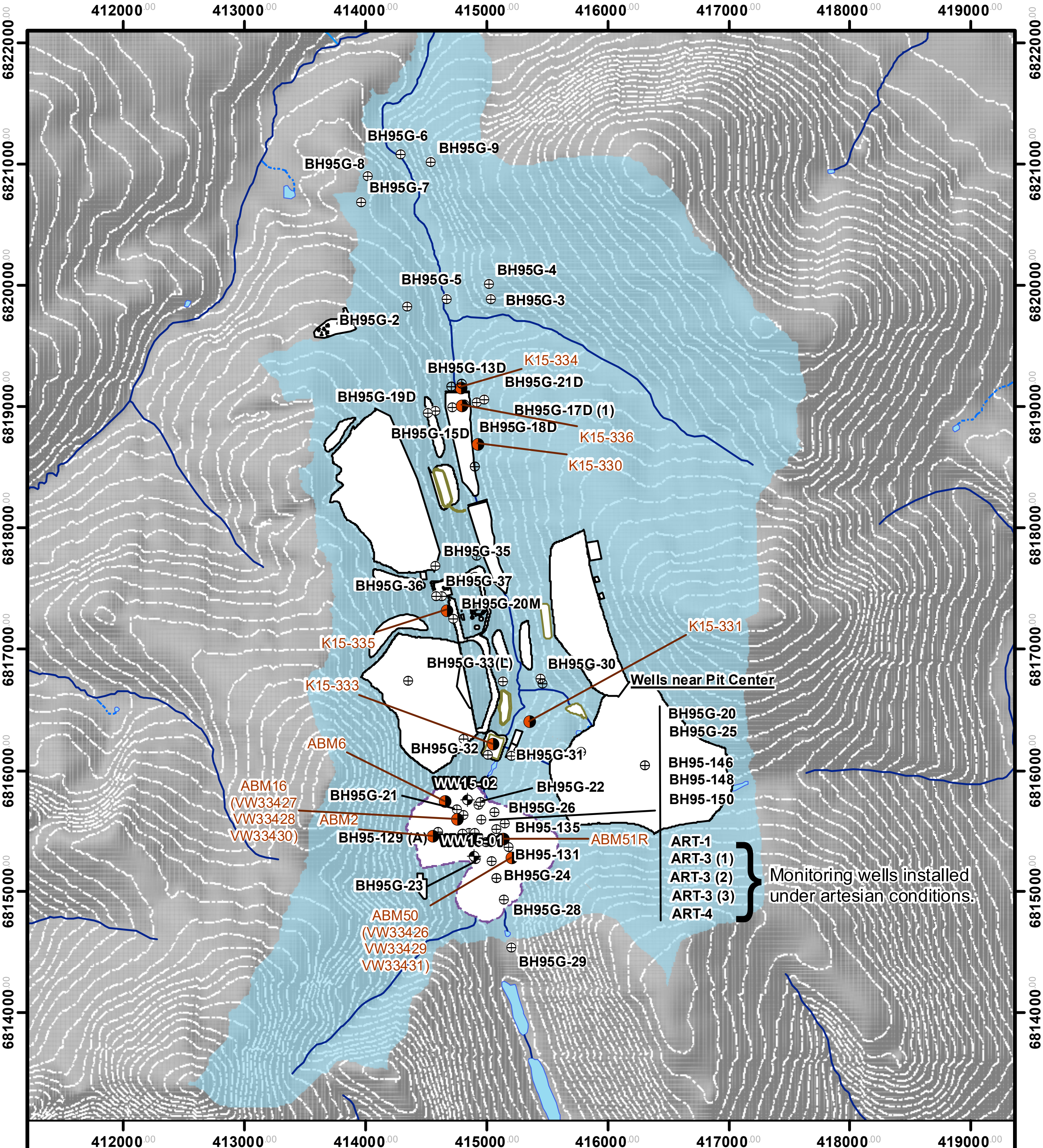
Streams and Surface Water Bodies

LOCATION:

Kudz Ze Kayah Project, Yukon, CA

TETRA TECH

APPROVED	GR	FIGURE
DRAFTED	CKG	2.5
PROJECT#	WENW03070	
DATE	08-30-2018	



0 0.5 1 2 3

Kilometers

Legend

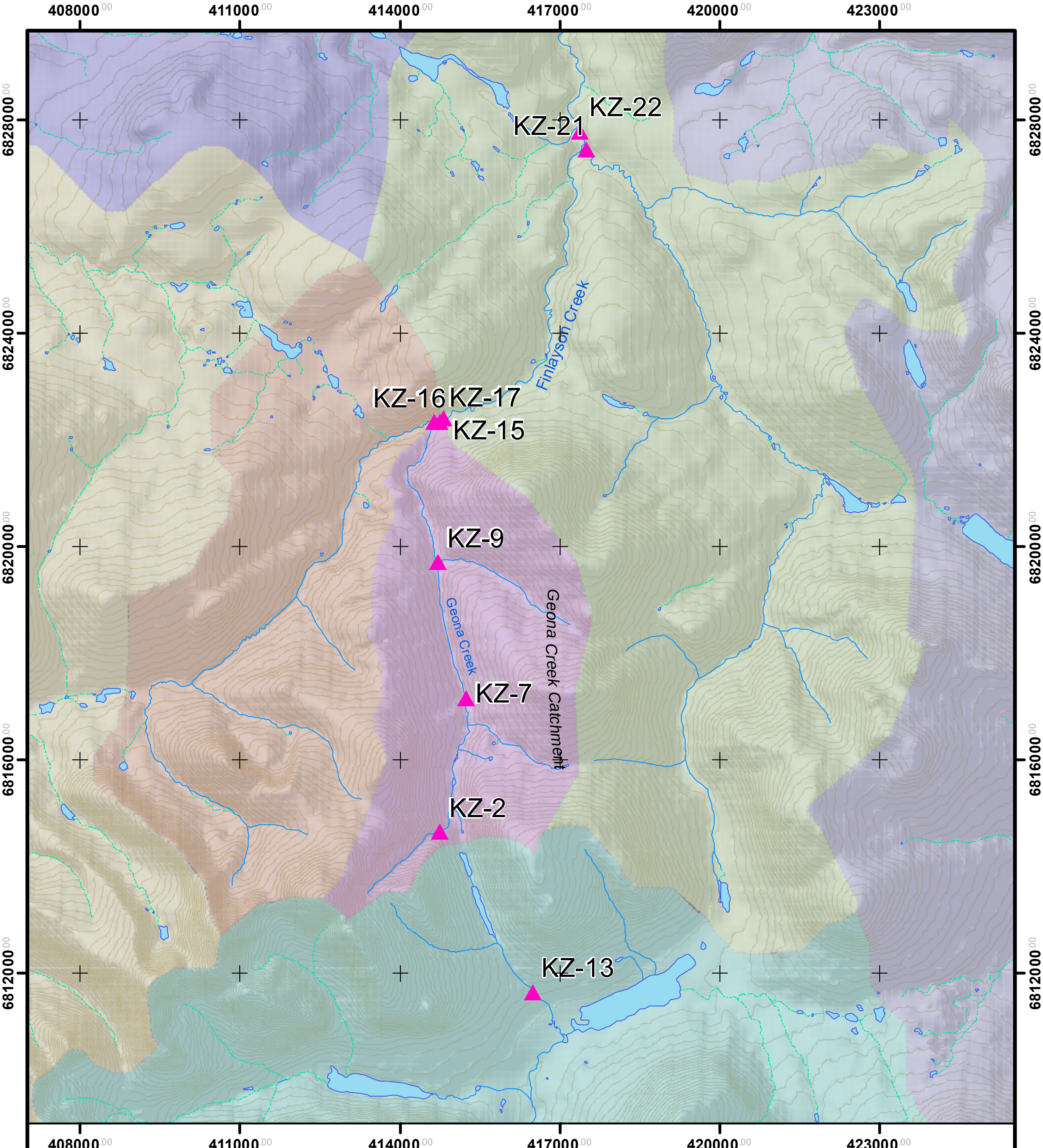
- Packer Test Locations (may have VWPs)
- Pumping Test Wells
- Monitoring Well
- Geona Creek Catchment

N W E S

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

TETRA TECH

APPROVED	GR	FIGURE
DRAFTED	CKG	2.6
PROJECT#	WENW03070	
DATE	09-28-16	



0 1 2 3 4 5
Kilometers

N W E S

Legend

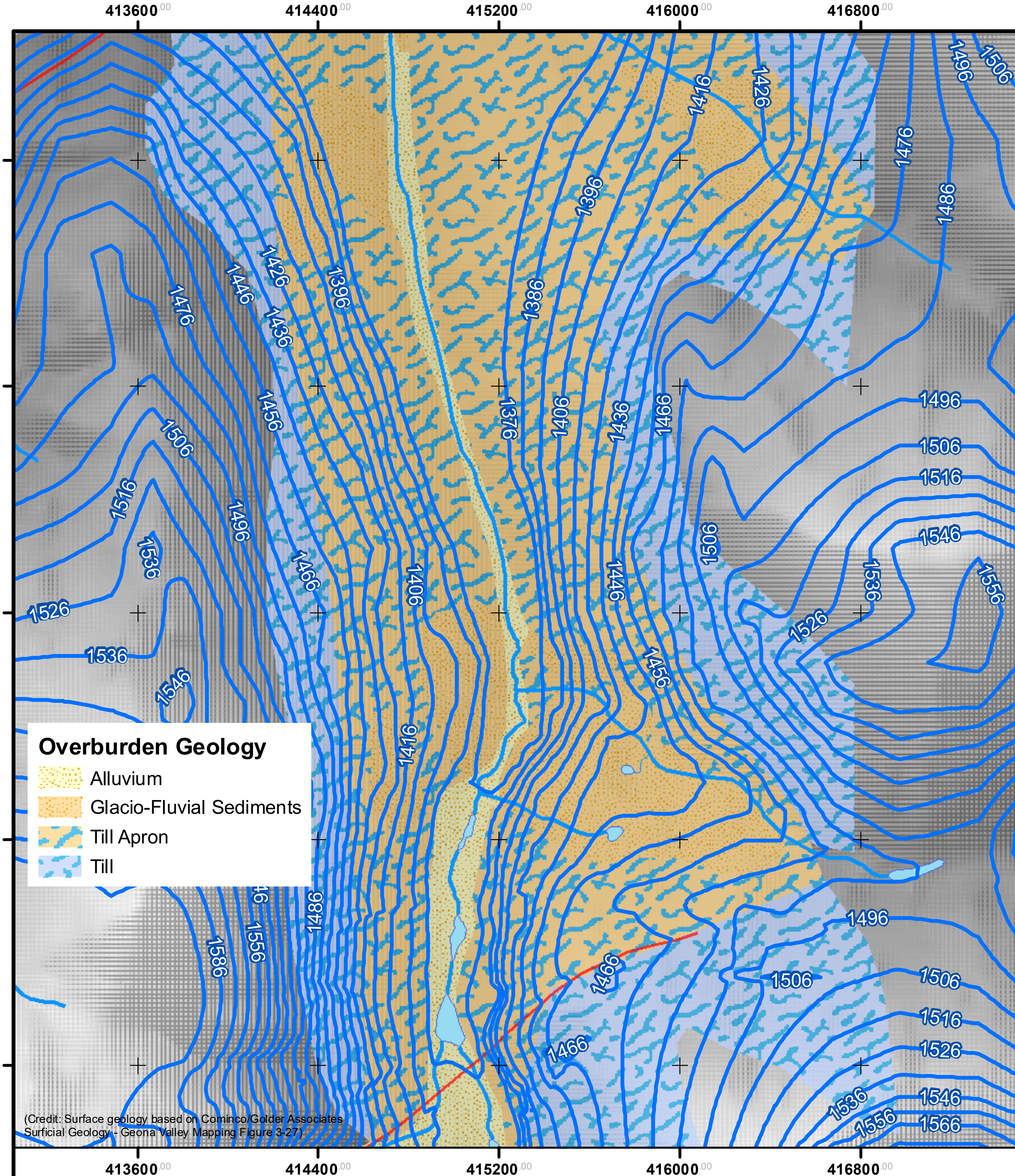
- ▲ Stream Gage
- Stream (Close proximity with simulated flow)
- Stream (> 5 Km Distance)

TITLE:
Streams and Gauging Stations

LOCATION:
Kudz Ze Kayah Project, Yukon, CA

TETRA TECH

APPROVED	GR	FIGURE
DRAFTED	CKG	2.7
PROJECT#	WENW03070	
DATE	08-07-2018	



0 0.5 1

Kilometers

N W E S

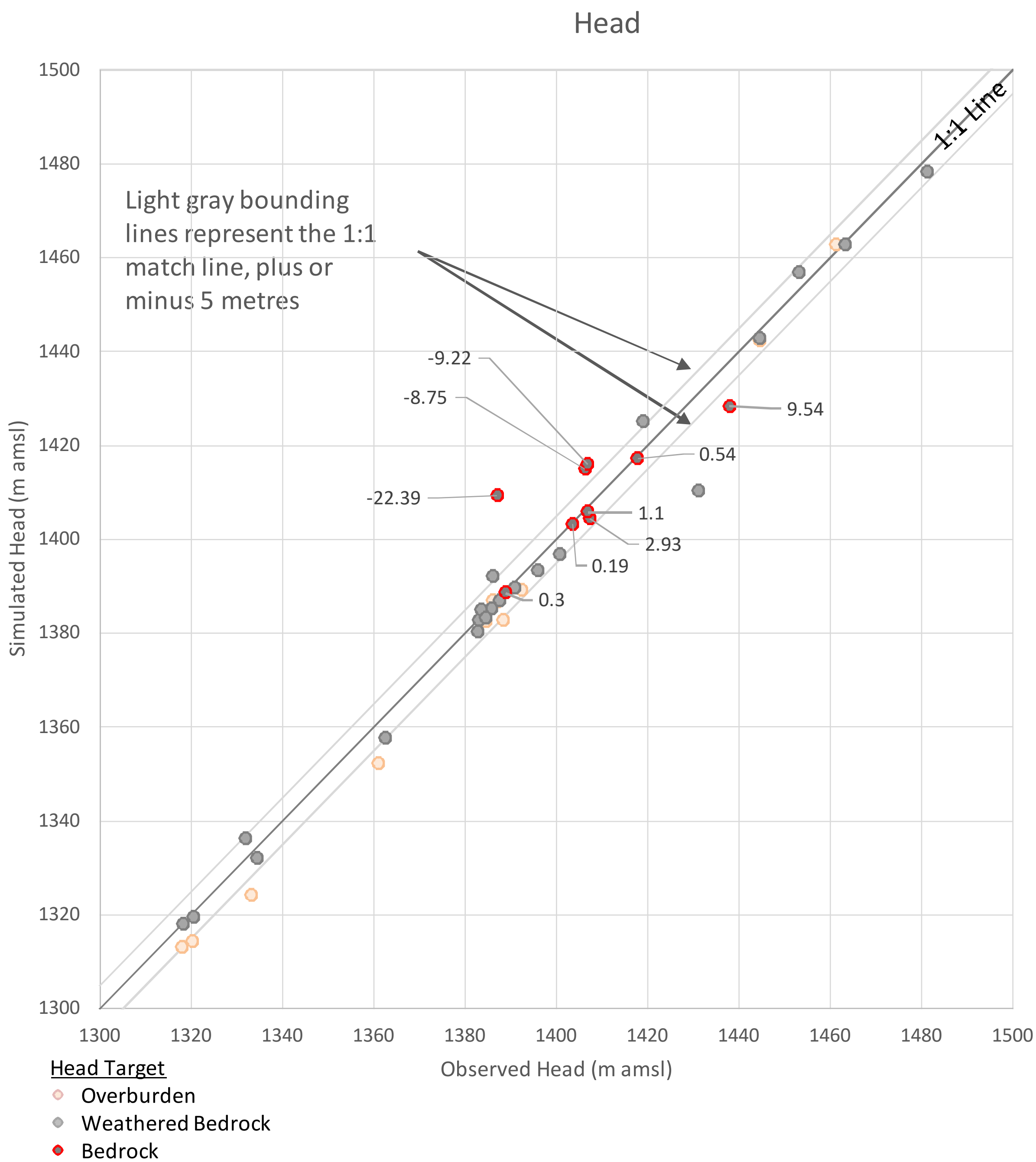
Legend

Pre-Pumping Water-Level Elevation

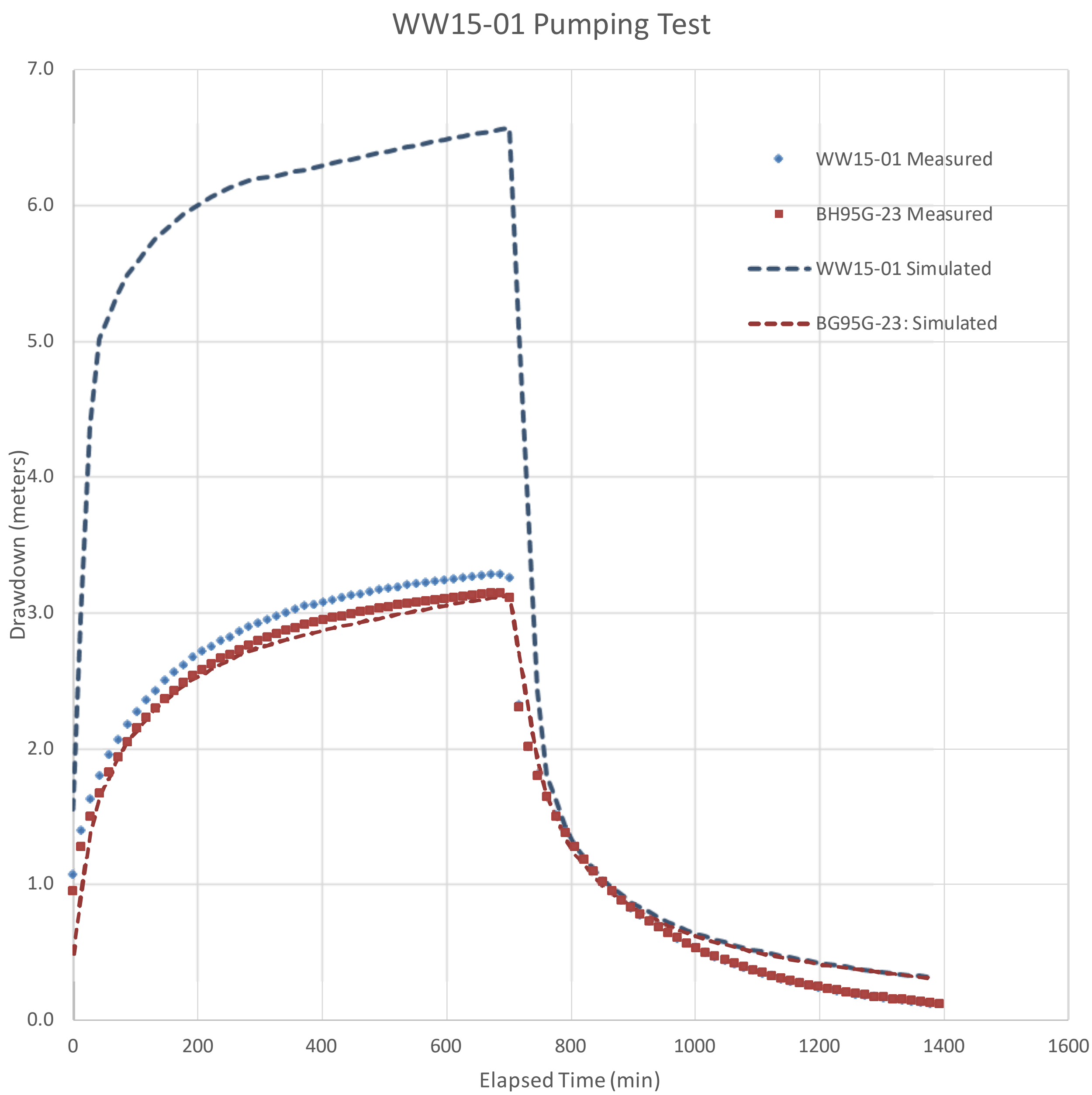
TITLE:	**Water-Table Elevation Contours**
LOCATION:	Kudz Ze Kayah Project, Yukon, CA

TETRA TECH

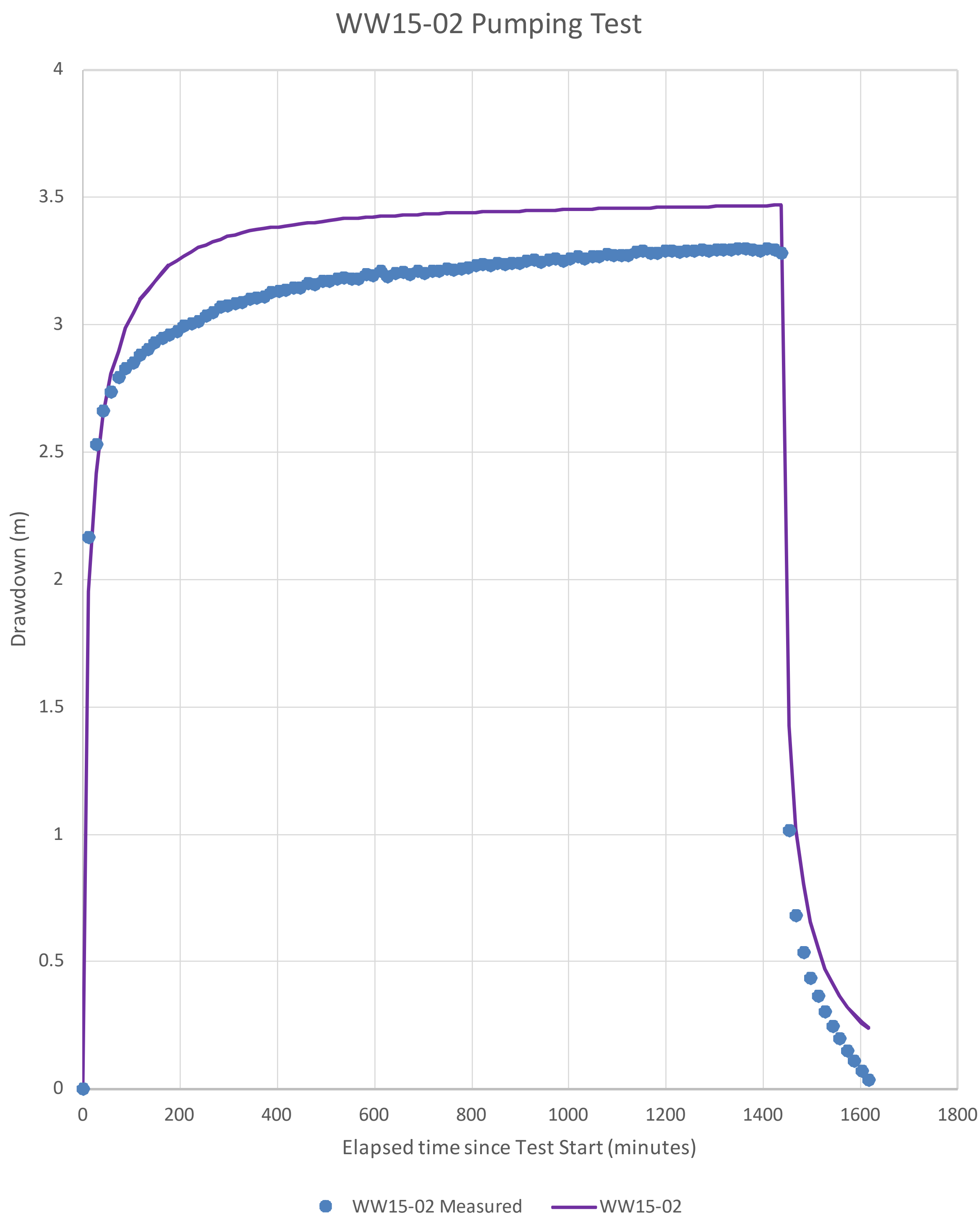
APPROVED	GR	FIGURE
DRAFTED	CKG	3.4.1
PROJECT#	WENW03070	
DATE	07-15-18	



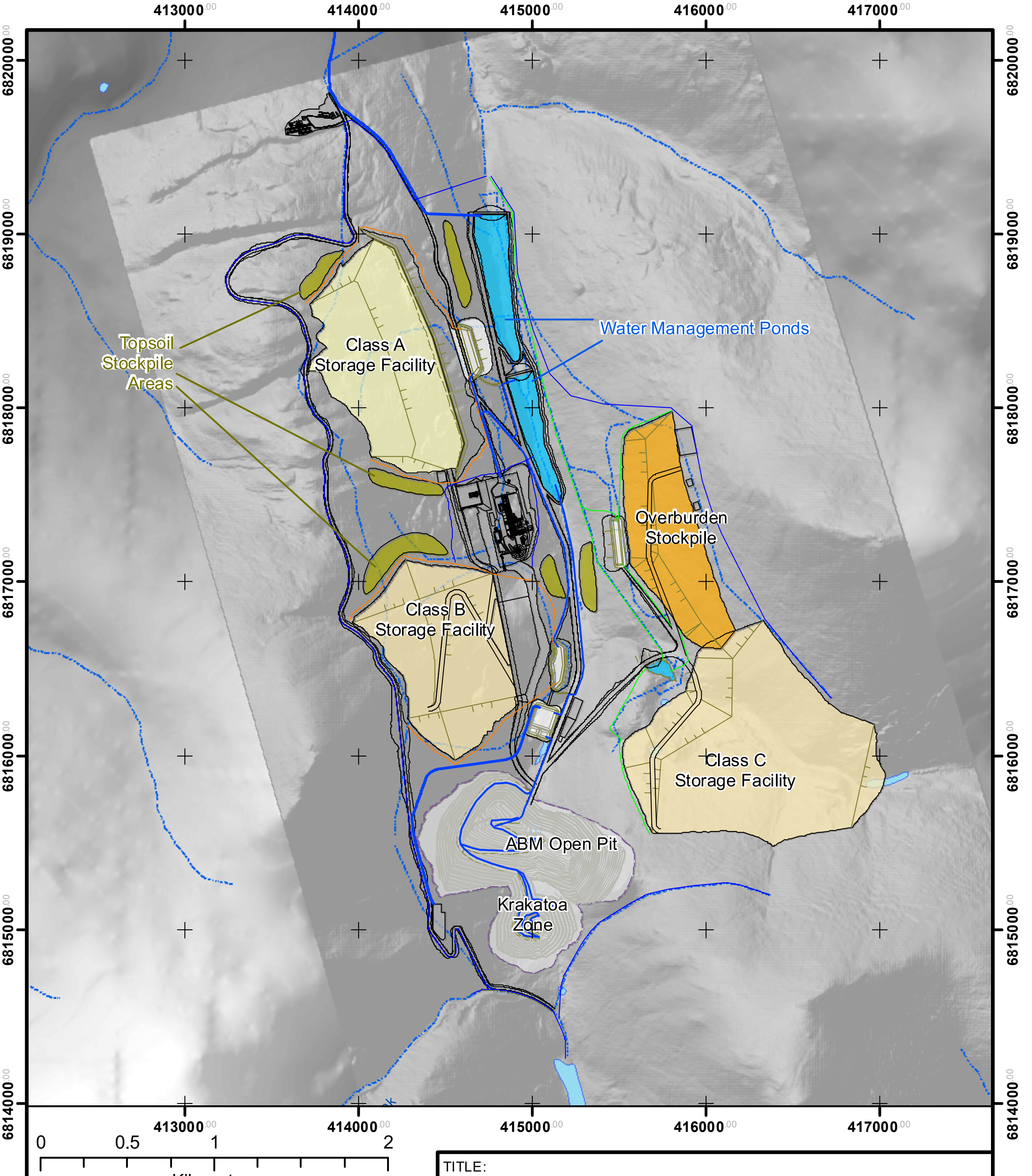
TITLE:	**OBSERVED VS SIMULATED HEAD COMPARISON**		
LOCATION:	**Kudz Ze Kayah Mine, Yukon, Canada**		
TETRA TECH	APPROVED	CG	FIGURE
	DRAFTED	CG	**3.4.2**
	PROJECT #	WENW03070	
	DATE	07-23-2018	



TITLE: **WW15-01 AQUIFER TEST, SIMULATED VS OBSERVED DRAWDOWN**			
LOCATION: **Kudz Ze Kayah Mine, Yukon, Canada**			
TETRA TECH	APPROVED	GR	FIGURE
	DRAFTED	CG	**3.4.3a**
	PROJECT #	WENW03070	
	DATE	08-30-2018	



TITLE:	**WW15-02 AQUIFER TEST, SIMULATED VS OBSERVED DRAWDOWN**			
LOCATION:	**Kudz Ze Kayah Mine, Yukon, Canada**			
TETRA TECH	APPROVED	GR	FIGURE	
	DRAFTED	CG	**3.4.3b**	
	PROJECT #	WENW03070		
	DATE	07-30-2018		



Legend

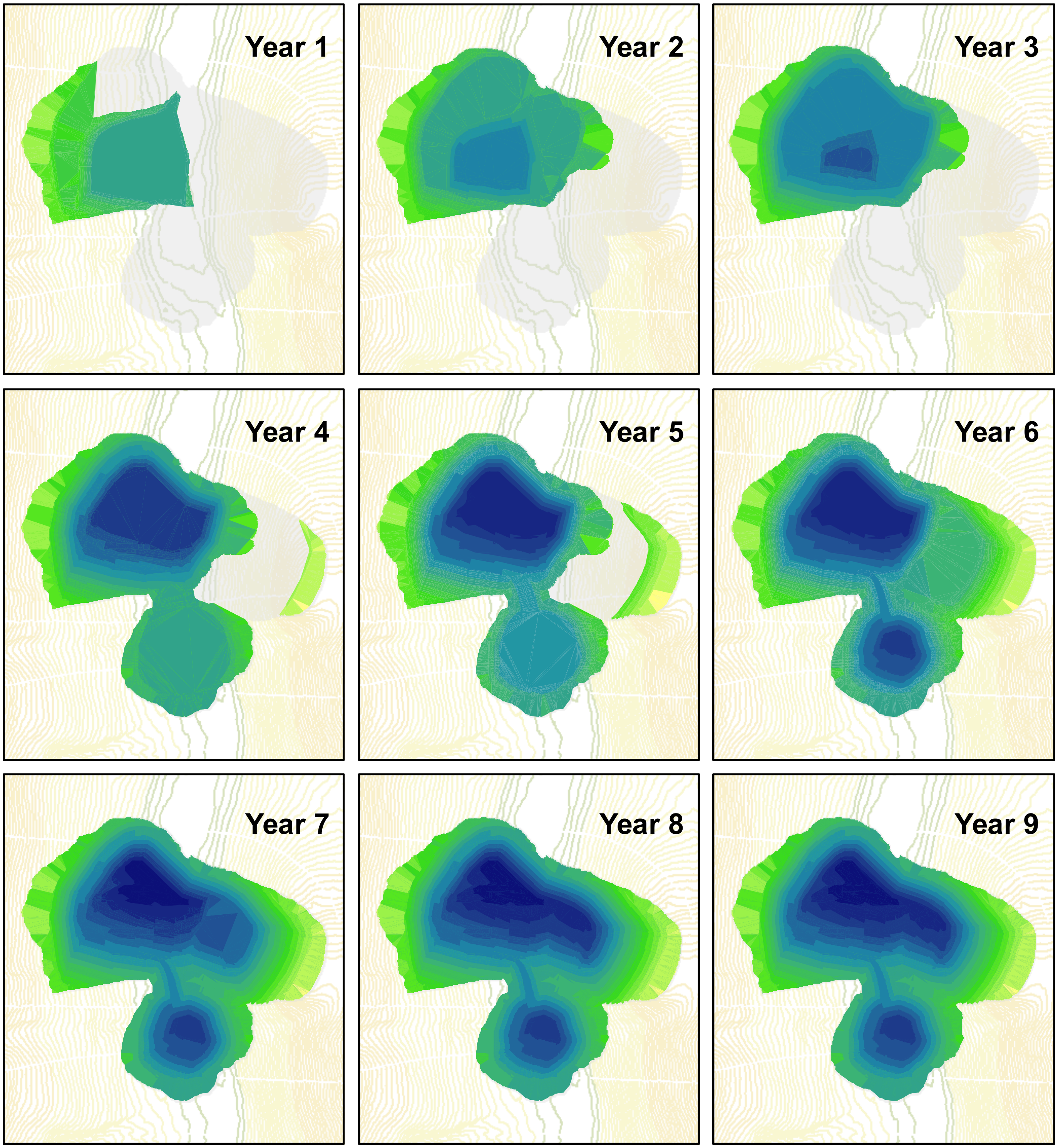
- Streams
- Class A and B Facility Interceptor Canal
- Storage Facility Drainage
- Surface Water Interceptor Ditch

TITLE:
Mine Plan and Ancillary Water Conveyance Features

LOCATION:
Kudz Ze Kayah Project, Yukon, CA

TETRA TECH

APPROVED	GR	FIGURE
DRAFTED	CKG	4.1.1
PROJECT#	WENW03070	
DATE	08-07-2018	

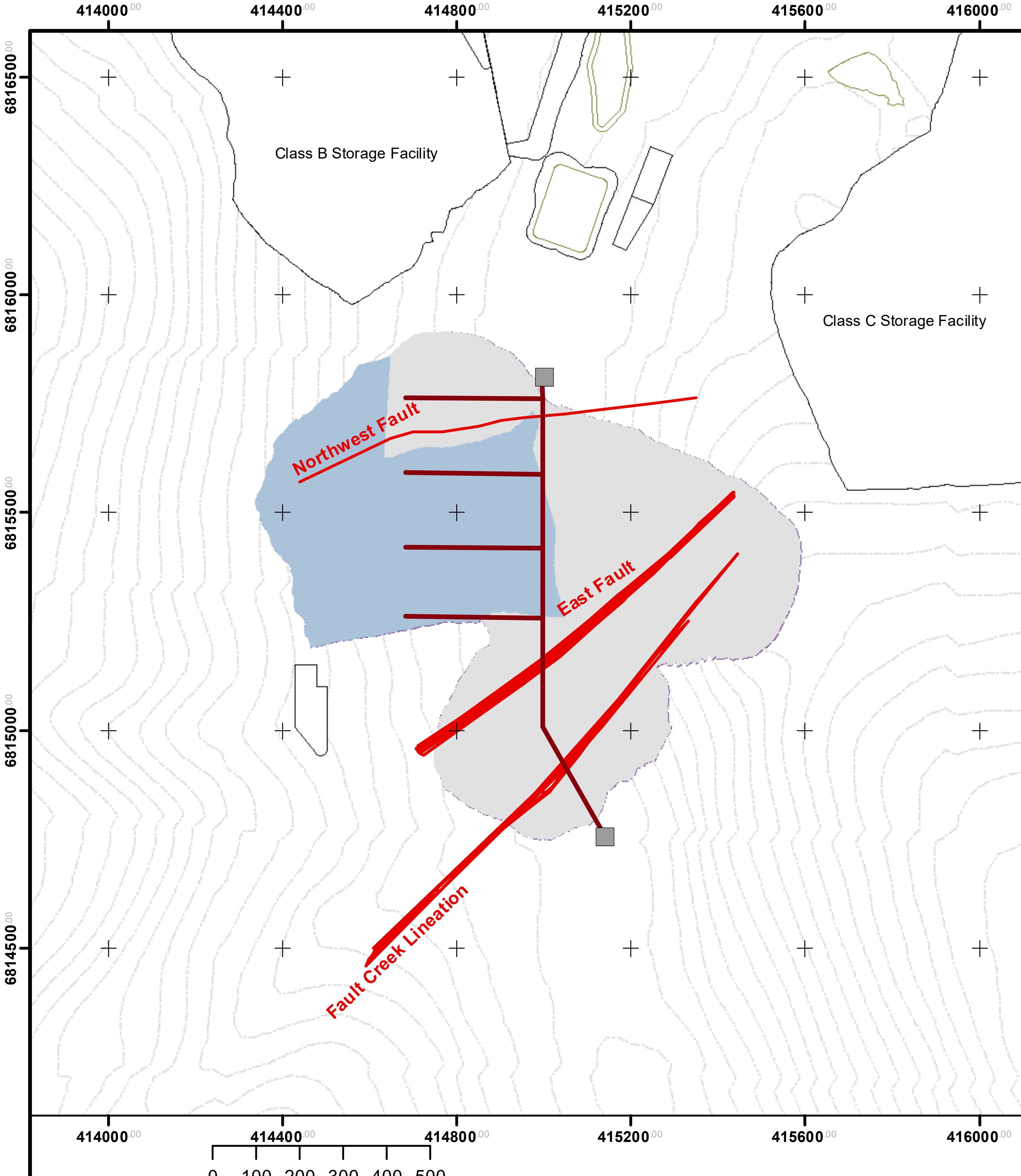


0 0.5 1
Kilometers

N
W E
S

1580 to 1220
Pit Elevation (m)

TITLE:	**Pit Sequence**		
LOCATION:	Kudz Ze Kayah Project, Yukon, CA		
TETRA TECH	APPROVED	GR	FIGURE
	DRAFTED	CKG	4.1.2
	PROJECT#	WENW03070	
	DATE	05-12-2016	

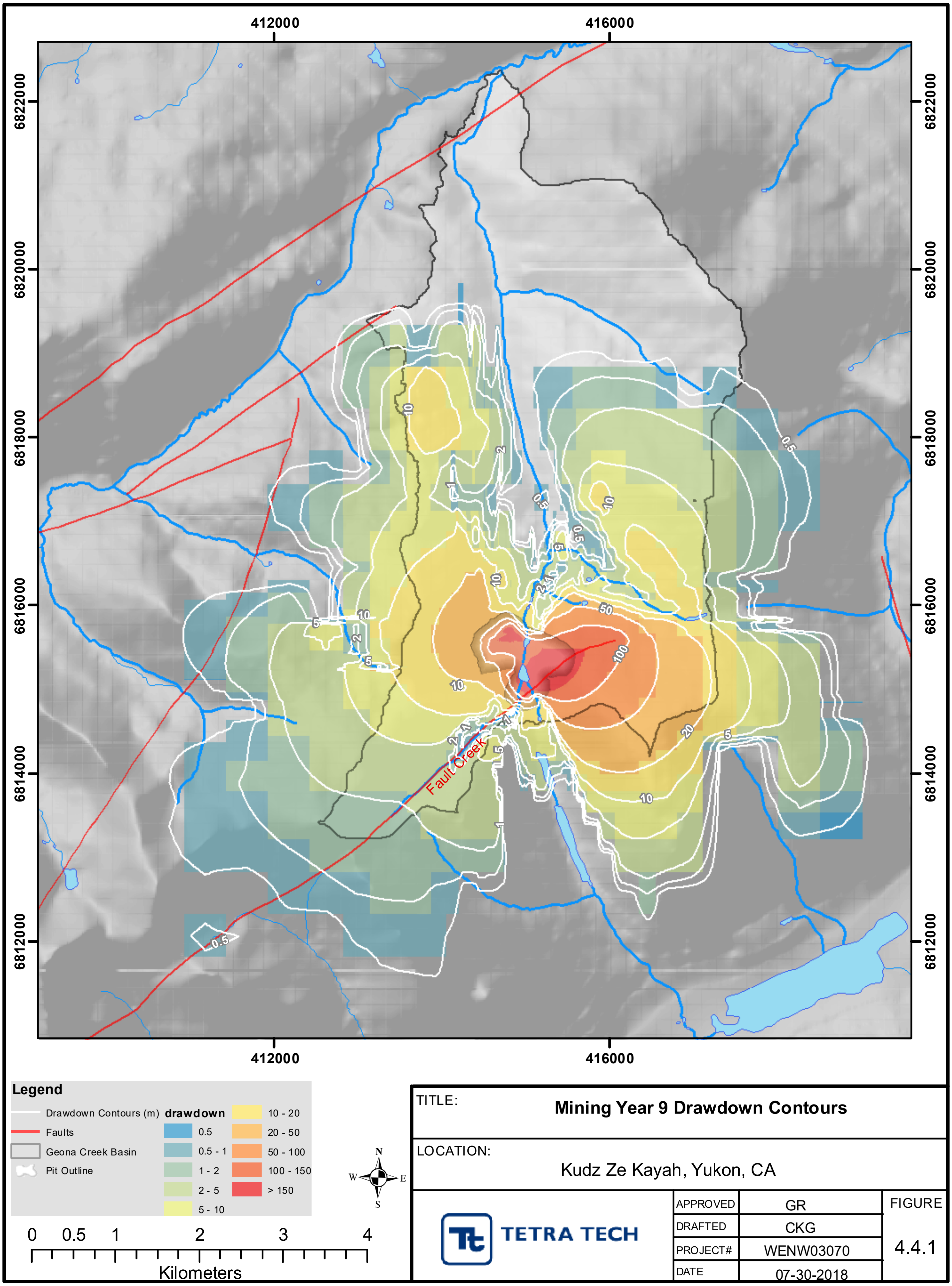


Legend

- Dewatering Trench Sump
- Dewatering Trench Pattern
- Pit Footprint
- Year 1 Pit Extent

N S E W

TITLE:	**Dewatering Trench Location**		
LOCATION:	Kudz Ze Kayah, Yukon, CA		
TETRA TECH	APPROVED	GR	FIGURE
	DRAFTED	CKG	4.2.1
	PROJECT#	WENW03070	
	DATE	06-07-2018	

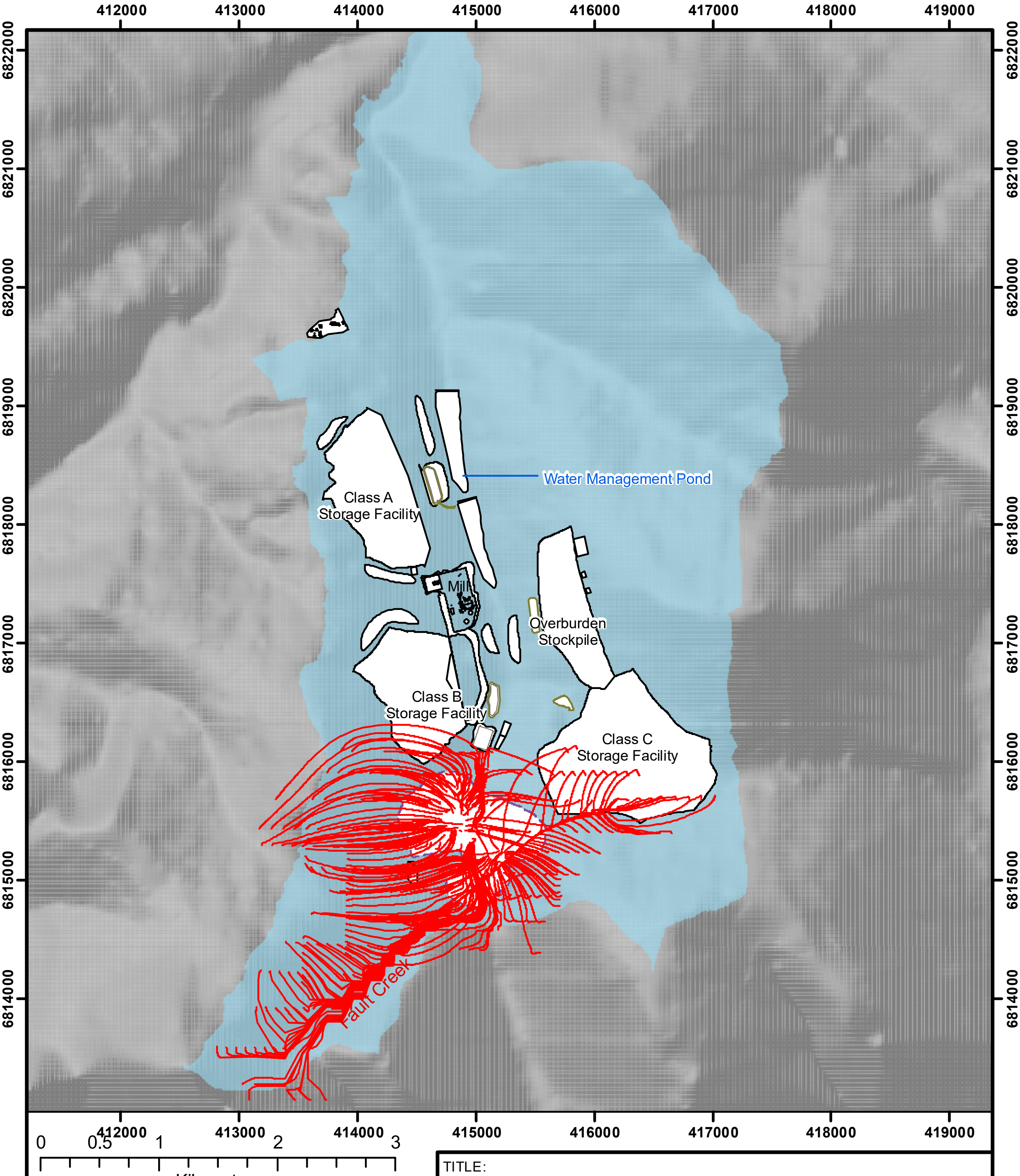


TITLE: **Mining Year 9 Drawdown Contours**

LOCATION: Kudz Ze Kayah, Yukon, CA

TETRA TECH

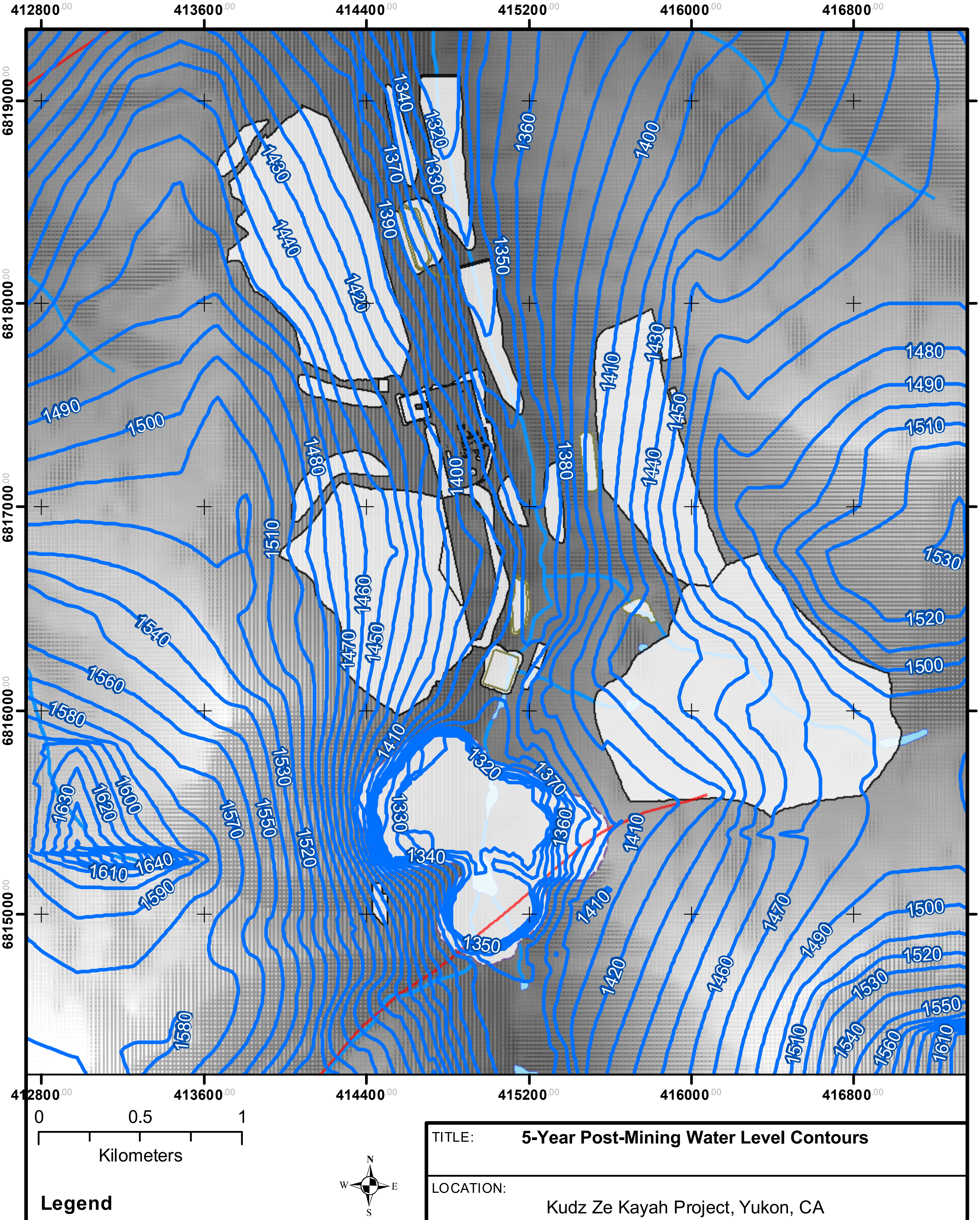
APPROVED	GR	FIGURE	
DRAFTED	CKG		4.4.1
PROJECT#	WENW03070		
DATE	07-30-2018		



Legend

- Influent Particle Pathline
- Geona Creek Catchment

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	07-30-2018	

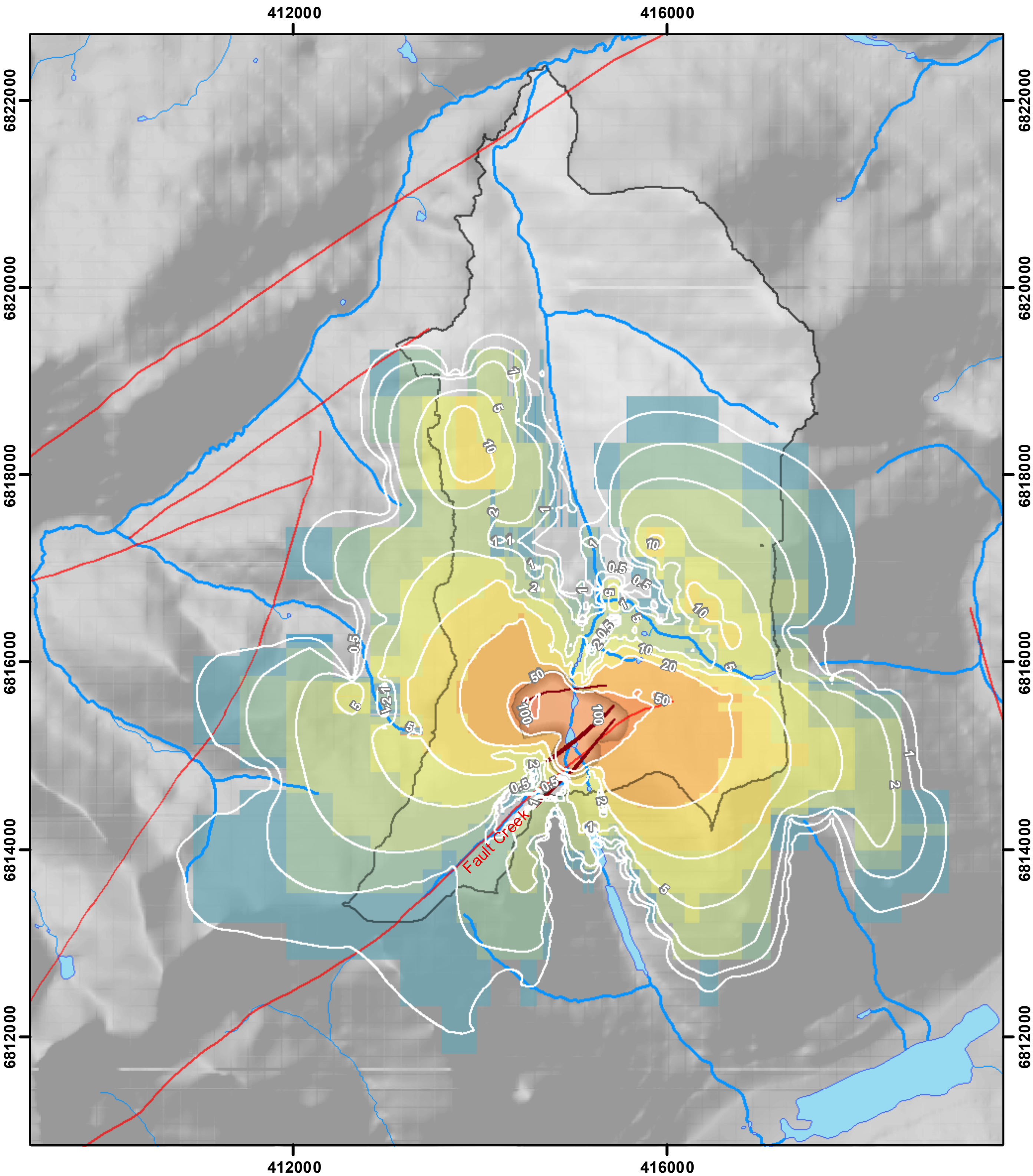


TITLE: **5-Year Post-Mining Water Level Contours**

LOCATION: Kudz Ze Kayah Project, Yukon, CA

TETRA TECH

APPROVED	GR	FIGURE
DRAFTED	CKG	4.5.1a
PROJECT#	WENW03070	
DATE	07-30-2018	



Note: Drawdown reported for water table (upper-most saturated layer)

Legend

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

Drawdown (m)
<0.5
0.6 - 1.0
1.1 - 2.0
2.1 - 5.0
5.1 - 10.0
10.1 - 20.0
20.1 - 50.0
50.1 - 100.0
100.1 - 150.0
150.1 - 200.0

N W E S

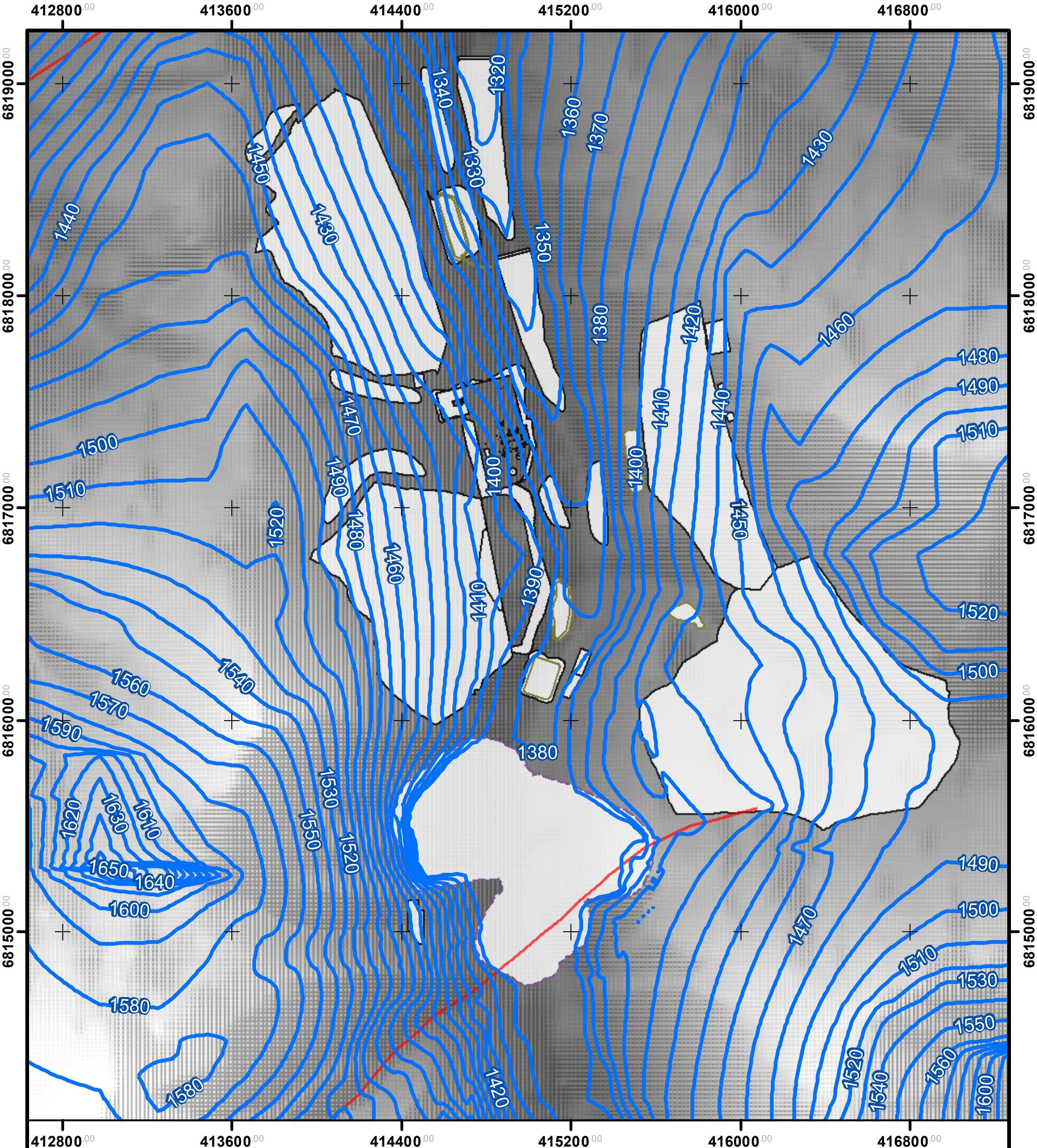
0 0.5 1 2 3 4
Kilometers

TITLE:
5-Year Post-Mining Drawdown Contours

LOCATION:
Kudz Ze Kayah, Yukon, CA

TETRA TECH

APPROVED	GR	FIGURE
DRAFTED	CKG	4.5.1b
PROJECT#	WENW03070	
DATE	07-30-2018	



0 0.5 1

Kilometers

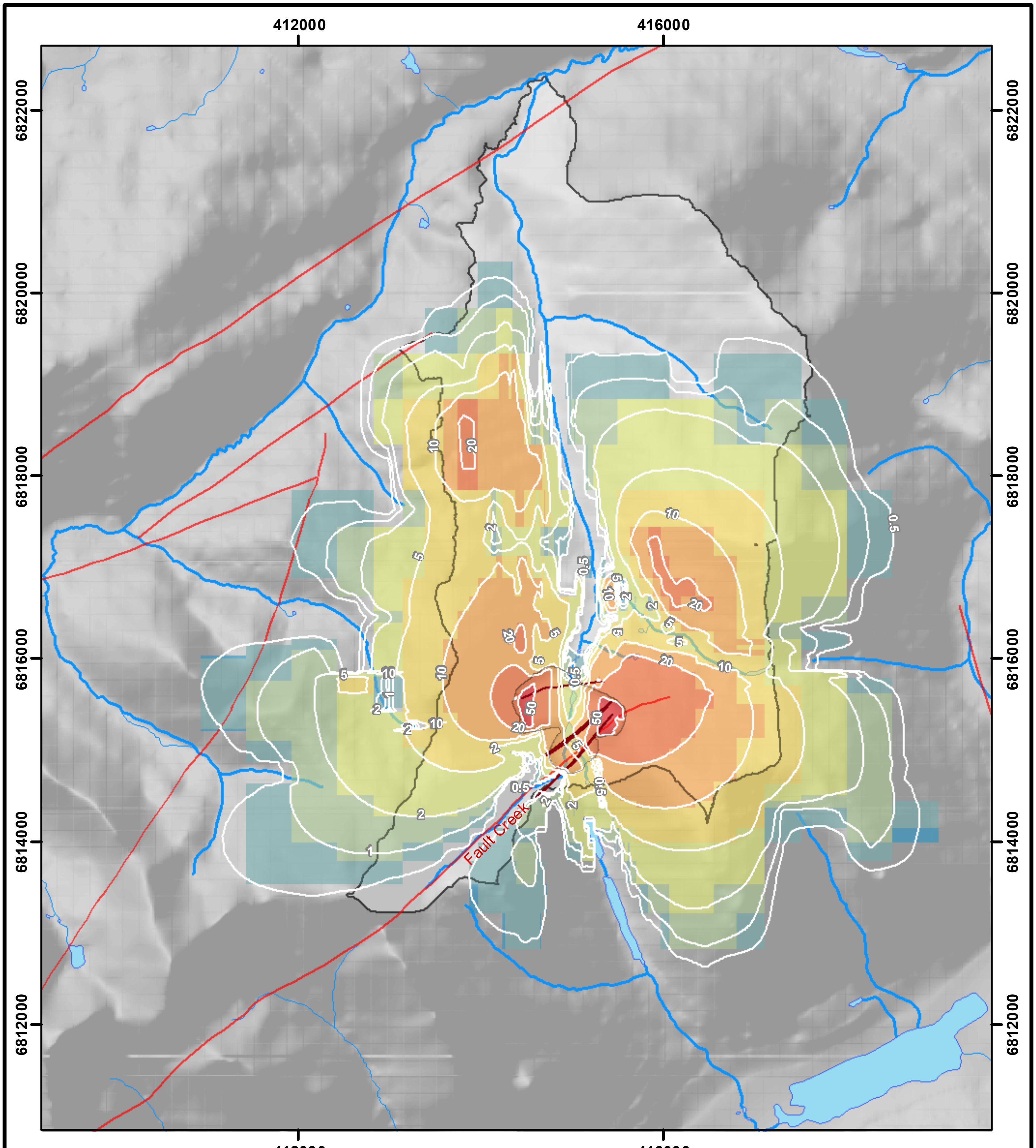
Legend

Water-Level Elevation

TITLE:	**30-Year Post-Mining Water Level Contours**
LOCATION:	Kudz Ze Kayah Project, Yukon, CA

TETRA TECH

APPROVED	GR	FIGURE
DRAFTED	CKG	4.5.1c
PROJECT#	WENW03070	
DATE	04-05-16	



Note: Drawdown reported for water table (upper-most saturated layer)

Legend

Drawdown Contours (m)
Faults
Geona Creek Basin

Drawdown (m)

0.5
0.6 - 1.0
1.1 - 2.0
2.1 - 5.0
5.1 - 10.0
10.1 - 20.0
20.1 - 50.0
50.1 - 100.0
Pit Outline

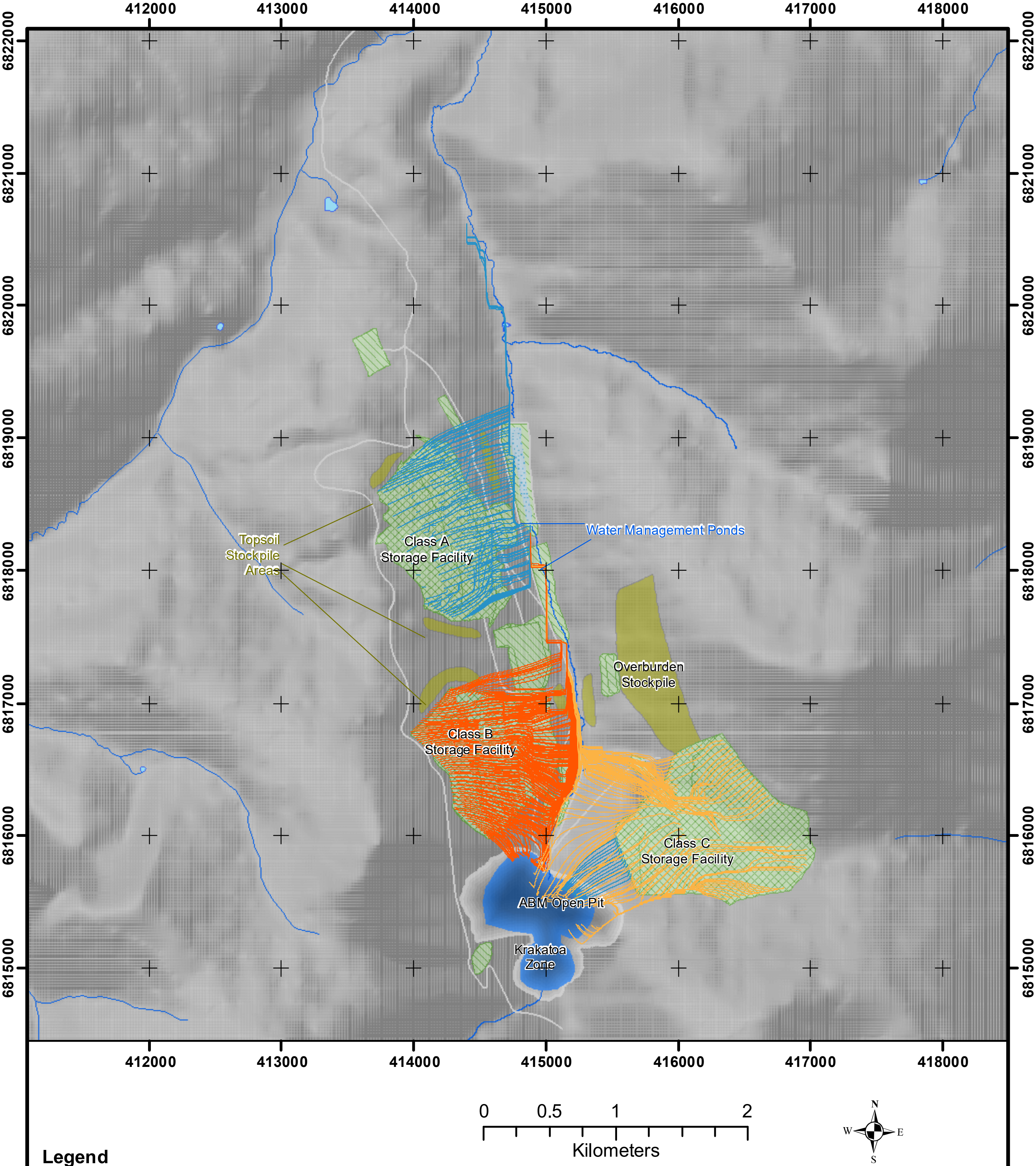
N
W E
S

0 0.5 1 2 3 4
Kilometers

TITLE:	**30-Year Post-Mining Drawdown Contours**
LOCATION:	Kudz Ze Kayah, Yukon, CA

TETRA TECH

APPROVED	GR	FIGURE
DRAFTED	CKG	4.5.1d
PROJECT#	WENW03070	
DATE	07-31-2018	



Legend

Facility

- Class A
- Class B
- Class C

Facilities

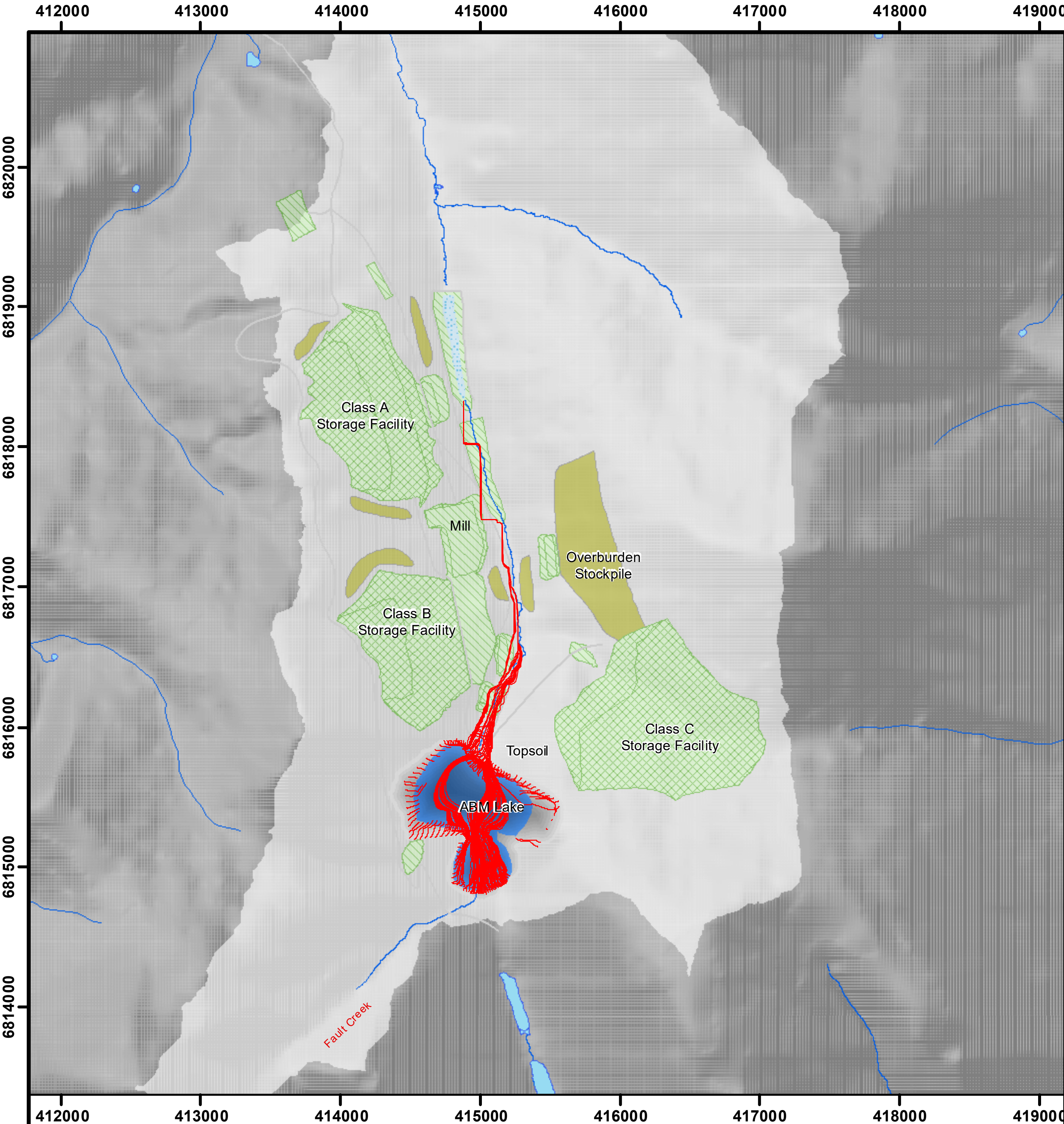
- Constructed Wetland
- Engineered Cover
- Covered with Overburden; Revegetated
- Materials used for Reclamation

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

TITLE:	**Post-Closure Waste Rock Particle Tracking**
LOCATION:	Kudz Ze Kayah, Yukon, CA

TETRA TECH

APPROVED	GR	FIGURE
DRAFTED	CKG	4.5.2
PROJECT#	WENW03070	
DATE	07-31-2018	



Legend

- Particle Tracks
- Roads
- Watercourses
- ABM Lake
- ABM Open Pit

Facilities

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

0 0.5 1 2
Kilometers

N W E S

TITLE:
Pit-Water Particle Tracking Post-Closure

LOCATION:
Kudz Ze Kayah, Yukon, CA

TETRA TECH

APPROVED	GR	FIGURE
DRAFTED	CKG	4.5.3
PROJECT#	WENW03070	
DATE	07-31-2018	

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.

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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.