K3.17 GROUNDWATER HYDROLOGY

This appendix contains additional information regarding baseline studies and technical information at the mine site on the following topics described in Section 3.17, Groundwater Hydrology:

- Groundwater investigation programs
- Aquifers and confining units
- Aquifer properties and hydraulic conductivity
- Groundwater flow systems
- Site water balance model
- Mine site groundwater model

K3.17.1 Groundwater Investigation Programs

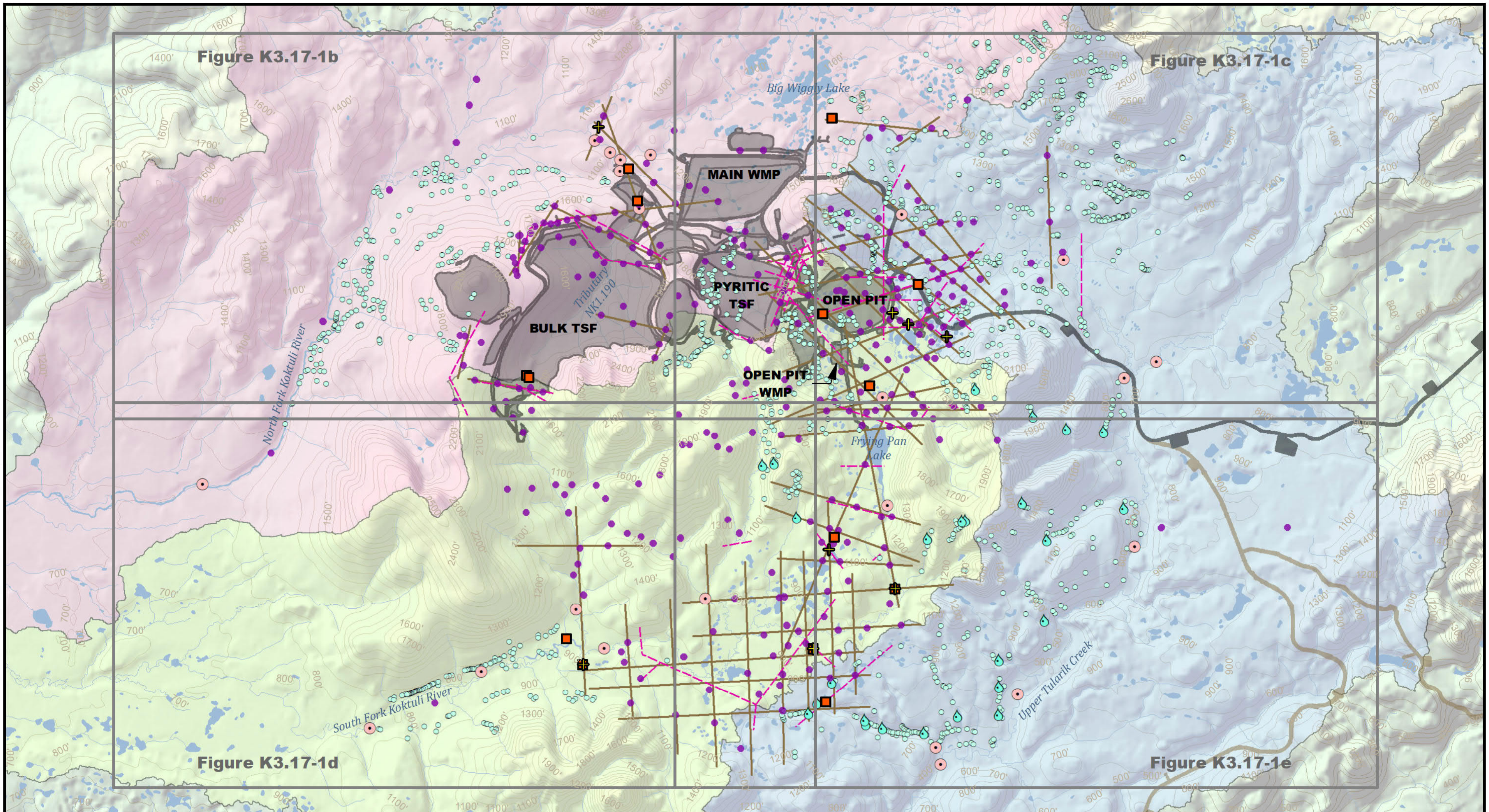
Hydrogeological data were collected during the course of several field programs between 2004 and 2012 (Schlumberger 2011a, 2015a), which involved logging of borings; installation of pumping wells, piezometers, and monitoring wells; permeability testing; streamflow gauging; monitoring of meteoric inputs and routine monitoring of groundwater levels; collection of streamflow and groundwater quality data; and aerial surveys of wintertime open-water leads. An overview and map index showing these data points are provided on Figure K3.17-1a, and detailed locations and identification numbers are shown on Figure K3.17-1b through Figure K3.17-1e. Well depths and completion lithologies are provided in Appendix K3.18, Water and Sediment Quality, Table K3.18-17.

Boreholes were advanced using a variety of drilling techniques, including mud rotary, air rotary Odex, and rotary sonic, with sampling and logging conducted according to standard methods defined by the American Society for Testing and Materials, and consistent with best industry practice.

Instrumentation installed prior to 2008 included the following: 39 nested monitoring wells at 21 locations, 240 nested piezometers at 103 locations, 216 single piezometers, one deep multi-level groundwater instrumentation system, nine cross-hole aquifer test wells at eight locations, and 70 piezometers installed as part of the wetlands program. In 2011, an additional 43 boreholes were drilled in the deposit area for geotechnical purposes, and several response tests were conducted to determine bedrock permeability. In 2012, an additional 18 boreholes were drilled to further investigate hydrogeology.

Piezometers were installed to depths of up to 232 feet below ground surface to collect information on stratigraphy, hydraulic conductivity, and groundwater levels. Vertical groundwater gradients were also characterized where a cluster of piezometers was installed near the same location. Piezometers were also installed as part of the geotechnical characterization program for the purposes of water-level monitoring and permeability testing.

Between 2004 and 2008, nine test-pumping wells with well screens were installed using air rotary drilling techniques, targeting the most permeable features encountered during drilling. In 2012, four additional pumping wells were installed using sonic drilling techniques to understand the requirements for pit dewatering. Three of these wells have not yet been tested, and one (GH12-334S) was tested in 2013 and used as a calibration target for the groundwater flow model.



Sources: PLP 2019-RFI153; Schlumberger 2011a, Figures 8.1-4 and 9.1-5

US Army Corps of Engineers

1 0 1 2
Miles

Location Type
- Pumping Well
- Monitoring Well
- Piezometer
- Stream Gaging Station
- Seep Sampling Location
- Seep Location

- 2004-2010 Seismic Line
- Cross Section Line

Watershed
- North Fork Koktuli River
- South Fork Koktuli River
- Upper Talarik Creek

Action Alternatives
- Alternative 1a
- Alternative 1

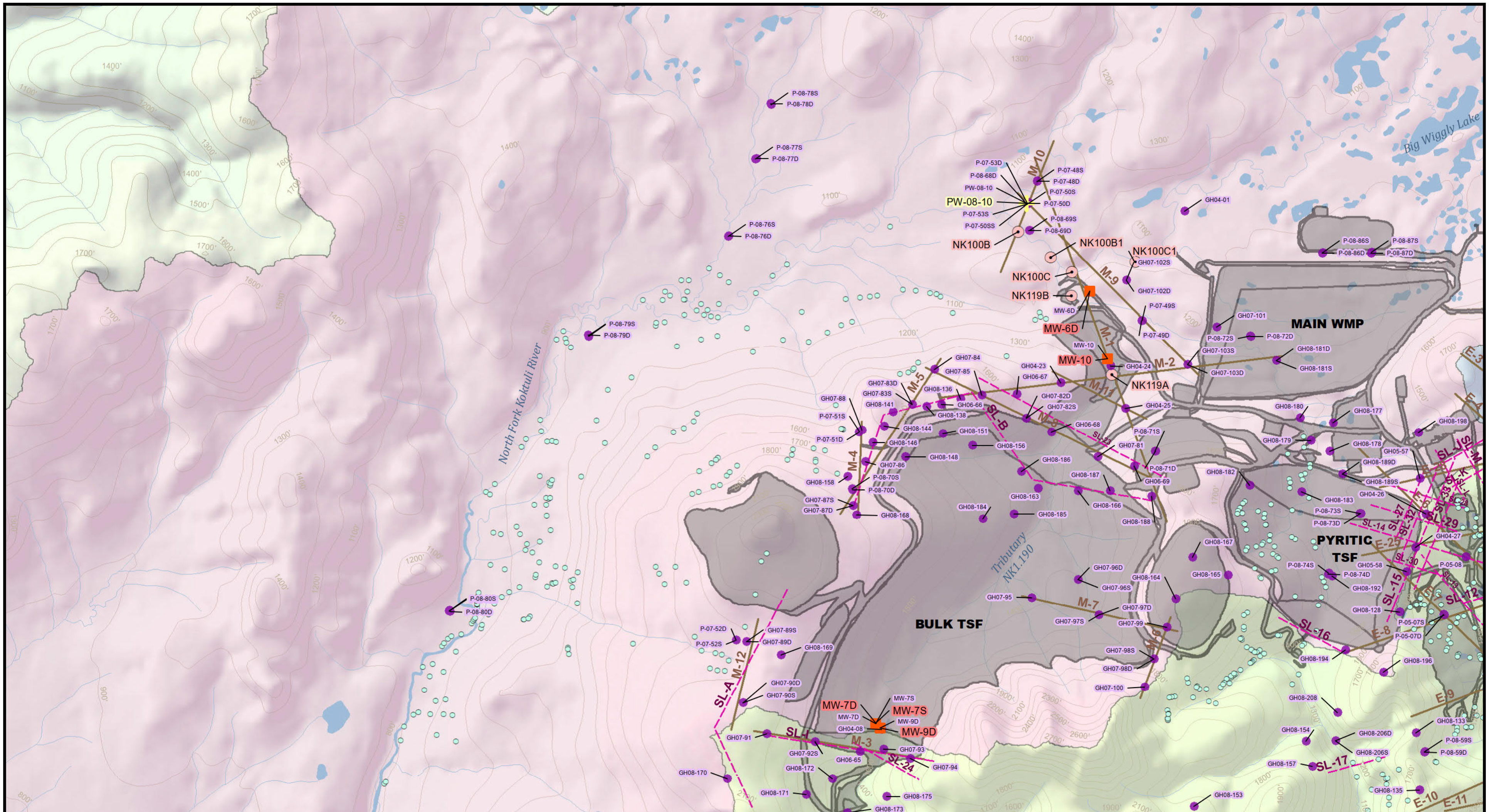
Other Features
- River/Stream
- Lake/Pond
- 100' Contour (Existing)

Note: Well depths and completions are provided in Table K3.18-17.

PEBBLE PROJECT EIS

WELL, PIEZOMETER, AND SEEP LOCATIONS - MAP INDEX

FIGURE K3.17-1a



Sources: AECOM 2019-RFI153;
Schlumberger 2011a, Figures 8.1-4 and 9.1-5

US Army Corps of Engineers

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Miles

Location Type
- Pumping Well
- Monitoring Well
- Piezometer
- Stream Gaging Station
- Seep Sampling Location
- Seep Location

- 2004-2010 Seismic Line
- Cross Section Line

Watershed
- North Fork Koktuli River
- South Fork Koktuli River
- Upper Talarik Creek

Action Alternatives
- Natural Gas Pipelines
- Alternative 1a
- Alternative 1

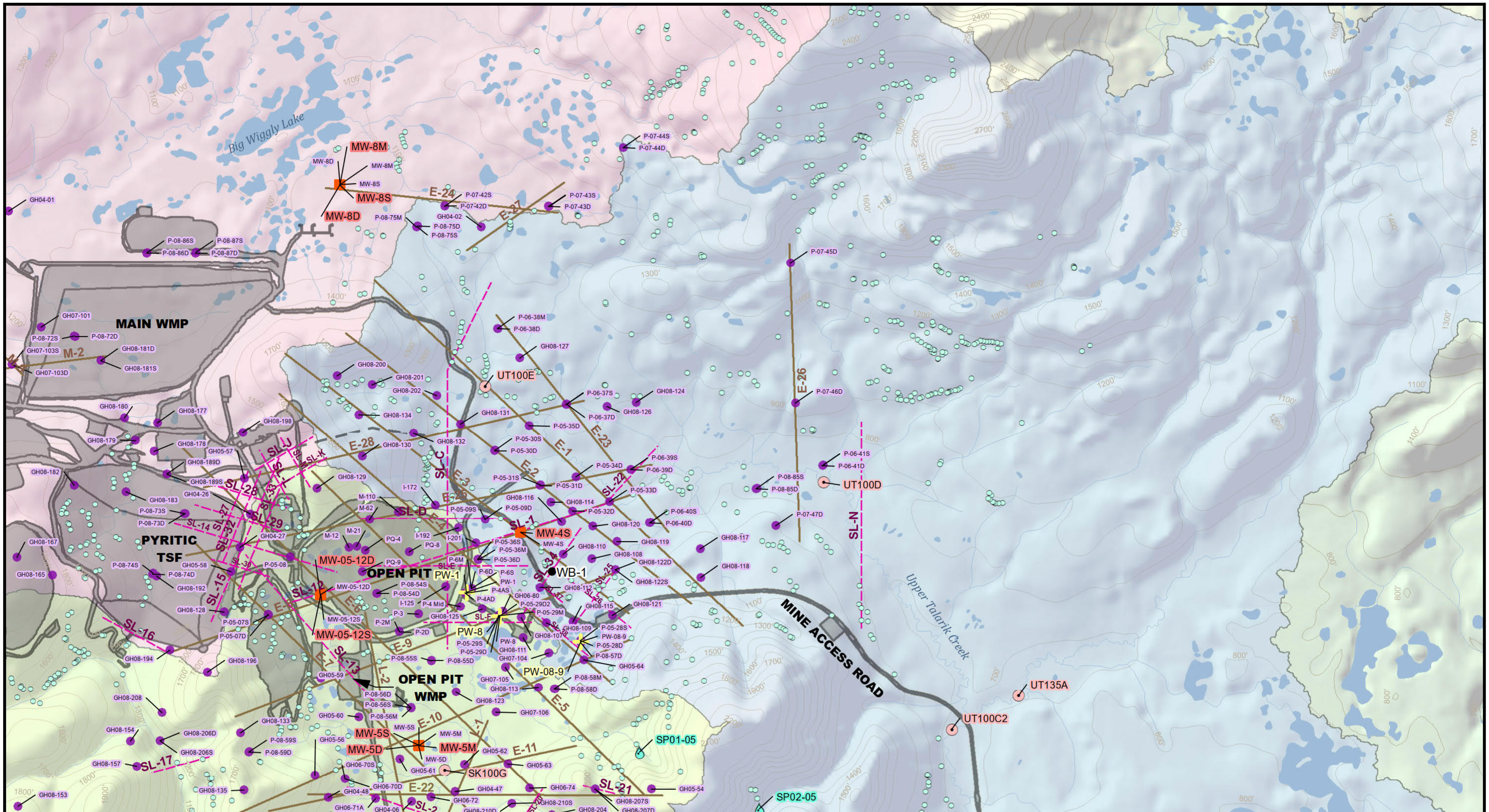
Other Features
- River/Stream
- Lake/Pond
- 100' Contour (Existing)

Note: Well depths and completions are provided in Table K3.18-17.

WELL, PIEZOMETER, AND SEEP LOCATIONS - NFK DRAINAGE

PEBBLE PROJECT EIS

FIGURE K3.17-1b



Sources: AECOM 2019-RFI153;
Schlumberger 2011a, Figures 8.1-4 and 9.1-5

US Army Corps of Engineers

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Miles

Location Type
- Pumping Well
- Monitoring Well
- Piezometer
- Stream Gaging Station
- Seep Sampling Location
- Seep Location

2004-2010 Seismic Line
Cross Section Line

Watershed
- North Fork Koktuli River
- South Fork Koktuli River
- Upper Talarik Creek

Action Alternatives
- Natural Gas Pipelines
- Alternative 1a
- Alternative 1

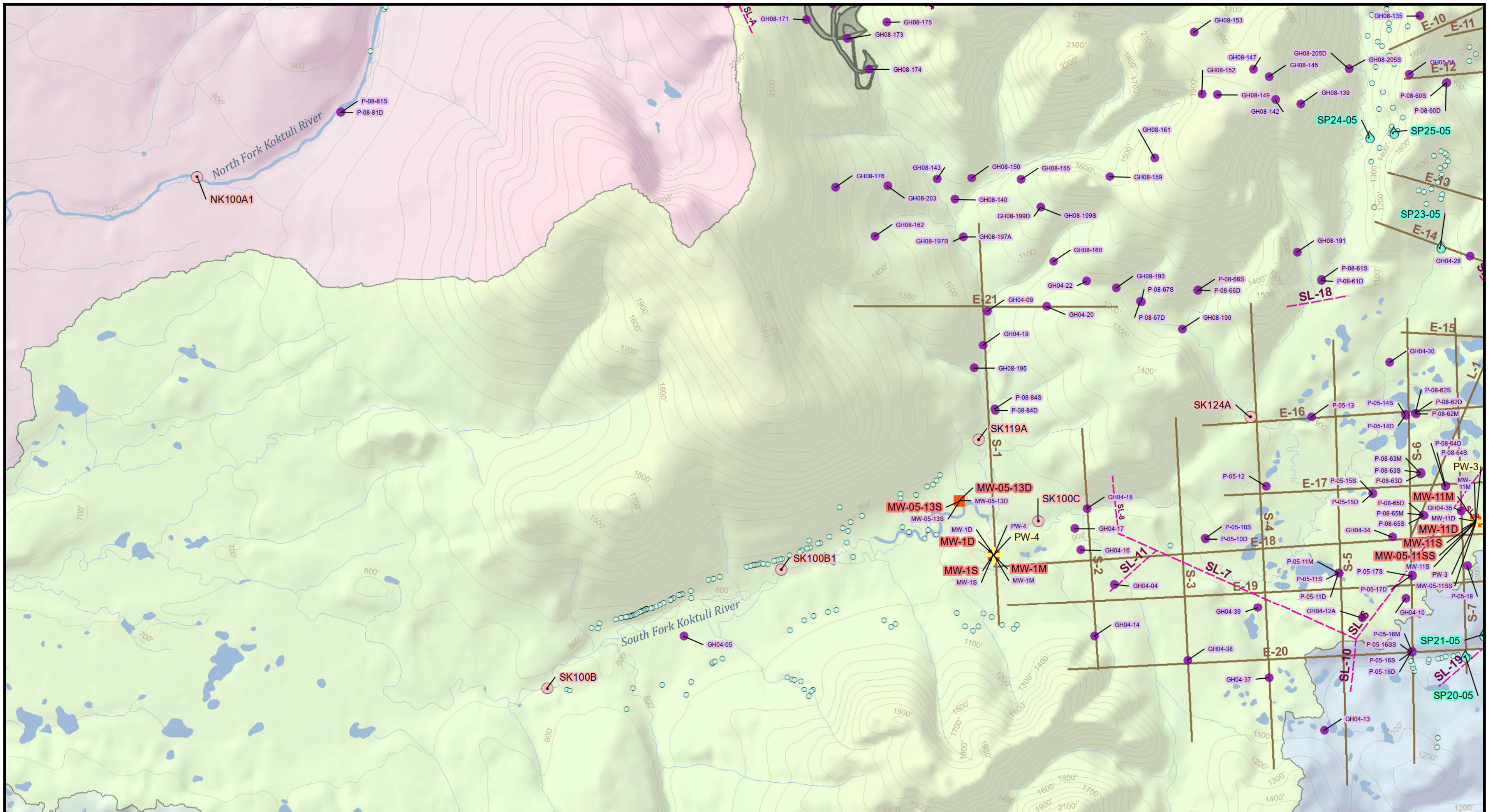
Other Features
- River/Stream
- Lake/Pond
- 100' Contour (Existing)

Note: Well depths and completions are provided in Table K3.18-17.

WELL, PIEZOMETER, AND SEEP LOCATIONS - UTC DRAINAGE NORTH

PEBBLE PROJECT EIS

FIGURE K3.17-1c



Sources: AECOM 2019-RFI153;
Schlumberger 2011a, Figures 8.1-4 and 9.1-5

US Army Corps of Engineers

0.5 0 0.5 1
Miles

Location Type
- Pumping Well
- Monitoring Well
- Piezometer
- Stream Gaging Station
- Seep Sampling Location
- Seep Location

- 2004-2010 Seismic Line
- Cross Section Line

Watershed
- North Fork Koktuli River
- South Fork Koktuli River
- Upper Talarik Creek

Action Alternatives
- Natural Gas Pipelines
- Alternative 1a
- Alternative 1

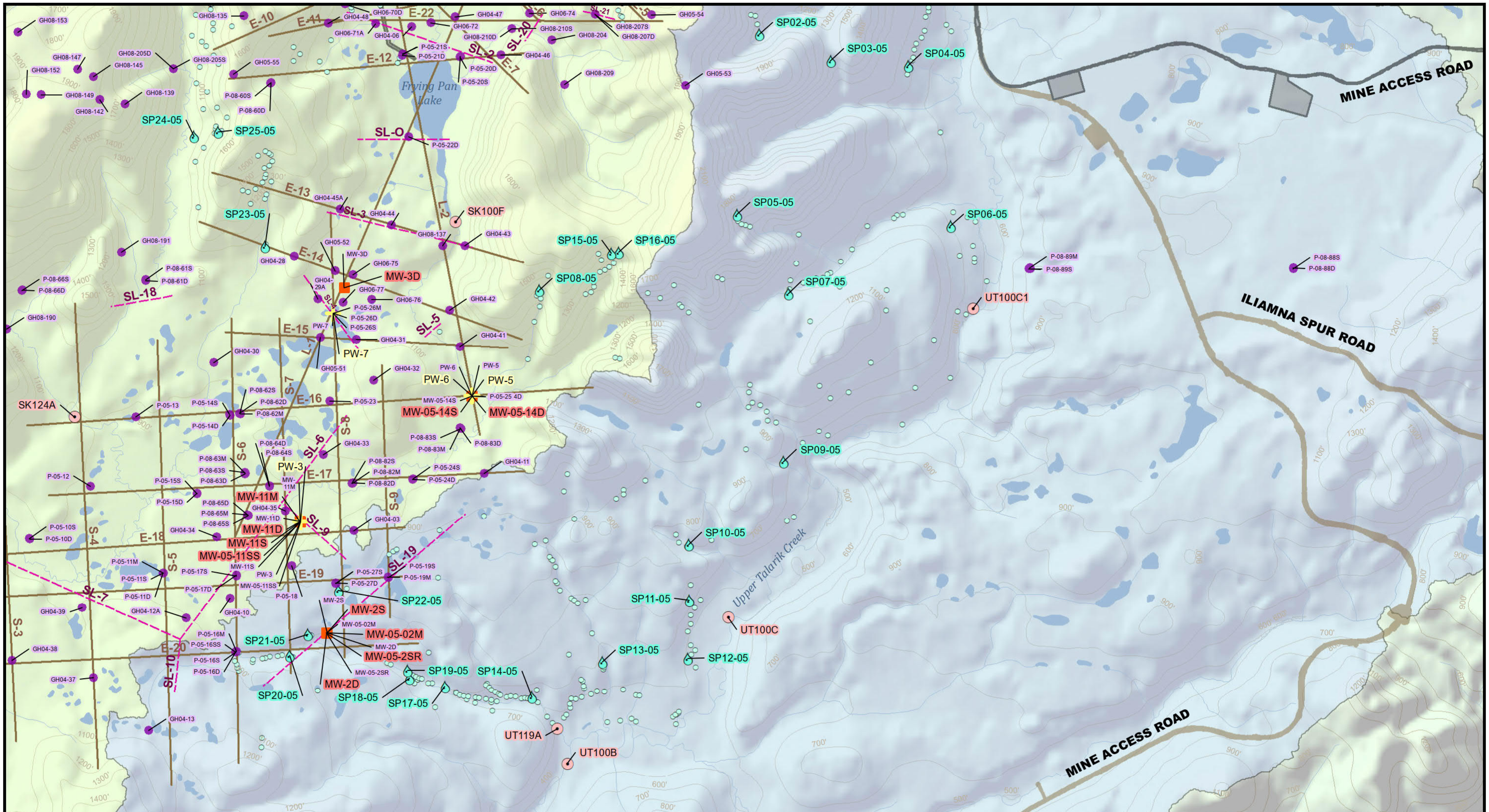
Other Features
- River/Stream
- Lake/Pond
- 100' Contour (Existing)

Note: Well depths and completions are provided in Table K3.18-17.

WELL, PIEZOMETER, AND SEEP LOCATIONS - LOWER SFK DRAINAGE

PEBBLE PROJECT EIS

FIGURE K3.17-1d



Sources: AECOM 2019-RFI153;
Schlumberger 2011a, Figures 8.1-4 and 9.1-5

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0.5 0 0.5 1
Miles

Location Type

- Pumping Well
- Monitoring Well
- Piezometer
- Stream Gaging Station
- Seep Sampling Location
- Seep Location

- 2004-2010 Seismic Line
- Cross Section Line

Watershed

- North Fork Koktuli River
- South Fork Koktuli River
- Upper Talarik Creek

Action Alternatives

- Natural Gas Pipelines
- Alternative 1a
- Alternative 1

Other Features

- River/Stream
- Lake/Pond
- 100' Contour (Existing)

Note: Well depths and completions are provided in Table K3.18-17.

WELL, PIEZOMETER, AND SEEP LOCATIONS - UPPER SFK AND UTC SOUTH DRAINAGES

PEBBLE PROJECT EIS

FIGURE K3.17-1e

Hydraulic conductivities were measured at wells using response (e.g., slug or packer) and pumping tests in areas of the project to characterize groundwater movement and interactions between aquifers and surface waterbodies and wetlands. A slug test is conducted by inserting an object (a slug) of known volume into a well or piezometer, then subsequently extracting it and measuring the rates of rise and/or fall of the water level as it returns to its original level. These data are used to calculate local hydraulic conductivity at an individual well. A pumping test involves pumping water from a well and measuring the drawdown of the water level at the well being pumped, and in other observation wells or piezometers in the area. Drawdown typically decreases with radial distance from the pumping well and increases as the length of time pumping continues. A pumping test can be conducted either with a submersible pump or by a method known as air-lift pumping, in which compressed air is used to lift water out of a well. Packer tests measure the hydraulic conductivity of discrete intervals in a borehole in bedrock that are isolated with movable, inflatable packers. The rate of water injected into the interval between two packers is measured and used to estimate hydraulic conductivity. Pumping tests are generally regarded as providing results that are characteristic of a larger volume of aquifer than slug tests or packer tests.

Deep bedrock was investigated through the installation of three Westbay multi-level groundwater monitoring systems (WB-1, WB-3, and WB-4) at three locations to depths of 4,054 feet, 600 feet, and 2,250 feet, respectively. WB-1 was installed in 2006 in the Pebble deposit area in a borehole drilled to a depth of 4,050 feet for mineral exploration purposes. After flushing the borehole, an assembly of 50 hydraulic head measurement ports and 24 sampling ports were installed to facilitate monthly monitoring of hydraulic head and groundwater quality to significant depths below the deposit. Cross-hole pump testing from a well 100 feet away, also drilled to a depth of 4,050 feet, was completed to allow for measurement of hydraulic conductivity for a larger volume of rock, as compared to response testing and packer testing. In 2010, an additional multi-level piezometer system (WB-3) was installed to a depth of approximately 600 feet to improve characterization of the area between tributaries NK1.190 and SK1.190. The primary objective was to characterize groundwater levels and gradients, and confirm groundwater flow directions. In 2012, a third multi-level system (WB-4) was installed in the pre-Tertiary bedrock in the western portion of the Pebble deposit area to a depth of 2,250 feet. The primary objective was to characterize groundwater levels and gradients in the deposit area.

Large-scale pumping tests were conducted at three locations at the Pebble deposit, at five locations downgradient of the Pebble deposit near the South Fork Koktuli (SFK) River, and at one location in the North Fork Koktuli (NFK) River drainage area (Schlumberger 2011a, Figure 8.1D-1). Pumping tests were conducted in both overburden and bedrock using air-lift pumping techniques for between 6 and 24 hours. Step tests were completed to determine the specific capacity of the pumping wells and a pumping rate for the constant-rate tests. Water levels and pumping well discharge were monitored in both the pumping wells and nearby monitoring wells using pressure transducers and manual water level meters during both pumping and recovery phases to allow for determination of aquifer properties.

Monthly water-level monitoring was conducted in monitoring wells from 2005 through 2012 using manual water-level probes; or calculated based on piezometric pressure measurements by vibrating wire piezometers and at measurement ports in the multi-level piezometer systems.

In support of the characterization of the physical groundwater flow system, a groundwater quality characterization program was also conducted. The program involved sampling of groundwater and seepage quality on a quarterly schedule, and is described in Section 3.18, Water and Sediment Quality. Field chemistry and flow measurements were collected at weirs to support development of the watershed and water-quality modeling.

K3.17.2 Aquifers, Confining Units, and Groundwater Flow Systems

Table K3.17-1 provides a summary of the distribution and characteristics of the overburden and bedrock aquifers in areas of the mine site that would be most affected by the project activities. These are grouped by SFK and NFK rivers and Upper Talarik Creek (UTC) watersheds.

Table K3.17-1: Summary of Aquifers at Mine Site

Drainage/ Catchment	Area/ Sub-Catchment (*Project Facility*)	Overburden or Bedrock	Aquifers	Description	Hydraulic Conductivity (K)
South Fork Koktuli Drainage	Pebble Deposit Area (*Open Pit*)	Overburden	Surficial Aquifer (multiple)	Clean sand (very little silt or clay) or sand and gravel. Beach, delta, and fan deposits.	K in overburden ranged from 5x10^{-8} to 1x10^{-3} m/s; geometric mean of 2x10^{-5} m/s; median of 3x10^{-5} m/s K in weathered bedrock ranged from 4x10^{-7} to 1x10^{-3} m/s; geometric mean of 2x10^{-5} m/s; median of 2x10^{-5} m/s
			Intermediate Aquifer	Sand and gravel between silty deposits. Located in two bedrock lows.	
			Deep Aquifer	Sands and gravels in bedrock low on the eastern side of deposit to depths of 163 feet. Based on pumping tests at PW-08-9 (Section 3.17, Groundwater Hydrology, Figure 3.17-2).	
		Bedrock	Weathered Bedrock Aquifer	Upper 10 to 50 feet of bedrock. Felsenmeer[1] or rock block field where exposed.	
			Upper Bedrock Aquifer	Below weathered bedrock, from 50 to 600 feet in depth. Considerably less permeable than weathered bedrock aquifer.	
			Fault Zones	Faults may function locally either as conduits or barriers to groundwater flow, or have no effect on groundwater flow; water-level mapping shows no apparent distortion to the flow field attributable to large-scale flow through faults.	
	Frying Pan Lake Area (*South WTP Discharge*)	Overburden	Surficial Aquifer (multiple)	Clean sand; sand and gravel. Largest is fan delta upstream of Frying Pan Lake.	K in overburden ranged from 6x10^{-8} to 9x10^{-4} m/s; geometric mean of 6x10^{-5} m/s; median of 3x10^{-4} m/s K in weathered bedrock ranged from 2x10^{-8} to 9x10^{-5} m/s; geometric mean of 4x10^{-6} m/s; median of 9x10^{-6} m/s
			Intermediate Aquifer	Sand and gravel between silty deposits. Under most of the valley floor. Thins to the east and south.	
			Deep Aquifer	Sand and gravel overlying bedrock, in valley thalweg. Thickens toward Frying Pan Lake. Not continuous with deep aquifer in Pebble deposit area.	
		Bedrock	Weathered Bedrock Aquifer	Uppermost 10 to 30 feet of bedrock. Most consistent aquifer in area.	
	South Fork Koktuli Flats	Overburden	SFK Valley Aquifer	Clean sand and gravel moraine downstream of Frying Pan Lake. Continuous with outwash, terrace, and alluvium[4] sand and gravel deposits in valley to west.	K in overburden ranged from 7x10^{-8} to 1x10^{-3} m/s; geometric

Table K3.17-1: Summary of Aquifers at Mine Site

Drainage/ Catchment	Area/ Sub-Catchment (*Project Facility*)	Overburden or Bedrock	Aquifers	Description	Hydraulic Conductivity (K)
	(from Frying Pan Lake, 5.5 miles downstream along SFK River)		SFK Channel Aquifer	Alluvium and terrace gravels along the channel from downstream of Frying Pan Lake to bedrock high to the east.	mean of 1x10^{-4} m/s; median of 4x10^{-4} m/s K in weathered bedrock ranged from 1x10^{-8} to 3x10^{-3} m/s; geometric mean of 2x10^{-5} m/s; median of 5x10^{-5} m/s
			MW-11 Aquifer	Sand and gravel near monitoring well MW-11 and south of bedrock high mantled with glacial drift (see above). (Section 3.17, Groundwater Hydrology, Figure 3.17-1.)	
			Surficial Aquifer	Outwash sand and gravel between SFK River and slope of UTC valley.	
			Intermediate Aquifer	Below surficial aquifer. Conveys majority of flow from SFK River Aquifer and MW-11 Aquifer to UTC Tributary UT1.190[2] at seasonal low and high water levels. Surface discharge upstream of gaging station UT100B.	
			Deep Aquifer	Sand and gravel; silty sand (based on logging of drill cuttings. No indication of direction of groundwater flow.	
		Bedrock	Weathered Bedrock Aquifer	Possible aquifer within upper 10 to 50 feet of weathered and fractured bedrock. Based on observations during drilling exploration borings.	
	SFK Discharge Area	Overburden	SFK Valley Aquifer	Outwash sand and gravel. Extends from approximately 1 mile upstream of the confluence of the SFK River and Tributary SK1.190 (gaging station SK119A) to approximately 2.4 miles downstream.	
NFK Drainage	Big Wiggly Basin (headwaters of NFK River)	Overburden	Surficial Aquifer	Sand and gravel aquifer underlies glacial till. Limited characterization of lateral and vertical extent.	K in overburden ranged from 8x10^{-9} to 2x10^{-3} m/s; geometric mean of 1x10^{-4} m/s; median of 3x10^{-4} m/s. K in weathered bedrock ranged from 9x10^{-9} to 3x10^{-4} m/s; geometric mean of
	NFK East - Area E (within Area 12) *(PAG/Pyritic TSF)*	Overburden	Intermediate Aquifer	Sand and gravel.	
		Bedrock	Weathered Bedrock Aquifer	Uppermost portion of bedrock.	
		Overburden	Surficial Aquifer	Thin aquifer composed of colluvium, drift, undifferentiated gravel, and undifferentiated drift.	

Table K3.17-1: Summary of Aquifers at Mine Site

<table>
<tr><th>Drainage/ Catchment</th><th>Area/ Sub-Catchment (Project Facility)</th><th>Overburden or Bedrock</th><th>Aquifers</th><th>Description</th><th>Hydraulic Conductivity (K)</th></tr>
<tr><td rowspan="4"></td><td>NFK West – Area G (within drainage Area 14)
(TSF)</td><td>Bedrock</td><td>Weathered Bedrock Aquifer</td><td>Uppermost portion of weathered and fractured bedrock.</td><td rowspan="4">1x10^{-6} m/s; median of 9x10^{-7} m/s.</td></tr>
<tr><td rowspan="3">North Fork Glacial Outwash Area [3] (aka Area 15)
(TSF Main Embankment Seepage Collection and Sediment Ponds)</td><td rowspan="2">Overburden</td><td>North Fork Outwash Aquifer</td><td>Sand and gravel.</td></tr>
<tr><td>Terrace and Alluvial Deposits</td><td>Sand and gravel downstream of North Fork Outwash Aquifer.</td></tr>
<tr><td>Bedrock</td><td>Weathered Bedrock Aquifer</td><td>Uppermost 10 to 50 feet of weathered and fractured bedrock.</td></tr>
<tr><td rowspan="5">UTC Drainage</td><td rowspan="2">Upper Talarik Creek
(East WTP Discharge)</td><td>Overburden</td><td>Glacial Outwash Aquifer</td><td>Sand and gravel upstream of stream gage UT100E (Section 3.16, Surface Water Hydrology, Figure 3.16-4).</td><td rowspan="5">K in overburden ranges from 2x10^{-6} to 4x10^{-5} m/s; geometric mean 1x10^{-5} m/s; median 1x10^{-5} m/s.
K in weathered bedrock ranges from 2x10^{-7} to 2x10^{-5} m/s; geometric mean 2x10^{-6}; median 5x10^{-6} m/s.</td></tr>
<tr><td>Bedrock</td><td>Weathered Bedrock Aquifer</td><td>Uppermost 10 to 50 feet of weathered and fractured bedrock.</td></tr>
<tr><td rowspan="3">Talarik Creek Outwash Plain (aka Area 10)</td><td rowspan="2">Overburden</td><td>Surficial Aquifer</td><td>Glacial outwash deposits (sand, gravel), east of UTC. Likely underlain by a low-permeability confining unit.</td></tr>
<tr><td>Intermediate Aquifer</td><td>Extension of aquifer originating in SFK Flats drainage. Located below surficial aquifer and conveys majority of groundwater flow from SFK River Aquifer and MW-11 Aquifer to UTC Tributary UT1.190. Discharges to surface upstream of stream gage UT100B.</td></tr>
<tr><td>Bedrock</td><td>Weathered Bedrock Aquifer</td><td>Uppermost 10 to 50 feet of weathered and fractured bedrock.</td></tr>
</table>

Notes:
[1] Felsenmeer = frost-weathered boulders at the surface.
[2] Numbered tributaries named for stream gaging stations (see Section 3.16, Surface Water Hydrology).
[3] Outwash – sediments deposited by glacial meltwater
[4] Alluvium – sediments deposited by stream, river, etc.
aka = also known as
m/s = meters per second
NFK = North Fork Koktuli
SFK = South Fork Koktuli
UTC = Upper Talarik Creek
PAG = potentially acid-generating
TSF = treatment storage facility
WTP = water treatment plant
Sources: Schlumberger 2011a, 2015a

SFK River Drainage near the Pebble Deposit—Hydrogeologic cross-section E-8 (see Figure 3.17-4), a southwest to northeast–trending section, shows the geological layering across the SFK River drainage near the Pebble deposit and north of Frying Pan Lake. Overburden deposits consist of interbedded gravels, sands, silts, and clays that overlie weathered bedrock. Groundwater recharge rates in the SFK drainage basin, calculated using the watershed model, ranged from 11.8 inches per year at the mine site (Area 3) to 46.8 inches per year along the SFK River downstream of Frying Pan Lake (Area 5), and averaged 24.2 inches per year (Schlumberger 2011a).

Groundwater in this area flows from the upland recharge areas toward the valley floor, where it discharges to the SFK River. Groundwater primarily flows through the overburden aquifers of sands and gravels and the uppermost 10 to 50 feet of weathered (fractured) bedrock before discharging to the SFK River. Groundwater in the vicinity of the deposit locally discharges to the upper reaches of the SFK River, and is unlikely to flow across groundwater divides or migrate appreciable distances down the valley before discharging to surface water.

The weathered bedrock is highly fractured from physical weathering and is much more permeable than the more competent bedrock below. Deeper bedrock is less weathered and exhibits lower hydraulic conductivity (K) values (a measure of the rate of water flow through the rock). Groundwater flow occurs in the deeper bedrock by permeability created by cross-cutting fractures and faults. Mapped bedrock faults are shown in Figure 3.17-1. Additional faulting and fracturing other than those shown in Figure 3.17-1 are likely to be present. Although fractures and faults are widespread in the deep bedrock, some of the features are infilled with fine-grained fault gouge[1] that tends to block groundwater flow and are offset relative to one another (cross-cutting). The faults and fractures therefore have the potential on a local scale to create groundwater compartments (compartmentalized flow) in the deeper bedrock, thereby reducing the potential for regional groundwater flow (Knight Piésold 2018l). On a larger scale, however, no significant deviations have been identified from reviews of water-level data to identify either compartmentalized flow or preferred conduits of groundwater flow (BGC 2019a).

Cross-sections L-3 and L-4 (see Figure 3.17-5 and Figure 3.17-6), trending northeast-southwest, show geological deposits along the SFK River drainage south of the Pebble deposit. Silty clay overburden deposits thicken from the Pebble deposit area toward Frying Pan Lake, continue to thicken south of the lake, then transition to mostly sand and gravel deposits several miles south of the lake. Groundwater levels in shallow weathered and fractured bedrock (upper 50 feet of bedrock) exhibit stronger seasonal fluctuations than in the overburden of sand and gravel.

Numerous vertical groundwater gradients have been measured in this area, as shown in Figure K3.17-2, Figure K3.17-3, Figure K3.17-4, Figure K3.17-5 (Schlumberger 2015a, Figures 8.1F1 through F4), and Figure K3.17-6 (BGC 2019a). During seasonal low-water periods of the year (such as wintertime), most vertical gradients are downward[2], indicating flow from shallow aquifers to deeper aquifers. However, some valley-bottom locations exhibit upward gradients, indicative of upward flow from aquifers to surface water and wetland areas, which maintains their wintertime baseflow. During wetter periods, a higher number of deeper aquifers exhibit upward flow, reflecting groundwater discharge to a wider area of lowland waterbodies and wetlands. This discharge likely originates from seasonal recharge in nearby ridges and knobs that rapidly flows

[1] Fault gouge is a zone of crushed rock formed between bedrock surfaces in a fault or fault zone from tectonic grinding forces.

[2] Upward and downward components of groundwater flow are defined by differences in water levels in stacked aquifers at the same location. When a well tapping a shallow aquifer, for example, has a higher water level than a well tapping a deeper aquifer, then the gradient is downward, indicating the potential for groundwater flow downward from the shallower aquifer to the deeper aquifer.

towards the lowland areas through the weathered bedrock and deeper aquifers. The vertical gradient data support the conceptual model of local groundwater flow systems involving recharge to the exposed weathered and fractured bedrock aquifer in ridge and knob areas, with subsequent migration toward valley bottoms, where the groundwater is eventually discharged to overlying surficial deposits, wetlands, or streams. A bedrock high[3] and the presence of low-permeability sediments at the downstream end of Frying Pan Lake generally act as a partial barrier to groundwater flow, and limit discharge from Frying Pan Lake to the underlying groundwater flow system.

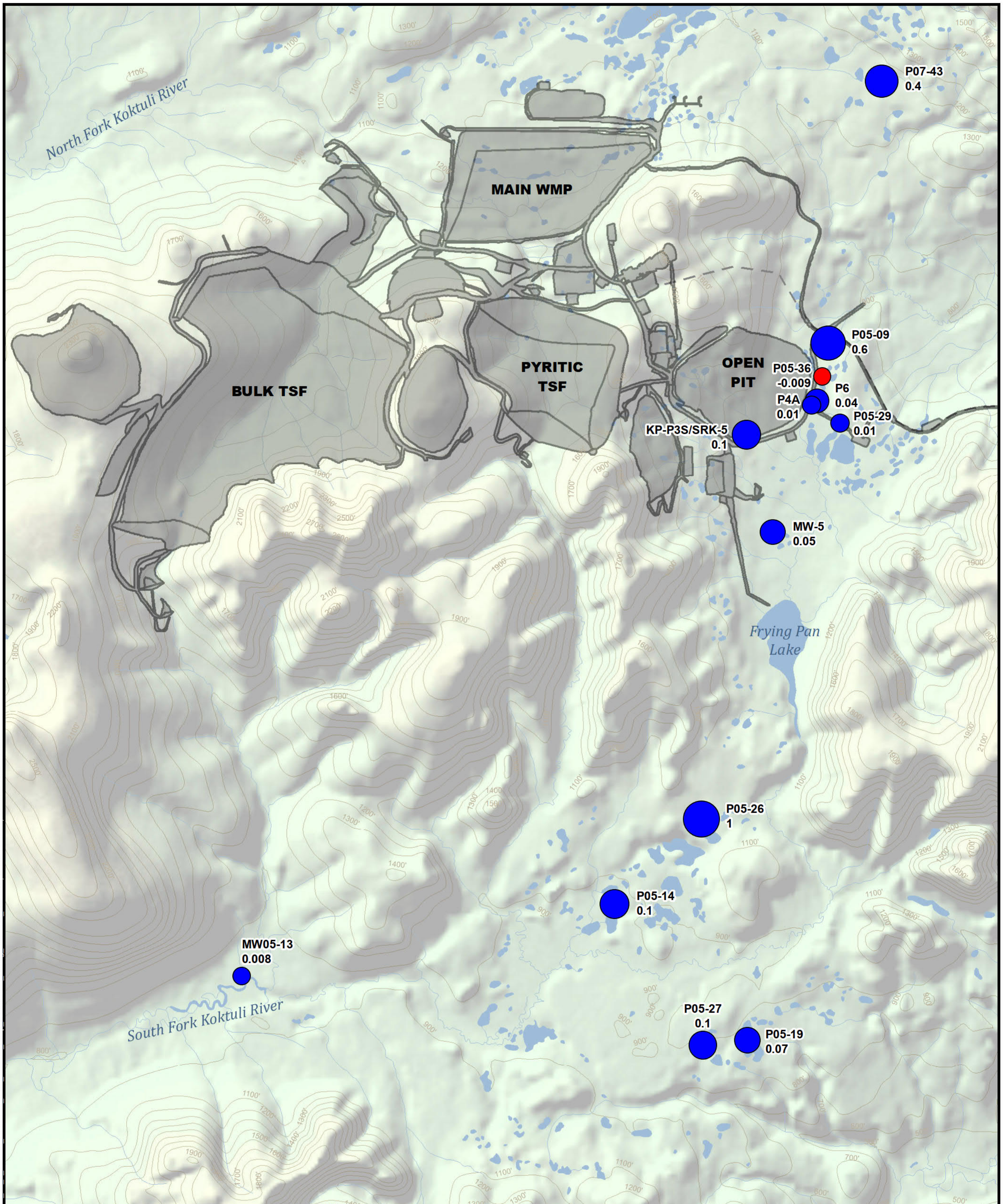
Frying Pan Lake Area and Upper Reaches of UTC Tributary UT1.190—The hydrogeology of the region from Frying Pan Lake to upper reaches of Tributary UT1.190 is also shown further south on hydrogeologic cross-sections L-3 and L-4 (see Figure 3.17-5 and Figure 3.17-6). Several overburden aquifers have been identified in this area, and overburden thickness under Frying Pan Lake varies from approximately 50 to 150 feet. Just upstream of Frying Pan Lake are surficial aquifers of mainly clean sand and gravel. Based on interpretation of borehole data, an intermediate aquifer occurs in the overburden between silty deposits under most of the valley floor that thins to the east and south. A deeper overburden aquifer of sands and gravels overlies the weathered and fractured bedrock and thickens toward Frying Plan Lake, but is not continuous with the deep overburden aquifer in the Pebble deposit area. The most areally extensive aquifer in this area is the weathered and fractured shallow bedrock aquifer.

South of Frying Pan Lake, silty layers are absent along the SFK River, where overburden consists of sand and gravel. Overburden is relatively thin as compared to beneath the lake, and is permeable beneath most valley floors, with valley walls dominated by colluvium[4] and shallow weathered and fractured bedrock, with the exception of some local thin till[5] deposits.

Groundwater recharge in the Frying Pan Lake area is derived locally from the weathered and fractured shallow bedrock on uplands, and on valley sides where recharge occurs on local topographic highs with discharge to ponds, wetlands, and streams. The valley floor is likely a groundwater discharge area; however, data indicate that during seasonal low-water periods, some of the valley floor recharges the lower sand and gravel aquifer and uppermost weathered and fractured shallow bedrock aquifer.

Groundwater at Frying Pan Lake is shallow and exhibits upward groundwater movement (groundwater discharge) toward the lake, while groundwater levels downstream of the lake are up to 60 feet below the stream bottom, indicating strong downward groundwater gradients and losses from the stream.

[3] An area where the bedrock is higher than the surrounding bedrock surface, similar to a hill in surface topography.
[4] Colluvium is coarse material originating from adjacent slopes, such as angular pieces of bedrock.
[5] Till is a mixture of many grain sizes deposited by glacial ice.



Sources: PLP 2019-RFI153; Schlumberger 2015a, Figure 8.1F-1

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0.5 0 0.5 1
Miles

Groundwater Gradient, May 2008

- SO-CZ/BR Upward Gradient
- SO-CZ/BR Downward Gradient

Alternative 1a

- Mine Site

BR - Bedrock
DO - Deep Overburden
SO - Shallow Overburden
P - Piezometer
CZ – Contact Zone
KP-P - Knight-Piesold Piezometer
MW - Monitoring Well
SRK - Steffan Robertson Kirsten

Other Features

- River/Stream
- Lake/Pond
- 100' Contour (Existing)

Notes:
1. Gradient = $\frac{\text{Head Difference}}{\text{Distance Between Screen Midpoints}}$

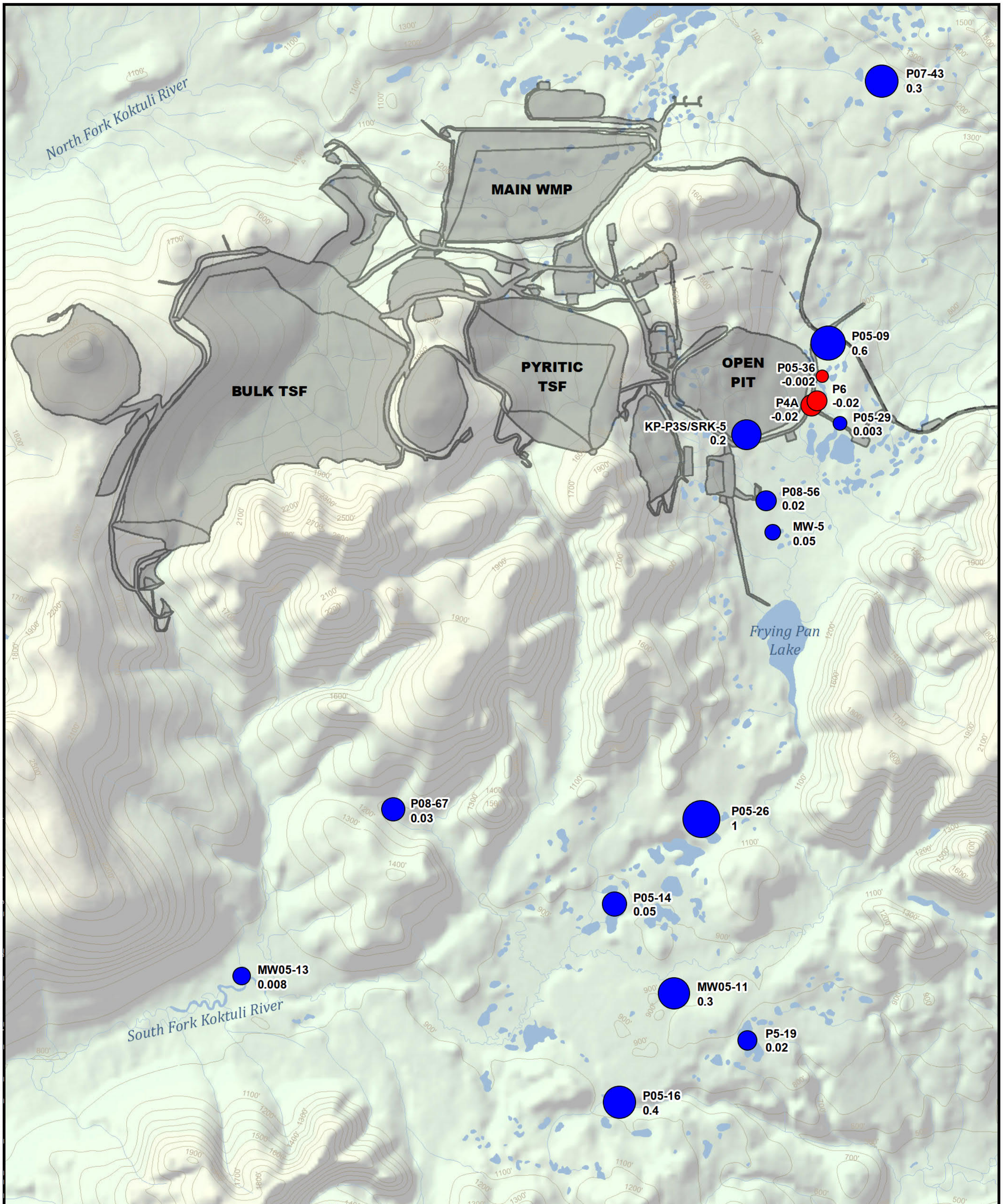
2. Diameter of circle is logarithmically proportional to the magnitude of the gradient.

3. Contact Zone: Zone immediately above and below the bedrock contact that is penetrated by the well screen and sand pack.

VERTICAL GRADIENTS BETWEEN SHALLOW OVERBURDEN AND DEEP OVERBURDEN DURING SEASONAL LOW

PEBBLE PROJECT EIS

FIGURE K3.17-2



Sources: PLP 2019-RFI153; Schlumberger 2015a, Figure 8.1F-2

US Army Corps of Engineers

0.5 0 0.5 1
Miles

Groundwater Gradient, June 2008

SO-CZ/BR Upward Gradient

SO-CZ/BR Downward Gradient

Alternative 1a

Mine Site

BR - Bedrock
DO - Deep Overburden
SO - Shallow Overburden
P - Piezometer
CZ – Contact Zone
KP-P - Knight-Piesold Piezometer
MW - Monitoring Well
SRK - Steffan Robertson Kirsten

Other Features

River/Stream

Lake/Pond

100' Contour (Existing)

Notes:
1. Gradient = $\frac{\text{Head Difference}}{\text{Distance Between Screen Midpoints}}$

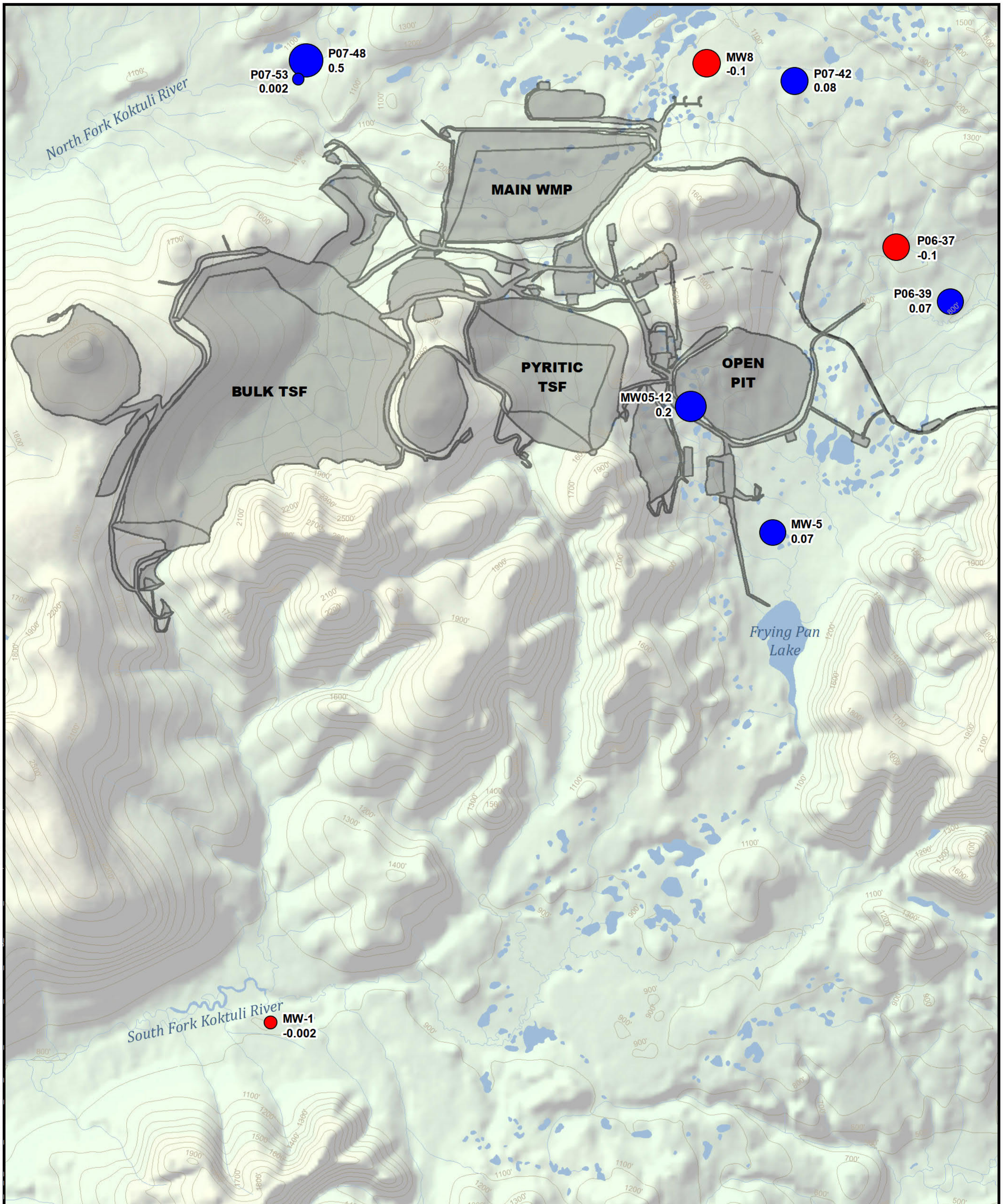
2. Diameter of circle is logarithmically proportional to the magnitude of the gradient.

3. Contact Zone: Zone immediately above and below the bedrock contact that is penetrated by the well screen and sand pack.

VERTICAL GRADIENTS BETWEEN SHALLOW OVERBURDEN AND DEEP OVERBURDEN DURING SEASONAL HIGH

PEBBLE PROJECT EIS

FIGURE K3.17-3



Sources: PLP 2019-RFI153; Schlumberger 2015a, Figure 8.1F-3

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0.5 0 0.5 1
Miles

Groundwater Gradient, May 2008

SO-CZ/BR Upward Gradient

SO-CZ/BR Downward Gradient

Alternative 1a

Mine Site

BR - Bedrock
DO - Deep Overburden
SO - Shallow Overburden
P - Piezometer
CZ – Contact Zone
KP-P - Knight-Piesold Piezometer
MW - Monitoring Well
SRK - Steffan Robertson Kirsten

Other Features

River/Stream

Lake/Pond

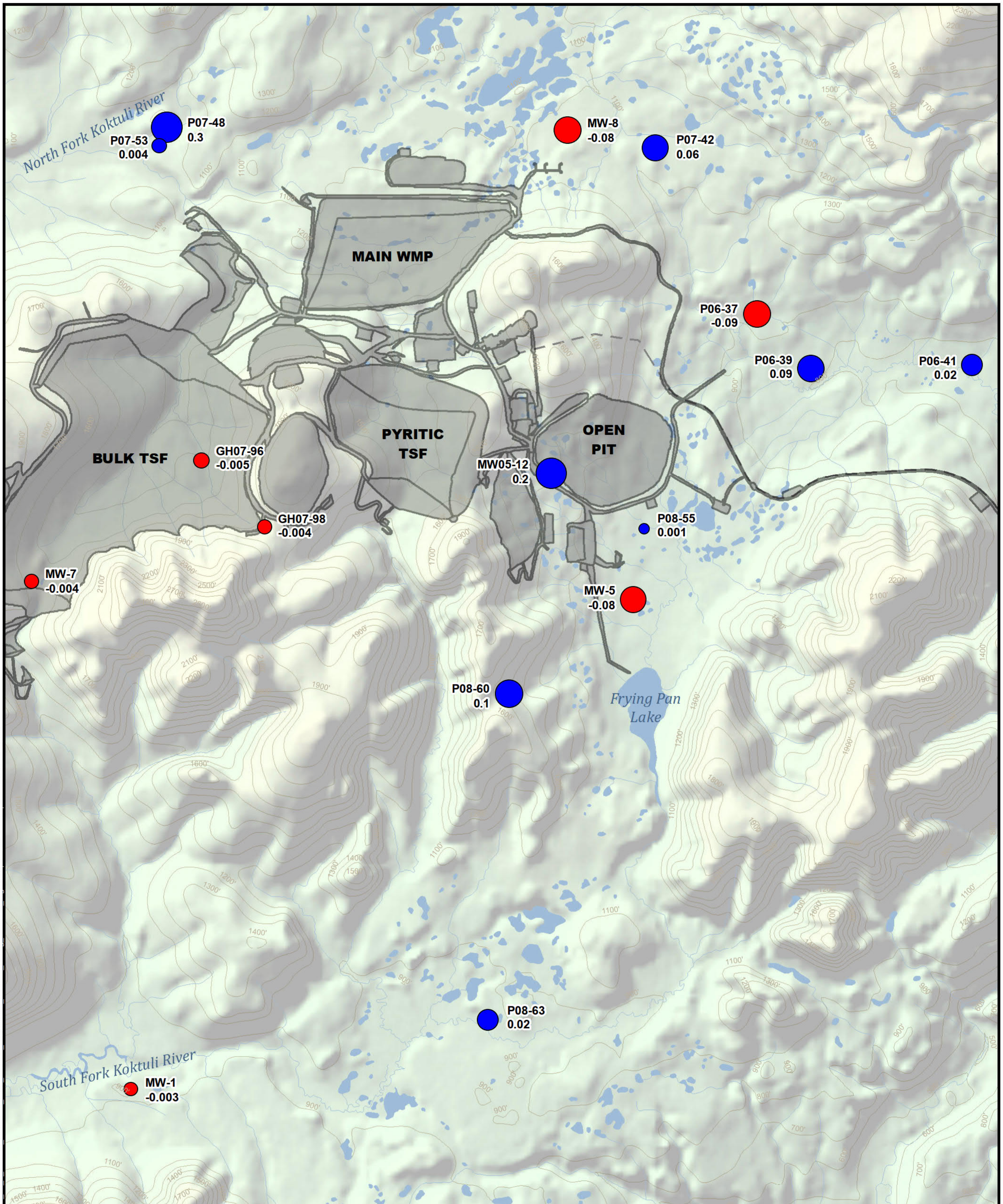
100' Contour (Existing)

Notes:
1. Gradient = $\frac{\text{Head Difference}}{\text{Distance Between Screen Midpoints}}$

2. Diameter of circle is logarithmically proportional to the magnitude of the gradient.

3. Contact Zone: Zone immediately above and below the bedrock contact that is penetrated by the well screen and sand pack.

VERTICAL GRADIENTS BETWEEN SHALLOW OVERBURDEN AND BEDROCK DURING SEASONAL LOW



Sources: PLP 2019-RFI153; Schlumberger 2015a, Figure 8.1F-4

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0.5 0 0.5 1
Miles

Groundwater Gradient, June 2008

- SO-CZ/BR Upward Gradient
- SO-CZ/BR Downward Gradient

Alternative 1a

- Mine Site

BR - Bedrock
DO - Deep Overburden
SO - Shallow Overburden
P - Piezometer
CZ – Contact Zone
KP-P - Knight-Piesold Piezometer
MW - Monitoring Well
SRK - Steffan Robertson Kirsten

Other Features

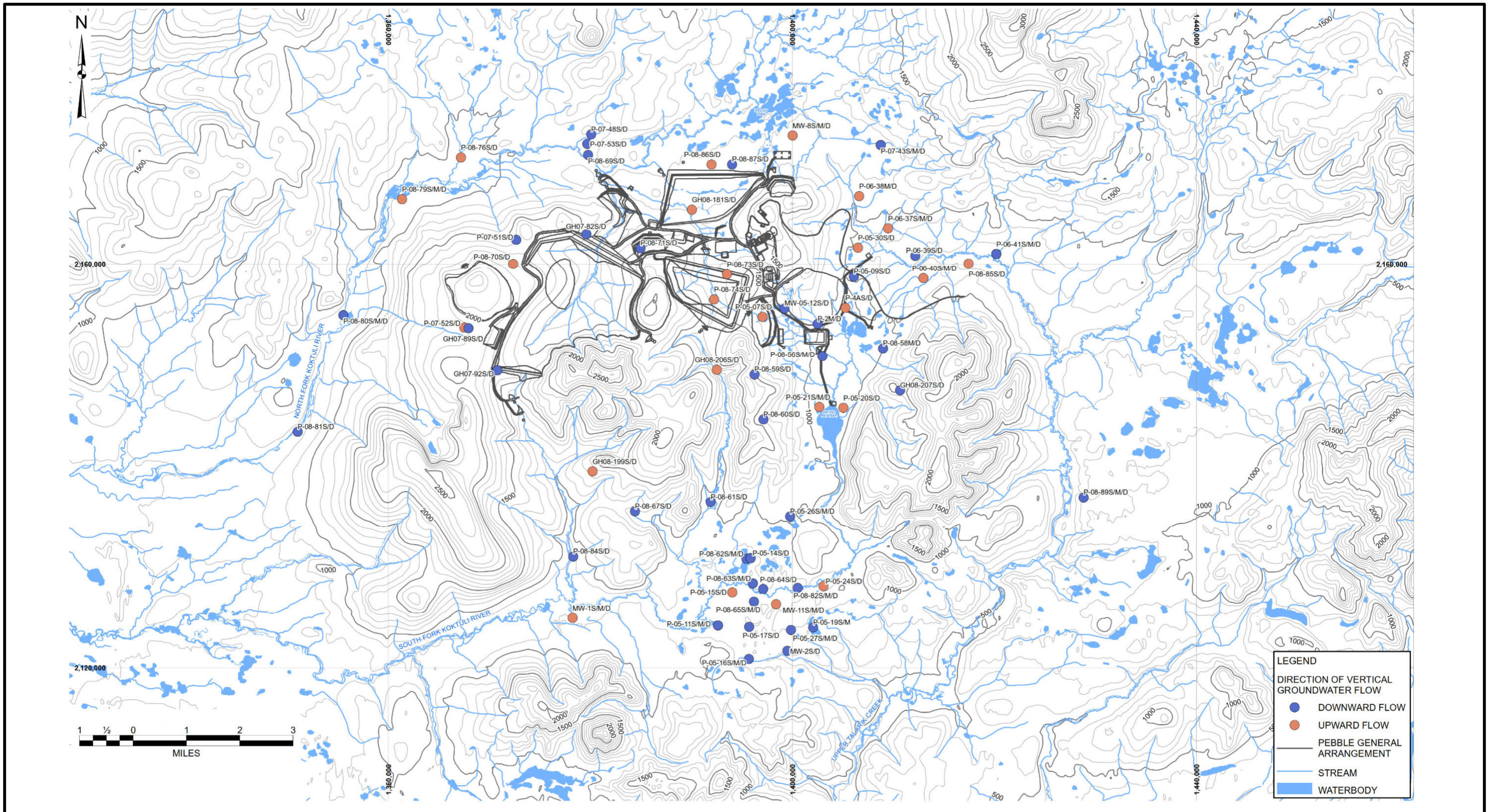
- River/Stream
- Lake/Pond
- 100' Contour (Existing)

Notes:
1. Gradient = $\frac{\text{Head Difference}}{\text{Distance Between Screen Midpoints}}$
2. Diameter of circle is logarithmically proportional to the magnitude of the gradient.
3. Contact Zone: Zone immediately above and below the bedrock contact that is penetrated by the well screen and sand pack.

VERTICAL GRADIENTS BETWEEN SHALLOW OVERBURDEN AND BEDROCK DURING SEASONAL HIGH

PEBBLE PROJECT EIS

FIGURE K3.17-5



Source: BGC 2019a

Note: Only sites are shown where vertical gradient direction is consistent throughout the year.

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VERTICAL DIRECTION OF GROUNDWATER FLOW

PEBBLE PROJECT EIS

FIGURE K3.17-6

The results of groundwater-level monitoring and a water-balance assessment (Schlumberger 2011a) suggests that approximately two-thirds of the groundwater flowing through the deep overburden aquifer downstream of Frying Pan Lake remains in the SFK River drainage, while the remaining one-third of the groundwater crosses the surface water drainage divide and contributes to base flow in Tributary UT1.190 and discharges to UTC. Figure 3.17-10 and Figure 3.17-11 show the divergent groundwater flow and the absence of a groundwater divide along the SFK/UTC watershed boundary in both the overburden and bedrock aquifers. The divergent groundwater flow pattern occurs both during seasonal-low and seasonal-high water periods.

SFK River Discharge Area—Hydrogeologic cross-section S-1 (see Figure 3.17-8) shows the hydrostratigraphy along SFK Tributary SK1.190 from north to south and across the SFK River. The upper slopes are underlain by weathered and fractured bedrock, and the mid-slopes are mapped as colluvium and glacial drift. A 125-foot-thick outwash gravel deposit occurs along the valley axis with adjoining terrace gravels. Response tests and sediment descriptions indicate that the gravels are very permeable ($3x10^{-5}$ to $6x10^{-4}$ meters per second [m/s]) in this area. The main aquifer along this portion of the SFK River is outwash sands and gravels, and the terrace deposits and alluvium that infill the valley (valley aquifer).

Meteoric recharge is expected along the weathered and fractured bedrock ridges and through the overburden in the valley bottom. A large portion of precipitation falling on the outwash sand and gravels and the terrace deposits along the valley floor is expected to recharge the aquifer. Additional recharge occurs from stream channels as they flow into the valley, particularly from the large catchments: SK1.190 and SK1.210. Similar but less-concentrated recharge of groundwater is expected adjacent to the valley sand and gravel deposits where runoff and shallow groundwater exit the adjacent slopes.

A relatively large groundwater flow enters the SFK discharge area from the SFK Flats area south of Frying Pan Lake. At times when the groundwater level is high, groundwater might discharge to the streambed near the boundary between Area 5 and Area 4. However, during low-flow periods, the SFK River streambed is dry upstream of the confluence with Tributary SK1.190. Additional water recharges the groundwater system in this area; both as direct recharge from rainfall and snowmelt, and as runoff from adjoining slopes that infiltrate in this area.

Immediately downstream of the confluence with Tributary SK1.190, groundwater discharges into the bottom of the stream channel. This discharge results from a reduction of the aquifer thickness and width in this area, and additional water contributed to the aquifer from tributaries SK1.190 and SK1.210. In the dry season, where little to no visible surface water flow is observed upstream of the confluence with Tributary SK1.190, surface water flows in the SFK River range up to 50 cubic feet per second (cfs) about 2.4 miles downstream of the confluence with Tributary SK1.190.

NFK Tributary NK1.190—Cross-section M-1 (see Figure 3.17-9) shows the hydrostratigraphy from the upland slopes adjacent to the NK1.190 drainage to the lower portion of this drainage and across the NFK River upstream of its confluence with Tributary NK1.190. The upland slopes are underlain by weathered and fractured bedrock and covered with a thin mantle of colluvium. Overburden is thin over much of the valley; however, several borings intercepted up to 100 feet of overburden. Response tests indicate that the overburden and the weathered and fractured shallow bedrock are very permeable.

Groundwater recharges on the upper slopes, with some discharging to numerous sustained seeps at a range of elevations (see Figure 3.17-2), and the balance of groundwater flowing downward toward the stream channel in the center of the valley. Groundwater also migrates downstream under the valley floor in the overburden and weathered and fractured shallow bedrock. Because the overburden is thin along the valley floor, most groundwater discharges to the streambed, contributing to stream baseflow; and groundwater levels are near ground surface over much of the catchment, and at or above the ground surface near the stream channel.

Upstream of stream gage NK100C (see Figure 3.16-4), the headwater drainage area for the NFK River is overlain by glacial drift and materials deposited at the bottom of former glacial lakes that have resulted in relatively thin, but laterally continuous aquifers. A terminal glacial moraine is near the confluence of the main stem NFK River and Tributary NK1.190. At this location, the surficial deposits transition to coarser-grained glacial outwash materials where the NFK River recharges the underlying aquifer.

The thin overburden limits groundwater recharge in this area. The average groundwater recharge rate calculated using the site-wide water balance model (WBM) is 11 inches per year, the lowest rate of the three watersheds in the project area (groundwater recharge in the SFK watershed is estimated at 24 inches per year, and UTC watershed at 16 inches per year).

NFK East Drainage—This area would contain the pyritic tailings storage facility (TSF). Two aquifers are identified in this area: overburden aquifer of sand and gravel that underlies glacial till (which is less porous and permeable); and the shallow weathered and fractured bedrock. Groundwater recharge is derived at higher elevations on hillsides and hill tops where weathered and fractured bedrock is close to the surface or exposed. Groundwater flows downslope toward the valley, discharging in seeps in weathered and fractured bedrock and the sands and gravels of the valley floor. Many seeps have been identified along hillsides in this area (see Figure 3.17-2) and are caused by high recharge on the upper slopes, as well as the variability of hydraulic conductivity and thickness of the weathered and fractured bedrock.

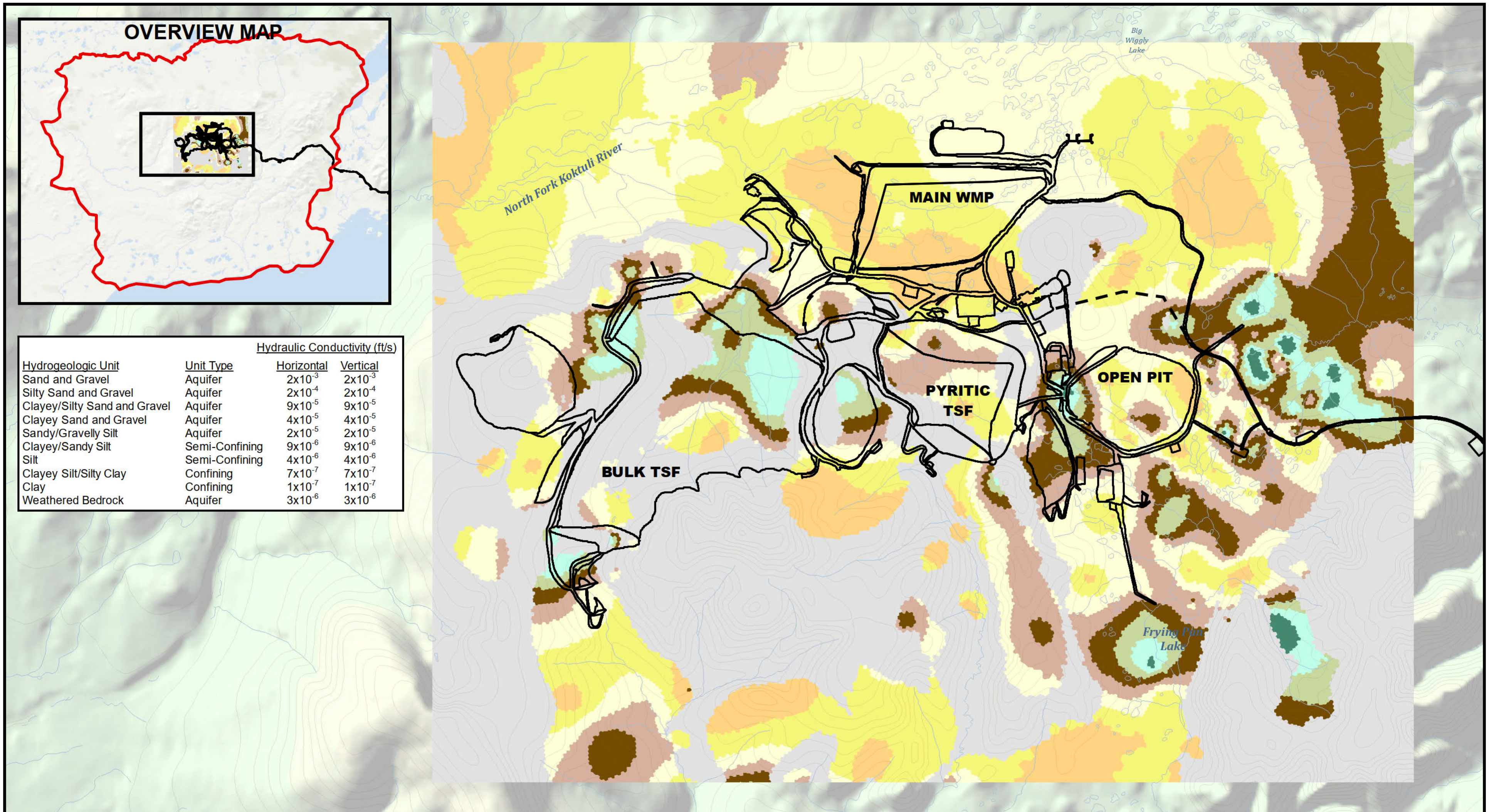
UTC Drainage—The only project features proposed in the UTC drainage are the water treatment plant #1 (WTP#1) discharge-east and a portion of the mine site access road. Primary aquifers in this area are sands and gravels of glacial outwash upstream of gage UT100E, and the shallow weathered and fractured bedrock.

Groundwater is locally recharged on the hilltops and hillsides of weathered bedrock. Upstream of UT100E, UTC and tributaries contribute additional recharge to groundwater (losing streams) and cross-basin groundwater flow from the NFK is also considered to occur at the area shown in Figure 3.17-10 and Figure 3.17-11. Recharge occurs through precipitation infiltrating the upper hillslopes and migrating downslope in the highly fractured shallow bedrock unit. The calculated average groundwater recharge rate is 14 inches per year. Where downslope groundwater movement is restricted by low-permeability sediments or discontinuities in the flow system, groundwater discharges to ground surface as seeps; seeps are abundant in this drainage, and often occur high on the hillslopes. Overburden deposits are variable in this drainage, and include silty sand and gravel to clean sand (low percentage of clay and silt) in the upper portion of the UTC drainage.

In the intermediate reaches of the drainage between UT1.135 and UT1.190, a large area has been filled with deltaic, glacial outwash, ice-contact sands, and sand and gravel. This area is inferred to be a groundwater recharge area because of the permeable surficial deposits, observations of very little to no runoff, and presence of springs downgradient from the area (Schlumberger 2011a, Appendix 8.1I). Tributary UT1.190 joins the UTC drainage downstream of the groundwater recharge area, and is inferred to transmit the majority of groundwater that migrates east from the SFK River drainage area across the surface-water drainage divide into the UTC drainage area. Most of the groundwater moves downgradient in the sand and gravel units and the weathered upper bedrock. Steep vertical gradients have been observed in some areas, suggesting the presence of fine sediments that restrict downward movement of groundwater.

Upstream of UT100B, groundwater inflow originating from the SFK drainage discharges into the UTC groundwater system (crossing under the surface watershed divide between SFK and UTC). This flow is primarily through the intermediate aquifer in the SFK Flats area, described in Table K3.17-1 and shown in Figure 3.17-10 and Figure 3.17-11 in Section 3.17, Groundwater Hydrology.

Aquifer, Semi-confining and Confining Unit Maps—Cross-sections, as described above and in Section 3.17, Groundwater Hydrology, do not have the ability to portray aquifers in plan view; however, this information has been compiled in detail and used as input files to the groundwater flow model of the mine area (the model is described in more detail under the "Mine Site Groundwater Model" subsection). Model layers 1, 2, and 3 represent unconsolidated materials. The distributions of these materials, as classified into aquifers, semi-confining units, or confining units, are shown in Figure K3.17-7, Figure K3.17-8, and Figure K3.17-9 respectively. These figures, along with the cross-sections shown in Section 3.17, Groundwater Hydrology, show a very complex distribution of deposits, with sand and gravel deposits commonly occurring in most areas around the mine site. The distribution of permeable deposits in the mine area, the relatively steep topographic gradients, and the relatively high annual precipitation and snowmelt contribute to a hydrogeologic environment in which groundwater recharge, groundwater, and surface water are closely inter-related at most locations near the mine site.



Hydrogeologic Unit	Unit Type	Hydraulic Conductivity (ft/s) Horizontal	Vertical
Sand and Gravel	Aquifer	$2x10^{-3}$	$2x10^{-3}$
Silty Sand and Gravel	Aquifer	$2x10^{-4}$	$2x10^{-4}$
Clayey/Silty Sand and Gravel	Aquifer	$9x10^{-5}$	$9x10^{-5}$
Clayey Sand and Gravel	Aquifer	$4x10^{-5}$	$4x10^{-5}$
Sandy/Gravelly Silt	Aquifer	$2x10^{-5}$	$2x10^{-5}$
Clayey/Sandy Silt	Semi-Confining	$9x10^{-6}$	$9x10^{-6}$
Silt	Semi-Confining	$4x10^{-6}$	$4x10^{-6}$
Clayey Silt/Silty Clay	Confining	$7x10^{-7}$	$7x10^{-7}$
Clay	Confining	$1x10^{-7}$	$1x10^{-7}$
Weathered Bedrock	Aquifer	$3x10^{-6}$	$3x10^{-6}$

Sources: PLP 2019-RFI153; BGC 2019h

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0.5 0 0.5 1

Miles

Hydrogeologic Unit (and Unit Type)

- Sand and Gravel (Aquifer)
- Silty Sand and Gravel (Aquifer)
- Clayey/Silty Sand and Gravel (Aquifer)
- Clayey Sand and Gravel (Aquifer)
- Sandy/Gravelly Silt (Aquifer)
- Clayey/Sandy Silt (Semi-Confining)
- Silt (Semi-Confining)
- Clay (Confining)
- Weathered Bedrock (Aquifer)
- Model Domain (Overview Map)

Alternative 1a

- Mine Site

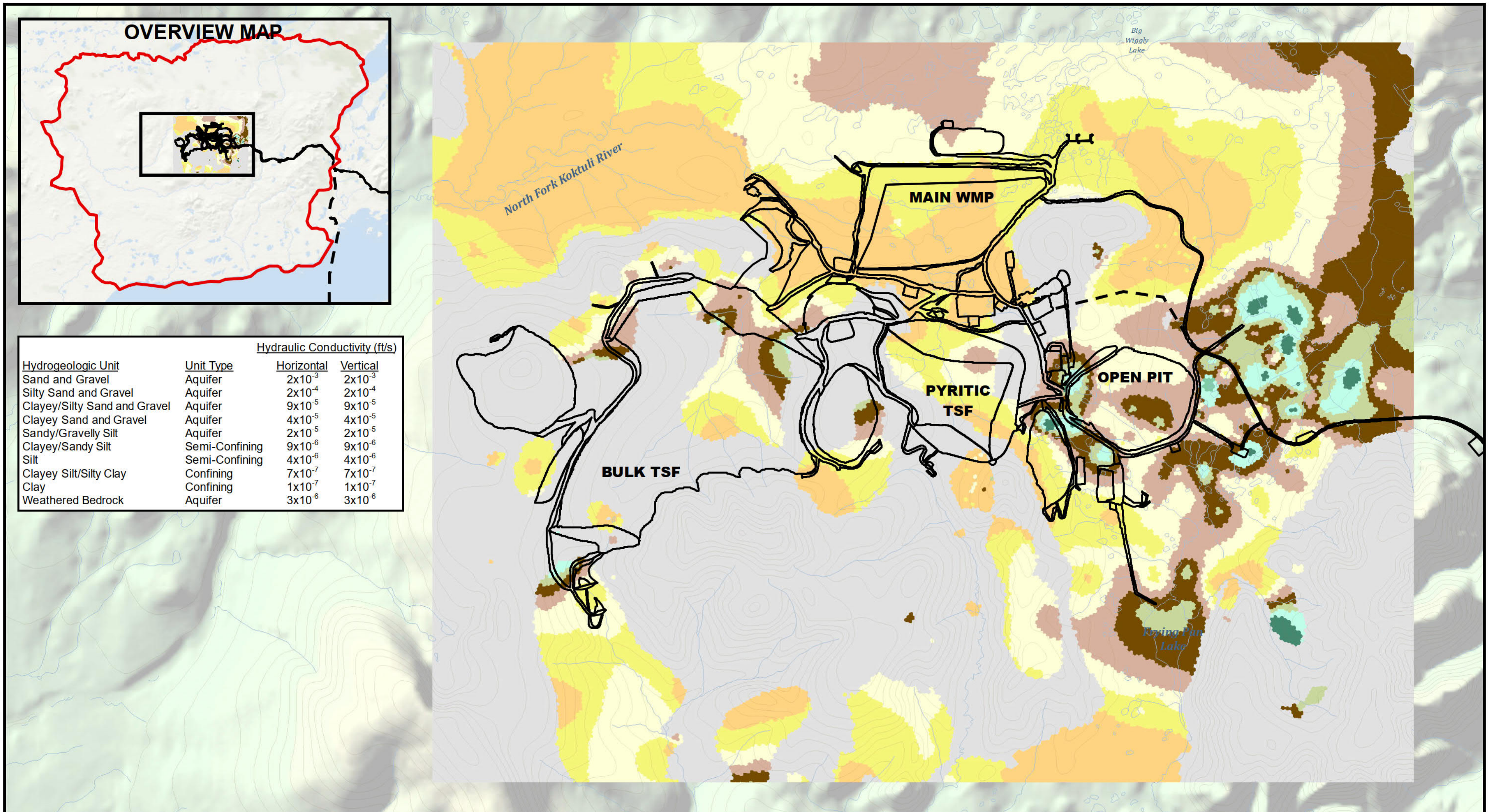
Other Features

- River/Stream
- Lake/Pond
- 100' Contour (Existing)

HYDRAULIC CONDUCTIVITY: MODEL LAYER 1

PEBBLE PROJECT EIS

FIGURE K3.17-7



Hydrogeologic Unit	Unit Type	Hydraulic Conductivity (ft/s) Horizontal	Vertical
Sand and Gravel	Aquifer	2×10^{-3}	2×10^{-3}
Silty Sand and Gravel	Aquifer	2×10^{-4}	2×10^{-4}
Clayey/Silty Sand and Gravel	Aquifer	9×10^{-5}	9×10^{-5}
Clayey Sand and Gravel	Aquifer	4×10^{-5}	4×10^{-5}
Sandy/Gravelly Silt	Aquifer	2×10^{-5}	2×10^{-5}
Clayey/Sandy Silt	Semi-Confining	9×10^{-6}	9×10^{-6}
Silt	Semi-Confining	4×10^{-6}	4×10^{-6}
Clayey Silt/Silty Clay	Confining	7×10^{-7}	7×10^{-7}
Clay	Confining	1×10^{-7}	1×10^{-7}
Weathered Bedrock	Aquifer	3×10^{-6}	3×10^{-6}

Sources: PLP 2019-RFI153; BGC 2019h

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0.5 0 0.5 1
Miles

Hydrogeologic Unit (and Unit Type)
- Sand and Gravel (Aquifer)
- Silty Sand and Gravel (Aquifer)
- Clayey/Silty Sand and Gravel (Aquifer)
- Clayey Sand and Gravel (Aquifer)
- Sandy/Gravelly Silt (Aquifer)
- Clayey/Sandy Silt (Semi-Confining)
- Silt (Semi-Confining)
- Clayey Silt/Silty Clay (Confining)
- Clay (Confining)
- Weathered Bedrock (Aquifer)
- Model Domain (Overview Map)

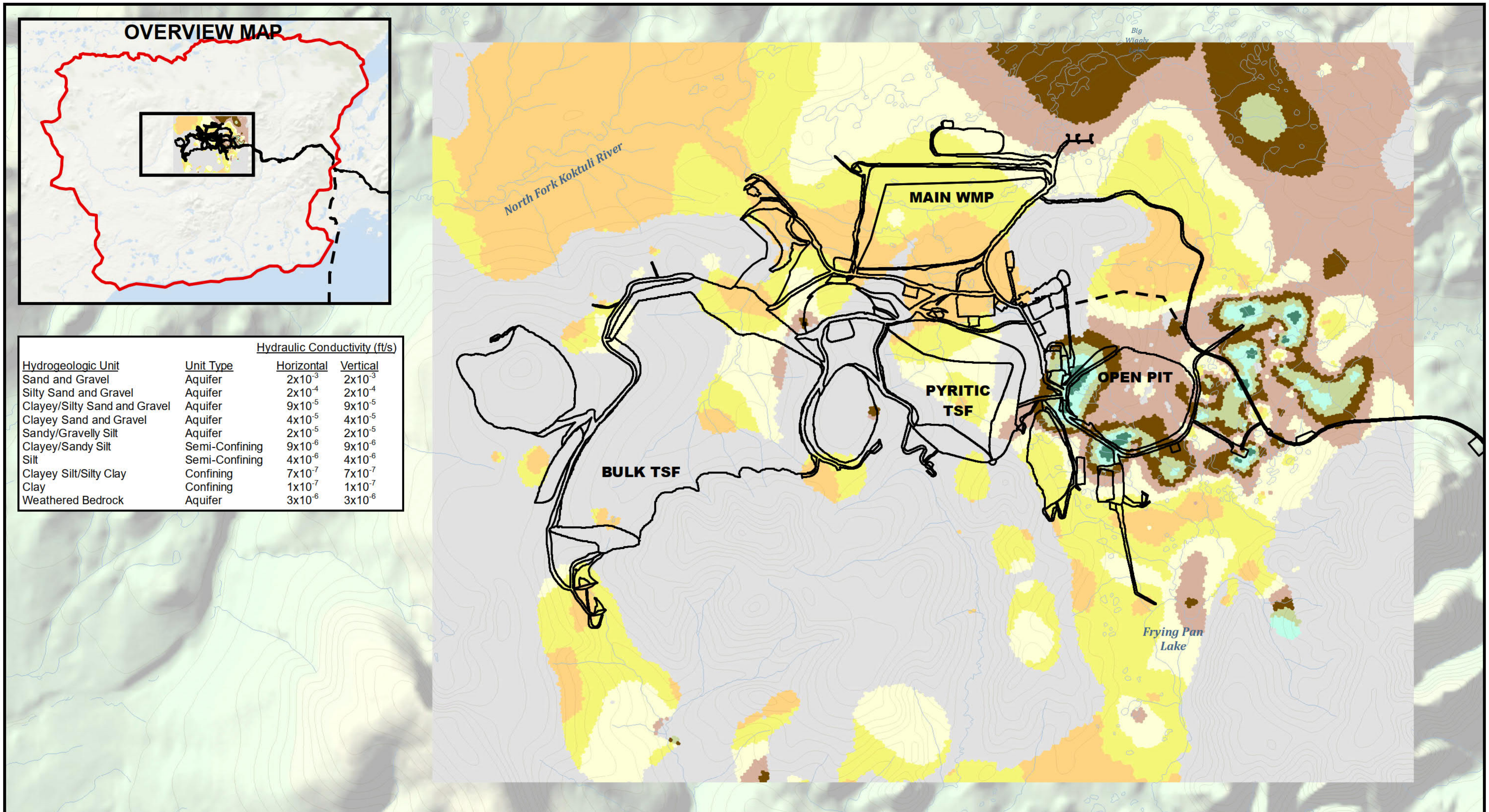
Alternative 1a
- Mine Site

Other Features
- River/Stream
- Lake/Pond
- 100' Contour (Existing)

HYDRAULIC CONDUCTIVITY: MODEL LAYER 2

PEBBLE PROJECT EIS

FIGURE K3.17-8



Hydrogeologic Unit	Unit Type	Hydraulic Conductivity (ft/s) Horizontal	Vertical
Sand and Gravel	Aquifer	2×10^{-3}	2×10^{-3}
Silty Sand and Gravel	Aquifer	2×10^{-4}	2×10^{-4}
Clayey/Silty Sand and Gravel	Aquifer	9×10^{-5}	9×10^{-5}
Clayey Sand and Gravel	Aquifer	4×10^{-5}	4×10^{-5}
Sandy/Gravelly Silt	Aquifer	2×10^{-5}	2×10^{-5}
Clayey/Sandy Silt	Semi-Confining	9×10^{-6}	9×10^{-6}
Silt	Semi-Confining	4×10^{-6}	4×10^{-6}
Clayey Silt/Silty Clay	Confining	7×10^{-7}	7×10^{-7}
Clay	Confining	1×10^{-7}	1×10^{-7}
Weathered Bedrock	Aquifer	3×10^{-6}	3×10^{-6}

Sources: PLP 2019-RFI153; BGC 2019h

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0.5 0 0.5 1

Miles

Hydrogeologic Unit (and Unit Type)

- Sand and Gravel (Aquifer)
- Silty Sand and Gravel (Aquifer)
- Clayey/Silty Sand and Gravel (Aquifer)
- Clayey Sand and Gravel (Aquifer)
- Sandy/Gravelly Silt (Aquifer)
- Clayey/Sandy Silt (Semi-Confining)
- Silt (Semi-Confining)
- Clayey Silt/Silty Clay (Confining)
- Clay (Confining)
- Weathered Bedrock (Aquifer)
- Model Domain (Overview Map)

Alternative 1a

- Mine Site

Other Features

- River/Stream
- Lake/Pond
- 100' Contour (Existing)

HYDRAULIC CONDUCTIVITY: MODEL LAYER 3

PEBBLE PROJECT EIS

FIGURE K3.17-9

K3.17.3 Aquifer Properties—Hydraulic Conductivity and Storativity

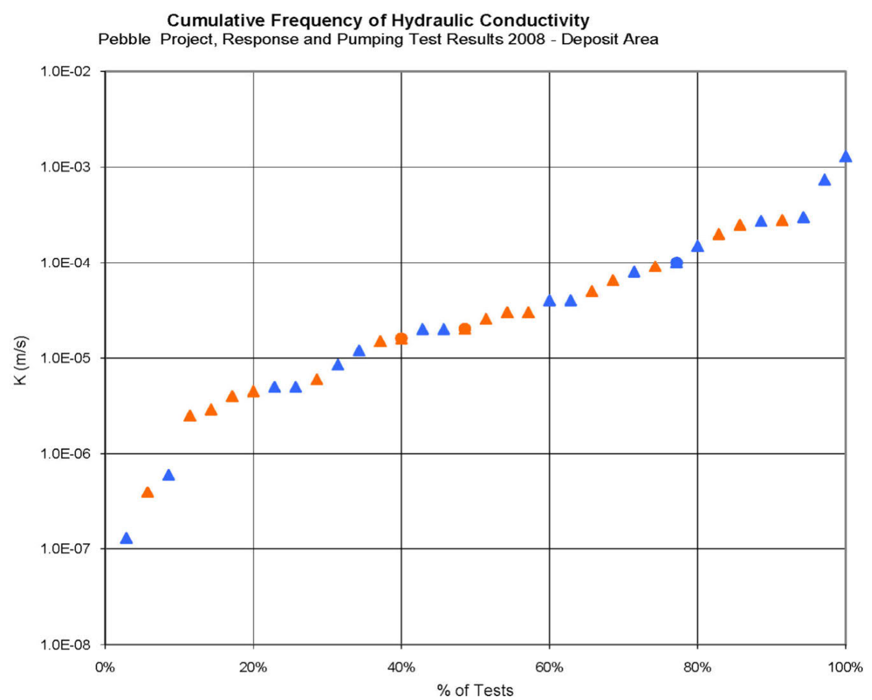
Table K3.17-2 and Figure K3.17-10 through Figure K3.17-14 provide a summary of hydraulic conductivity testing conducted at the mine site, based on individual testing results presented in Schlumberger (2015a) and as presented by BGC (2019f).

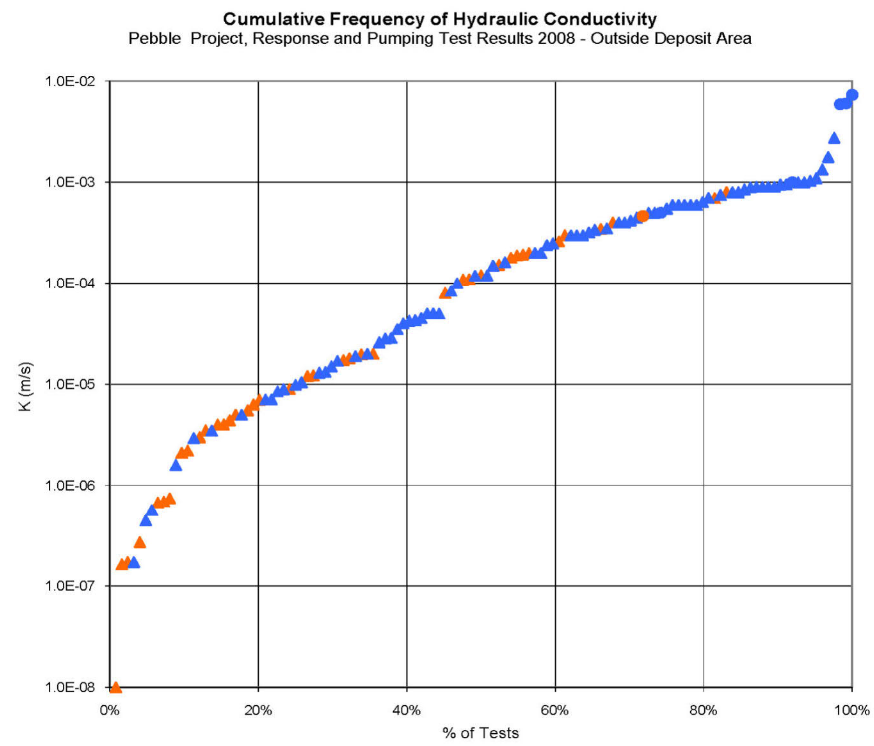
Table K3.17-2: Summary of Hydraulic Conductivity Testing Results from Slug Tests

Aquifer	Statistic	Hydraulic Conductivity (m/s)				
		Pebble Deposit Area	Frying Pan Lake Area	South Fork Koktuli Area	North Fork Koktuli Area	Upper Talarik Area
Overburden	Number of Tests	33	6	45	22	4
	Geometric Mean	2.23×10^{-5}	6.40×10^{-5}	1.00×10^{-4}	9.74×10^{-5}	1.05×10^{-5}
	Median	3.00×10^{-5}	3.25×10^{-4}	4.00×10^{-4}	3.00×10^{-4}	1.45×10^{-5}
	Maximum	1.30×10^{-3}	8.70×10^{-4}	1.00×10^{-3}	1.78×10^{-3}	4.24×10^{-5}
	Minimum	5.10×10^{-8}	6.10×10^{-8}	7.00×10^{-8}	7.80×10^{-9}	1.60×10^{-6}
Bedrock	Number of Tests	52	10	20	50	8
	Geometric Mean	1.78×10^{-5}	4.38×10^{-6}	2.00×10^{-5}	9.68×10^{-7}	1.86×10^{-6}
	Median	1.65×10^{-5}	8.50×10^{-6}	5.00×10^{-5}	9.15×10^{-7}	4.50×10^{-6}
	Maximum	1.40×10^{-3}	9.13×10^{-5}	3.00×10^{-3}	3.00×10^{-4}	2.00×10^{-5}
	Minimum	3.95×10^{-7}	1.60×10^{-8}	1.00×10^{-8}	9.40×10^{-9}	1.73×10^{-7}

Note:
m/s = meters per second

Source: Schlumberger 2015a (Tables 8.1-1 through 8.1-5)





Source: Schlumberger 2015a, Figure 8.1-9b

Legend:

- Pumping test - bedrock
- Pumping test - overburden
- Response test - bedrock
- Response test - overburden

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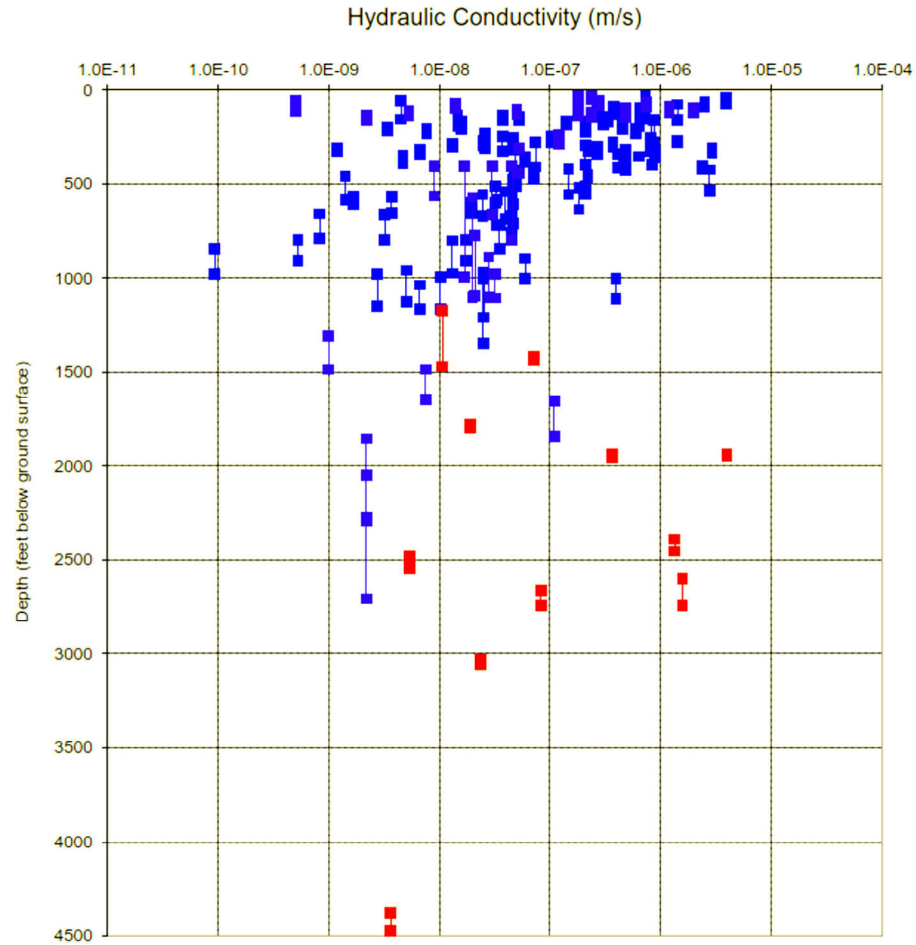
CUMULATIVE FREQUENCY OF HYDRAULIC CONDUCTIVITY MEASUREMENTS FROM PUMPING AND RESPONSE TESTS



Source: Schlumberger 2015a, Figure 8.1-11a

Legend

Packer Testing Interval Collected by Knight Piesold (2004 to 2012) (2004 to 2008)

Packer Testing Interval Collected by SLR

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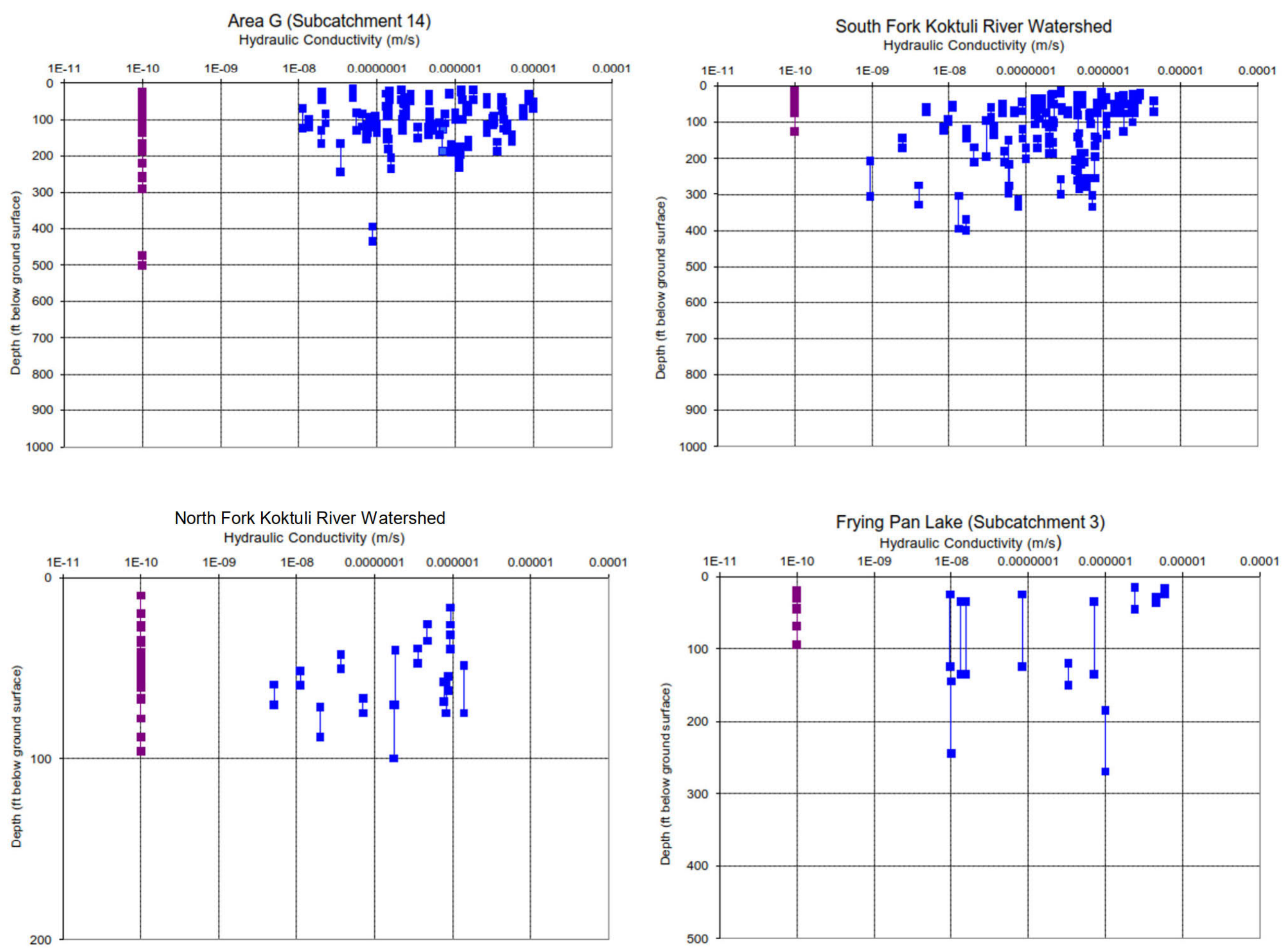
HYDRAULIC CONDUCTIVITY IN BEDROCK VERSUS DEPTH IN PEBBLE DEPOSIT AREA FROM PACKER TESTS



Source: Schlumberger 2015a, Figure 8.1-11b

Legend

Packer Testing Intervals Collected by Knight Piesold (2004 to 2012)

Packer Testing Interval with No Water Take

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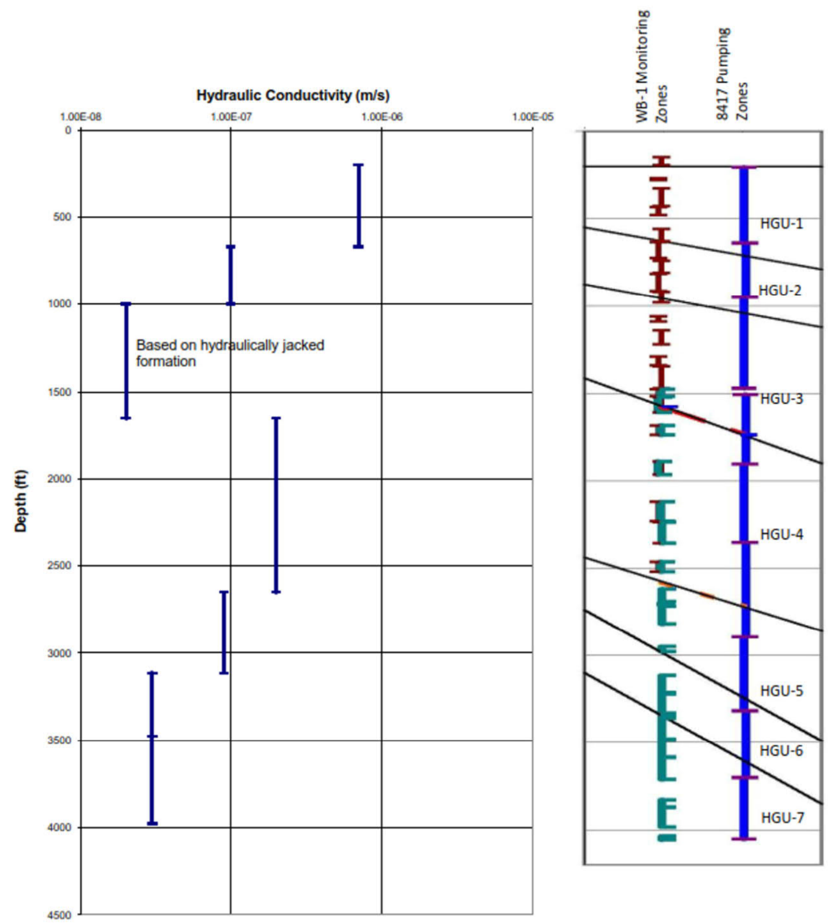
HYDRAULIC CONDUCTIVITY IN BEDROCK VERSUS DEPTH OUTSIDE THE PEBBLE DEPOSIT AREA FROM PACKER TESTS



Note: HGU = Hydrogeologic Unit

Source: Schlumberger 2015a, Figure 8.1-11c

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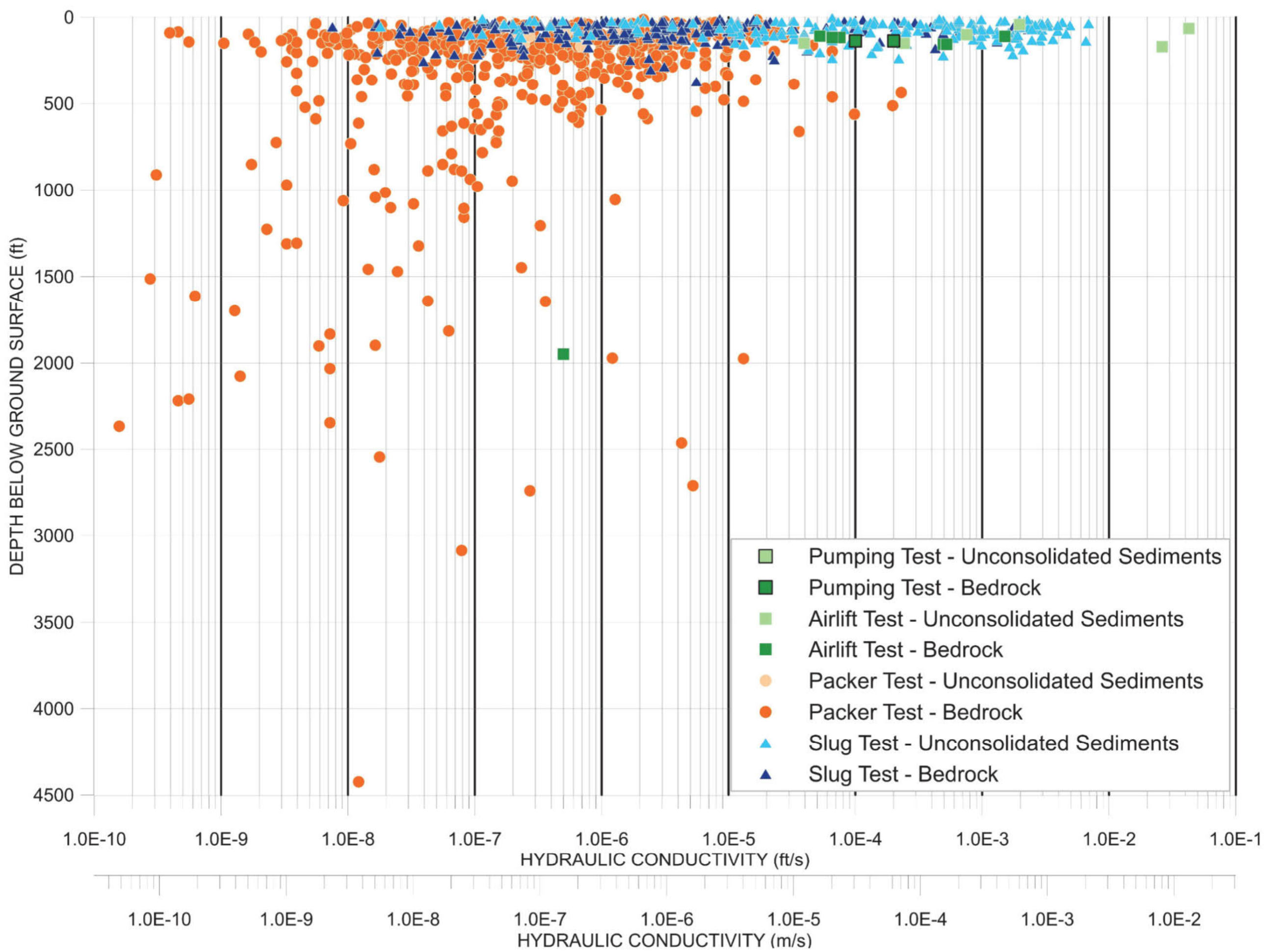
HYDRAULIC CONDUCTIVITY PROFILE FOR DEEP BEDROCK

PEBBLE PROJECT EIS

FIGURE K3.17-13



Source: BGC 2019f

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HYDRAULIC CONDUCTIVITY ESTIMATES WITH DEPTH: ALL TESTING DATA COMBINED

Based on a total of 110 response tests, the hydraulic conductivity of overburden ranges from 7.8x10^{-9} to 1.78x10^{-3} m/s in the mine site. The hydraulic conductivity of overburden is similar throughout the mine site, with geometric mean values between 1.05x10^{-5} m/s and 1.0x10^{-4} m/s for each area. Hydraulic conductivity values for overburden materials in the Pebble deposit and UTC areas were an order of magnitude lower than those measured in the rest of the mine site based on the median values, likely due to the presence of silty deposits in this area.

Based on a total of 140 response tests, the hydraulic conductivity of bedrock ranges from 9.4x10 ^{9} to 3.0x10^{-3} m/s in the mine site. Similar to overburden, the hydraulic conductivity of the bedrock is about the same throughout the mine site, with geometric mean values between 9.7x10^{-7} and 2.0x10^{-5} m/s. Hydraulic conductivity values for bedrock in the Pebble deposit and SFK areas are about 1 to 2 orders of magnitude higher than those measured in the NFK and UTC areas, possibly due to the presence of batholith granodiorite in parts of these areas.

Larger-scale hydraulic conductivity values were also assessed by conducting nine pumping tests, finding that the hydraulic conductivity of overburden was almost 10 times higher than values derived from response tests (Schlumberger 2011a). Pumping rates ranged from approximately 10 to 356 gallons per minute (gpm); although seven of the nine tests reported well yields between 45 and 85 gpm. Water-level responses were observed at monitoring wells up to 760 feet away from the pumping wells, allowing for a more representative analysis of aquifer transmissivity (hydraulic conductivity) and storativity (specific yield) than is possible using response testing and packer testing alone. Detailed analyses and results are presented in Schlumberger (2011a: Table 8.1-6). Calculated transmissivity values ranged from 8.0x10^{-5} to 1.1x10^{-1} square meters per second (m^2/s), indicating the aquifers are capable of conveying moderate to large quantities of groundwater. Calculated storativity values ranged from 1x10^{-5} to 2.5x10^{-2}, which is characteristic of confined aquifers. Calculated specific yield values range from 0.02 to 0.1, which is characteristic of unconfined aquifers. This indicates that single-well response testing may underestimate the hydraulic conductivity of the aquifer, which may be due to constrictions associated with the well screen, surrounding sand filter pack, and/or borehole damage during drilling. Pumping test results for wells completed in weathered bedrock were similar to those for response tests.

Hydraulic conductivity values were also measured by conducting borehole packer testing and Lugeon tests as part of geotechnical investigations to depths of up to 4,500 feet near the Pebble deposit, and at depths of up to 400 feet outside of the deposit area. The highest values were typically measured in the upper 500 feet, but similar values were also measured at considerable depths. Examination of Figure K3.17-13 shows 24 measured values of hydraulic conductivity at depths below 1,500 feet below land surface, most of which are below the planned depth of the pit, suggesting that hydraulic conductivity of deep bedrock is adequately characterized. Overall, bedrock hydraulic conductivity values are lower at depth than shallow bedrock in the deposit area. The available data support the conceptual model that there is a widely occurring upper zone of fractured and weathered bedrock approximately 50 feet thick with hydraulic conductivity, with a mean of approximately 1x10^{-6} m/s, underlain by deeper bedrock with less weathering and fewer fractures with a mean hydraulic conductivity approximately two orders of magnitude lower, around 1x10^{-8} m/s. However, in each bedrock zone there is considerable local variability, plus or minus two to three orders of magnitude (multiplication factor of 100 to 1,000) in each zone.

K3.17.4 Groundwater Flow Seasonality

Hydrographs of monitoring wells (MW) MW-11 (SFK Flats area) and MW-5 (Pebble deposit area) are shown in Figure K3.17-15 and Figure K3.17-16 to illustrate short-term and seasonal groundwater-level fluctuations. These examples show groundwater levels from three to four different screened intervals (at different depths) over a 9-year period compared to precipitation and stream flow.

The water table typically lies at the greatest depths below upland areas, and is near the surface in valley bottoms. The lowest groundwater levels were typically recorded during late winter immediately prior to spring freshet, while the highest water levels were typically observed during spring freshet or during fall rains, with water levels fluctuating on the order of 10 feet to 20 feet seasonally. Vertical groundwater gradients were found to be variable; both in time and with depth. Similar to groundwater levels, measured discharge from seeps varied by a factor of between 3 and 10 seasonally, with a median flow of 44 gpm.

Based on the results of tritium analysis, the majority of the groundwater in mine site aquifers was likely recharged after 1972, which indicates that groundwater moves through the aquifers relatively quickly. This interpretation is supported by the measurement of relatively high hydraulic conductivities in overburden and shallow bedrock, and the seasonal behavior of groundwater levels and the discharges of seeps in response to rainfall and snowmelt.

K3.17.5 Site Water Balance Model

A detailed description of the site baseline watershed model is provided in Schlumberger (2011a: Appendix 8.1I; Knight Piésold 2019f). The model was used to validate the meteoric data and the variability in precipitation across the site. Continuous streamflow records from a total of 12 gauging stations were used to calibrate the model from 2004 to 2008. Sub-catchments were delineated and drainage areas calculated for each gauging station. Inputs to the model and calibration are further described in Section 3.16, Surface Water Hydrology.

The results of the watershed model indicate that groundwater recharge varies from 11 to 23 inches per year for the NFK River, UTC, and SFK River drainage areas. The majority of groundwater that recharges in each catchment tends to discharge to surface in the same drainage, with the exception of the inter-catchment transfer of approximately 21 cfs that occurs between the SFK River and UTC drainages, and 0.9 cfs estimated to flow from the NFK watershed to the UTC watershed (Knight Piésold 2019h).

In 2018, the water balance model was recalibrated and climate variability was incorporated to a larger degree than earlier baseline efforts with development of a 76-year synthetic record of monthly temperature and precipitation, as described in the hydrometeorology report (Knight Piésold 2018g).

K3.17.6 Mine Site Groundwater Model

A groundwater flow model was initially developed in 2004 through 2008 (Schlumberger 2011a), and progressively updated through 2013 to better represent the groundwater flow system and improve the match to observed groundwater elevations and streamflows (Schlumberger 2015a; Piteau Associates 2018a; Knight Piésold 2018n). A new groundwater flow model was subsequently developed (BGC 2019a), and is the basis for all analysis in this EIS. The BGC (2019a) version of the model was used for the effects analysis discussed in Section 4.17, Groundwater Hydrology.

The finite difference code MODFLOW-USG (Panday et al. 2013) was used to construct the three-dimensional groundwater flow model. This code is based on an industry-standard US Geological Survey (USGS)-developed code, MODFLOW, which has been widely used for groundwater flow simulations of this nature for more than 30 years. Other numerical codes were considered as part of the code selection processes, including fully integrated codes that solve for surface water, unsaturated zone, and groundwater flow simultaneously. Fully integrated codes were not selected for use due to the large amount of data required to adequately parameterize a model of the scale required for the project, as well as substantial execution times required for the large number of simulations performed to simulate multiple mine scenarios and parameter sensitivity analysis runs. The groundwater flow model was used to perform a robust uncertainty analysis that likely would have been prohibitively difficult or impossible using a fully integrated code.

The model domain encompasses a total area of about 1,100 square miles, and includes the majority of the mine site and subcatchments that were included in the watershed model (Figure K3.17-17). A grid was developed consisting of 80,211 cells per layer for 12 layers, totaling 962,532 model cells. In the mine area, model cells are approximately 300 feet across. The complex site geology was translated into the groundwater model using three layers to represent overburden units, which vary laterally in thickness, grain size, and permeability (Figure K3.17-18). The fourth layer represents the uppermost 50 feet of fractured and weathered bedrock, and the fifth through twelfth layers represent the underlying bedrock to an elevation of 5,500 feet below mean sea level.

Boundary conditions that characterize groundwater inflows and outflows were defined using the following MODFLOW packages: rivers, lakes, and streams were represented using the streamflow routing or general head boundary packages; seeps or springs using the drain (DRN) package; meteoric recharge using the recharge (RCH) package; and groundwater evapotranspiration (EVT) using the EVT Package. Inflow and outflow at the domain edges were represented with DRN or Specified Gradient Boundaries packages.

The RCH Package assumes that flow through the unsaturated zone is relatively rapid, and there are no changes to the amount of water in storage during the simulation. This is reasonable, considering that soils are relatively permeable throughout much of the area; water tables are not deep in most places; and groundwater-level data show rapid responses to precipitation events (Figure K3.17-15 and Figure K3.17-16). Initial recharge values were assigned to individual grid cells based on calculations performed exterior to the model. Initial recharge was determined by subtracting actual evapotranspiration and sublimation from precipitation, partitioning out surface water runoff, and considering soil types. Recharge values were subsequently adjusted through a calibration process, and ranged from 2 inches per year (in/yr) to 31.5 in/yr in the calibrated model.

Maximum groundwater evapotranspiration was set to be equal to the difference between potential and actual evapotranspiration (which varied according to month). The actual groundwater evapotranspiration was computed by the groundwater flow model based on the simulated water table depth. In unconsolidated soils where the water table was 2 feet or more below ground surface or in bedrock areas where the water table was 1 foot or more below ground surface, groundwater evapotranspiration was assumed to be 0.

According to BGC (2019g), groundwater outflow or discharge from the model was simulated at ground surface as seepage using the DRN package. Water removed from the model through this boundary condition was tracked in the model output and treated as runoff to the simulated surface-water network. Although this methodology does not allow the discharged water to recharge the groundwater system further downslope, this is considered a reasonable approach, considering the relatively steep topography in the area.

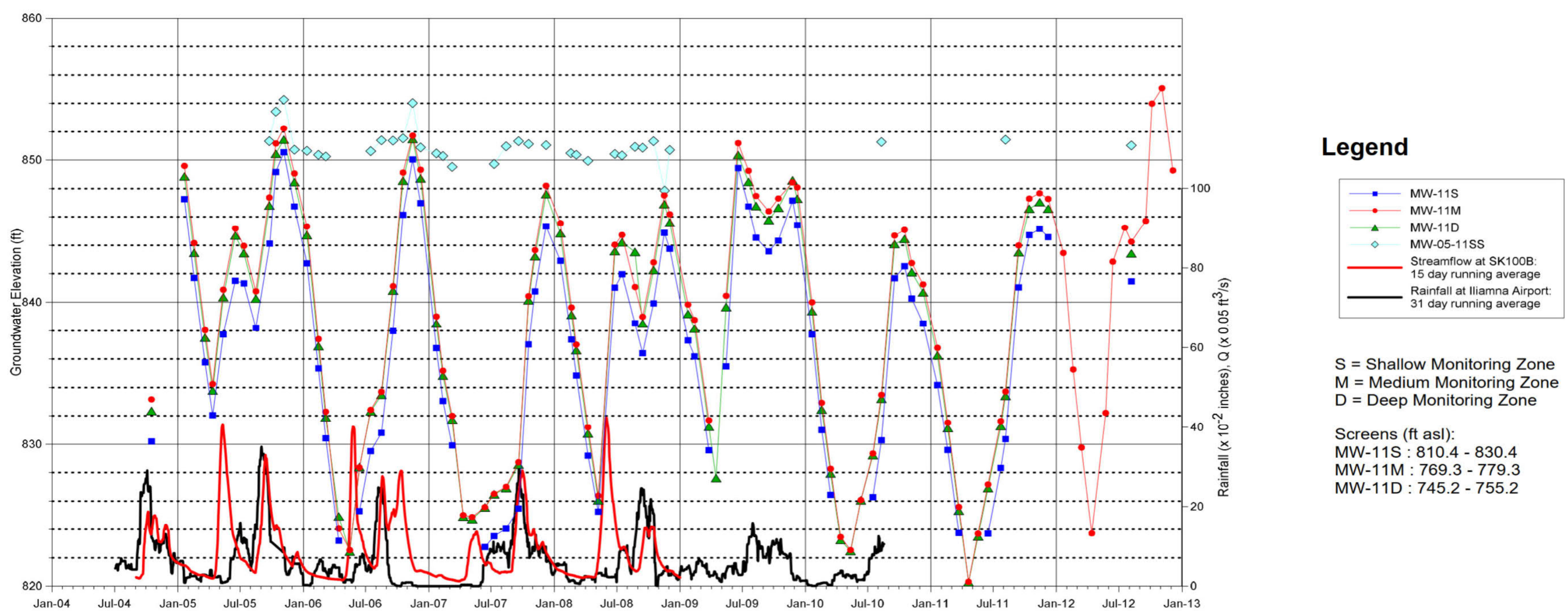
In the project area, many seeps are quickly responsive and exhibit highly variable flow depending on recent rainfall events or snowmelt water activity. As a result of the generally transient and variable nature of measured seep flows, groundwater seeps were not used as quantitative targets for calibration of the groundwater flow model. Instead, visual comparison of seepage locations relative to observed locations was used to qualitatively evaluate results of the groundwater flow model.

Hydrogeologic units representing overburden in the model domain were represented by different hydraulic conductivity zones based on aquifer material types, thicknesses, and positions in the model domain. Geologic cross-sections such as those shown in Section 3.17, Groundwater Hydrology, Figure 3.17-5 through Figure 3.17-9, were used to define areas of similar aquifer materials in the upper three layers. Initial vertical and horizontal hydraulic conductivity and storage values were assigned to each zone based on the results of aquifer-test data, and were subsequently adjusted through model calibrations (BGC 2019a).

Because groundwater levels and flow exhibit strong seasonality in long-term average conditions, the model was developed as both a steady-state and a transient model. The transient model used monthly timesteps to simulate monthly average groundwater levels and streamflow data from 2004 to 2012. Although hydrologic events are known to occur on shorter (hourly or daily) timeframes, most of the impacts to groundwater estimated to occur from Alternative 1a are large-scale and long-term effects that are adequately understood with monthly timesteps. Projected changes in wintertime baseflow, for example, can be evaluated in the context of wintertime streamflow, which tends to be relatively constant over the duration of a typical wintertime month such as January or February.

The groundwater model was calibrated under four conditions: 1) steady-state simulation (average annual); 2) transient simulation of average monthly conditions; 3) simulation of 2004 to 2012 conditions; and 4) simulation of an aquifer test with several monitoring wells.

The calibrated groundwater model produced water table (hydraulic head) elevations and streamflows that follow the same general pattern as field measurements. The Normalized Root Mean Square Error of 2 percent for groundwater levels and 6.6 percent for stream flows, respectively, are well within recommended guidelines (NBLM 2006; BCMOE 2012). A total of 551 locations with data spanning 2004-2012 was used to calibrate hydraulic heads and calculate hydraulic head residuals to evaluate the calibration of the model. Summary statistics and evaluation of results indicated that the model adequately represented groundwater levels, the direction of vertical hydraulic groundwater gradients, and stream flows (BGC 2019a). In particular, the average condition of the hydrogeologic system was well-replicated by the steady-state model; simulated seasonal trends in stream flows are well-represented by the transient model; the model provided a good representation of changes in groundwater levels and stream flows for the 2004-2012 period of simulation; and the model well-replicated the response to pumping at the GH12-334S pumping test (BGC 2019a).



Source: Schlumberger 2015a, Figure 8.1-13a

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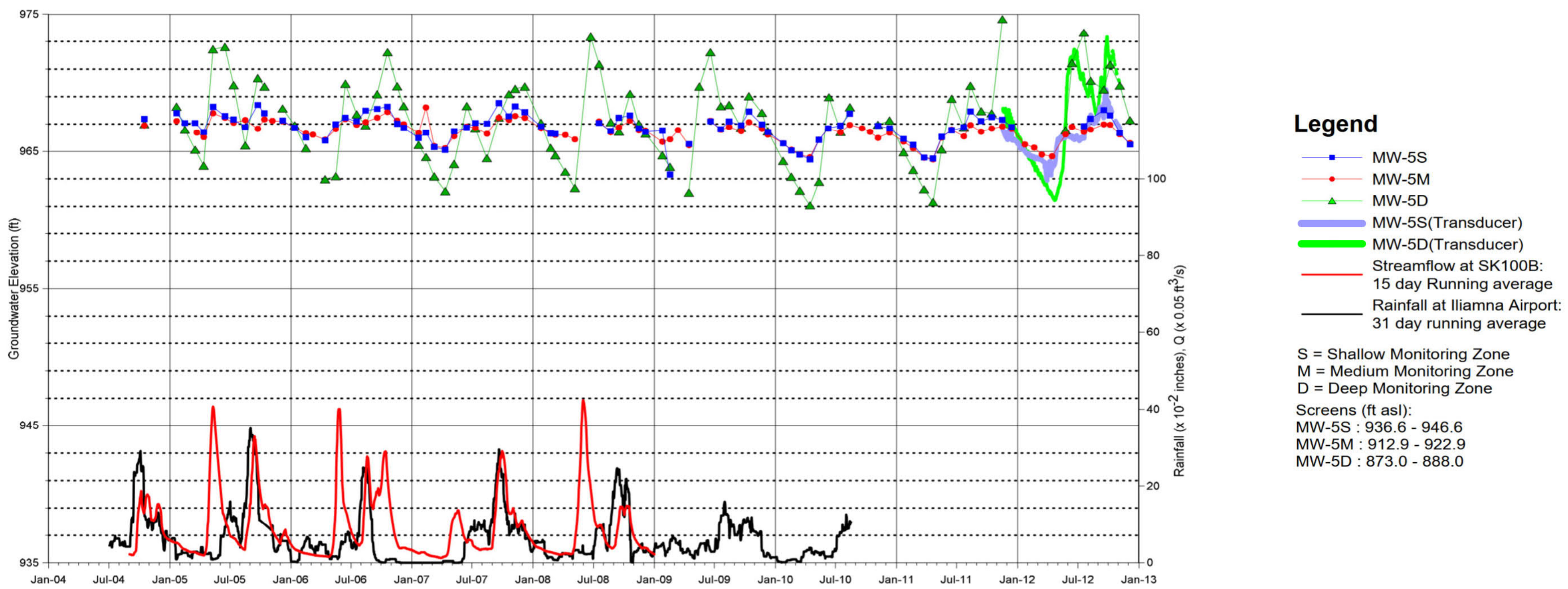
TIME SERIES OF PIEZOMETRIC ELEVATIONS, SOUTH FORK KOKTULI FLATS AREA, 2004-2009



Source: Schlumberger 2015a, Figure 8.1-13b

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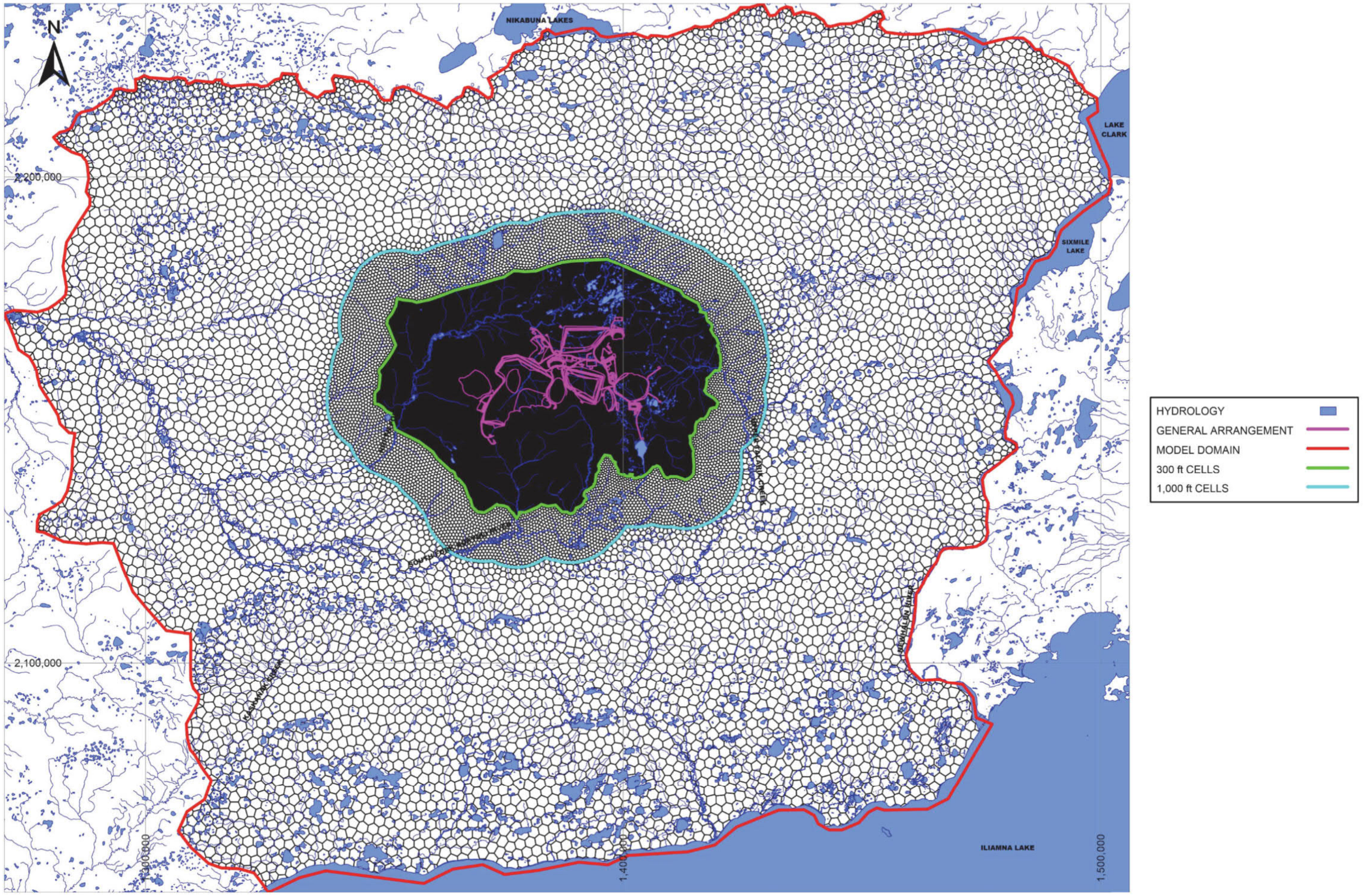
TIME SERIES OF PIEZOMETRIC ELEVATIONS, PEBBLE DEPOSIT AREA, 2004-2009

PEBBLE PROJECT EIS

FIGURE K3.17-16



Source: BGC 2019a

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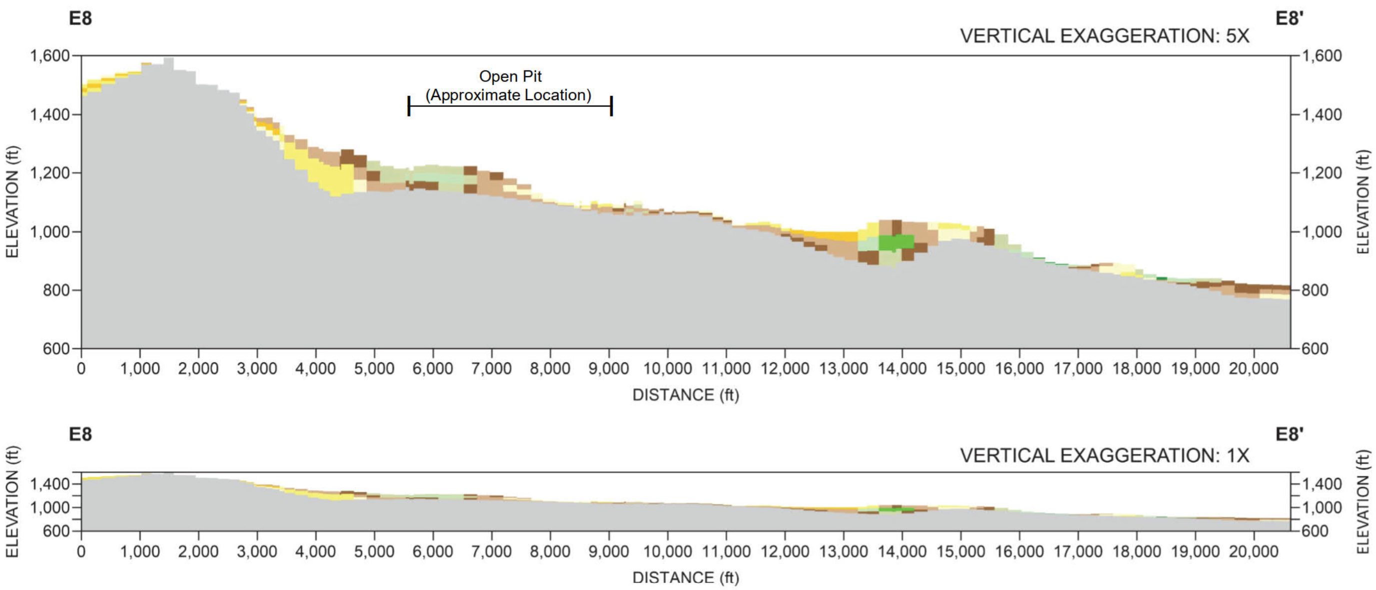
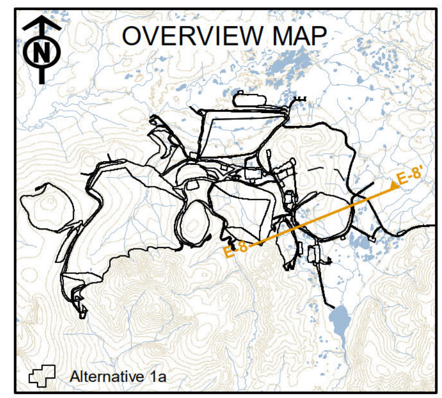
GROUNDWATER MODEL GRID

PEBBLE PROJECT EIS

FIGURE K3.17-17



GENERAL ARRANGEMENT
MODEL DOMAIN
CROSS-SECTION
HYDROGEOLOGIC UNIT
SAND AND GRAVEL
SILTY SAND AND GRAVEL
CLAYEY/SILTY SAND AND GRAVEL
CLAYEY SAND AND GRAVEL
SANDY/GRAVELLY SILT
CLAYEY/SANDY SILT
SILT
CLAYEY SILT/SILTY CLAY
CLAY
BEDROCK



Source: BGC 2019a

US Army Corps of Engineers

MODEL-ASSIGNED HYDROGEOLOGIC UNITS ALONG SURFICIAL GEOLOGY CROSS-SECTION E-8

The final calibrated model used uniform values of hydraulic conductivity of $1x10^{-6}$ m/s for the weathered bedrock zone and $1x10^{-8}$ m/s for the competent bedrock zone. These values are representative of the wide range of measured values of hydraulic conductivity in the area (Figure K3.17-14). Most of the measured values of hydraulic conductivity were obtained from single-well testing that measures only a small portion of an aquifer around a well compared to the hundreds of feet of a typical cell size in the groundwater model. This difference in scale, together with the wide range of measured hydraulic conductivity values, results in hydraulic conductivity being commonly recognized as a major source of uncertainty in groundwater models. To address this, sensitivity analyses were performed that varied these values (increase and decrease) by factors of 10, and the results have been propagated through other hydrologic analyses to assess the influence of this uncertainty on prediction of impacts in this EIS. The results of this approach are presented in more detail in Section 4.17 and Appendix K4.17, Groundwater Hydrology.

The sensitivity of groundwater model results to variations in input parameters was tested using many different model parameter and boundary condition variations. These variations of inputs included recharge, unconsolidated sediment and bedrock hydraulic conductivity, streambed hydraulic conductivity, faults, and bulk TSF tailings hydraulic conductivity and pond configurations. The hydraulic conductivity of bedrock was found to be one of the most important factors influencing model results, along with the hydraulic conductivity of faults, so these two parameters were varied under different project development and closure scenarios to determine the possible range of variability in predictive components of this EIS. All of the sensitivity analyses considered were deemed to be plausible, except a few that are specifically described in Section 4.17 and Appendix K4.17, Groundwater Hydrology, as not plausible, based on model results (e.g., severely deteriorated model calibration results).