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

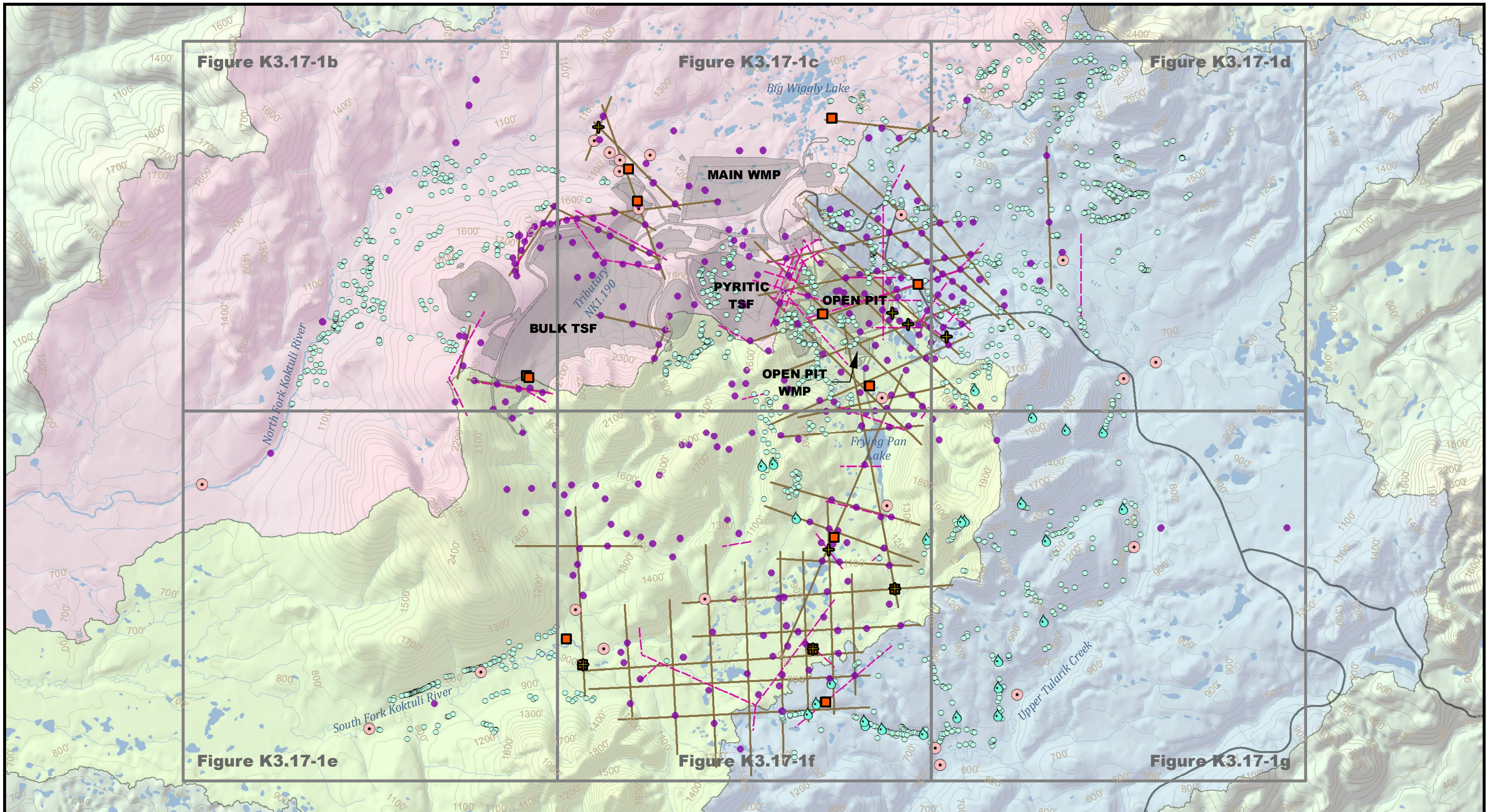
Hydrogeological data were collected during the course of several field programs between 2004 and 2012 (Schlumberger 2011a, 2015a), which involved logging of borings, installation of pumping wells, piezometers, and monitoring wells, as well as permeability testing, streamflow gauging, monitoring of meteoric inputs and routine monitoring of groundwater levels, and collection of streamflow and groundwater quality data. The location and identification numbers for these data points are shown on Figure K3.17-1a through Figure K3.17-1g. 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 pumping wells were installed using air rotary drilling techniques and telescopic well screens, 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, but these wells have not yet been tested.



Sources: Schlumberger 2011a, Figures 8.1-4 and 9.1-5
Note: Well depths and completions are provided in Table K3.18-17.

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

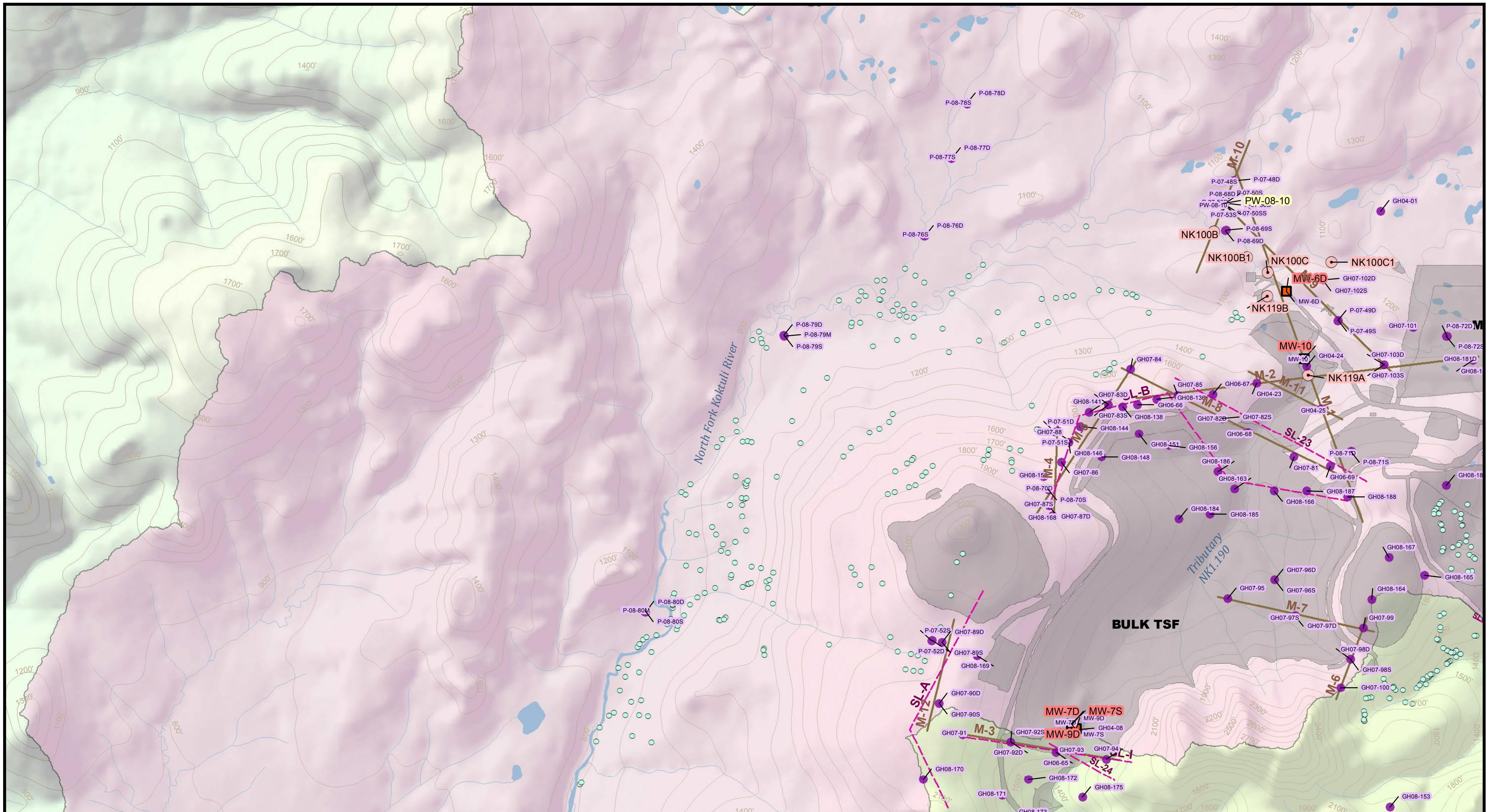
Alternative 1
- Mine Site
- Transportation Corridor
- Natural Gas Pipeline

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

WELL, PIEZOMETER, AND SEEP LOCATIONS - MAP INDEX

PEBBLE PROJECT EIS

FIGURE K3.17-1a



Sources: Schlumberger 2011a, Figures 8.1-4 and 9.1-5
Note: Well depths and completions are provided in Table K3.18-17.

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

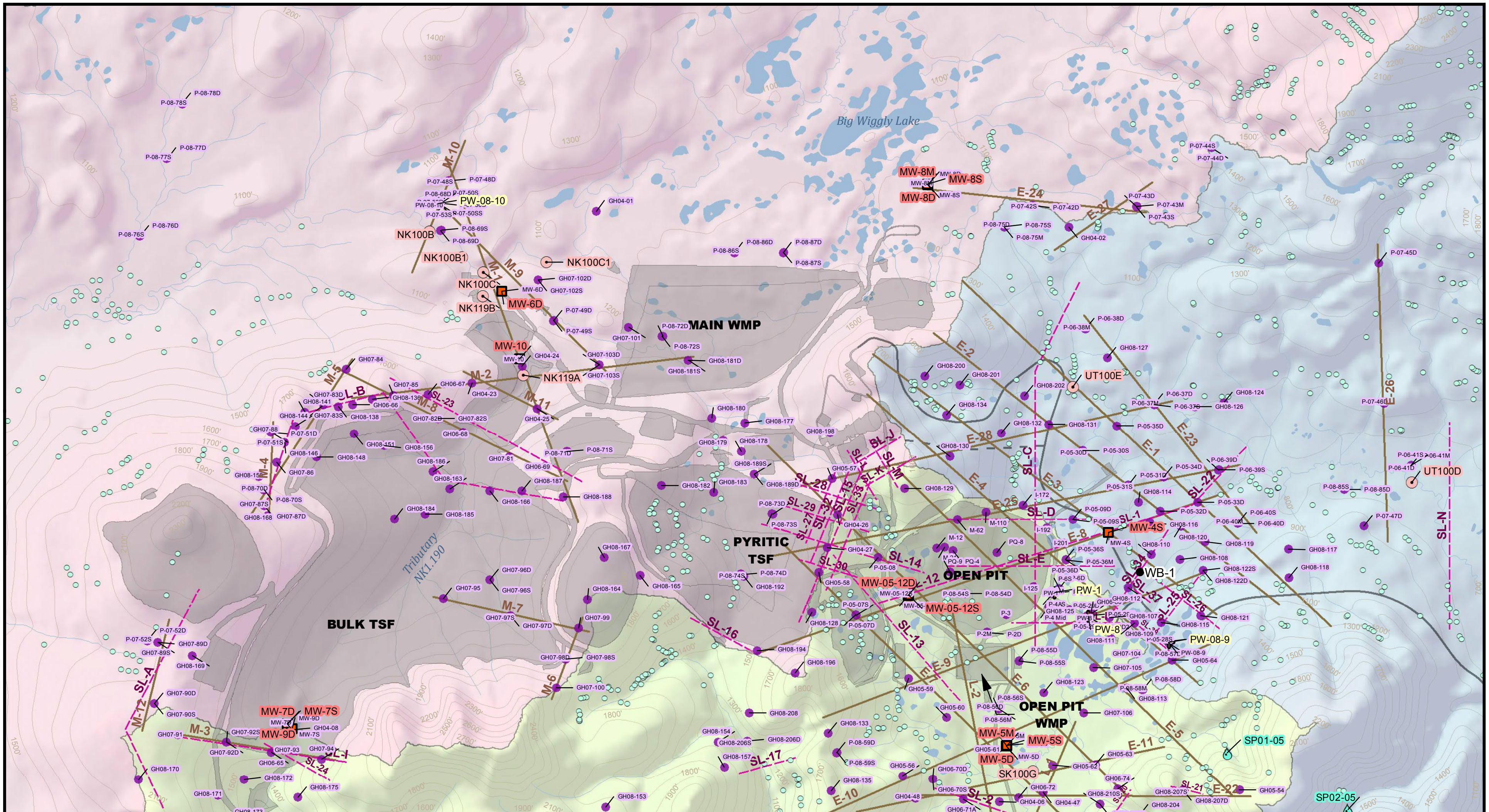
Action Alternative 1
- Mine Site
- Transportation Corridor
- Natural Gas Pipeline

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

WELL, PIEZOMETER, AND SEEP LOCATIONS - NFK DRAINAGE

PEBBLE PROJECT EIS

FIGURE K3.17-1b



Sources: Schlumberger 2011a, Figures 8.1-4 and 9.1-5

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

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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 Alternative 1

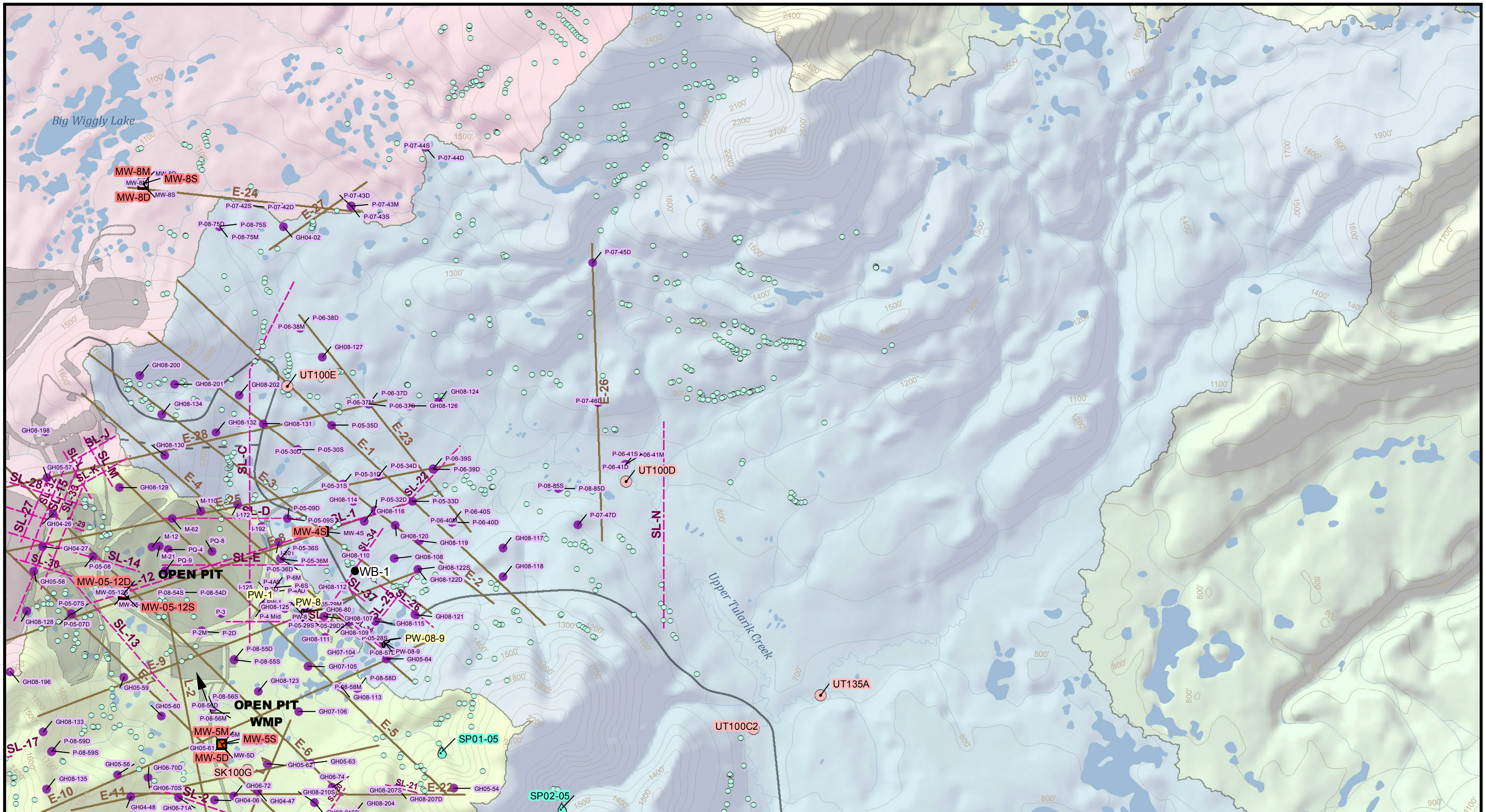
- Mine Site
- Transportation Corridor
- Natural Gas Pipeline

Other Features

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

WELL, PIEZOMETER, AND SEEP LOCATIONS - MINE FOOTPRINT

FIGURE K3.17-1c



Sources: Schlumberger 2011a, Figures 8.1-4 and 9.1-5

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

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N

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 Alternative 1

- Mine Site
- Transportation Corridor
- Natural Gas Pipeline

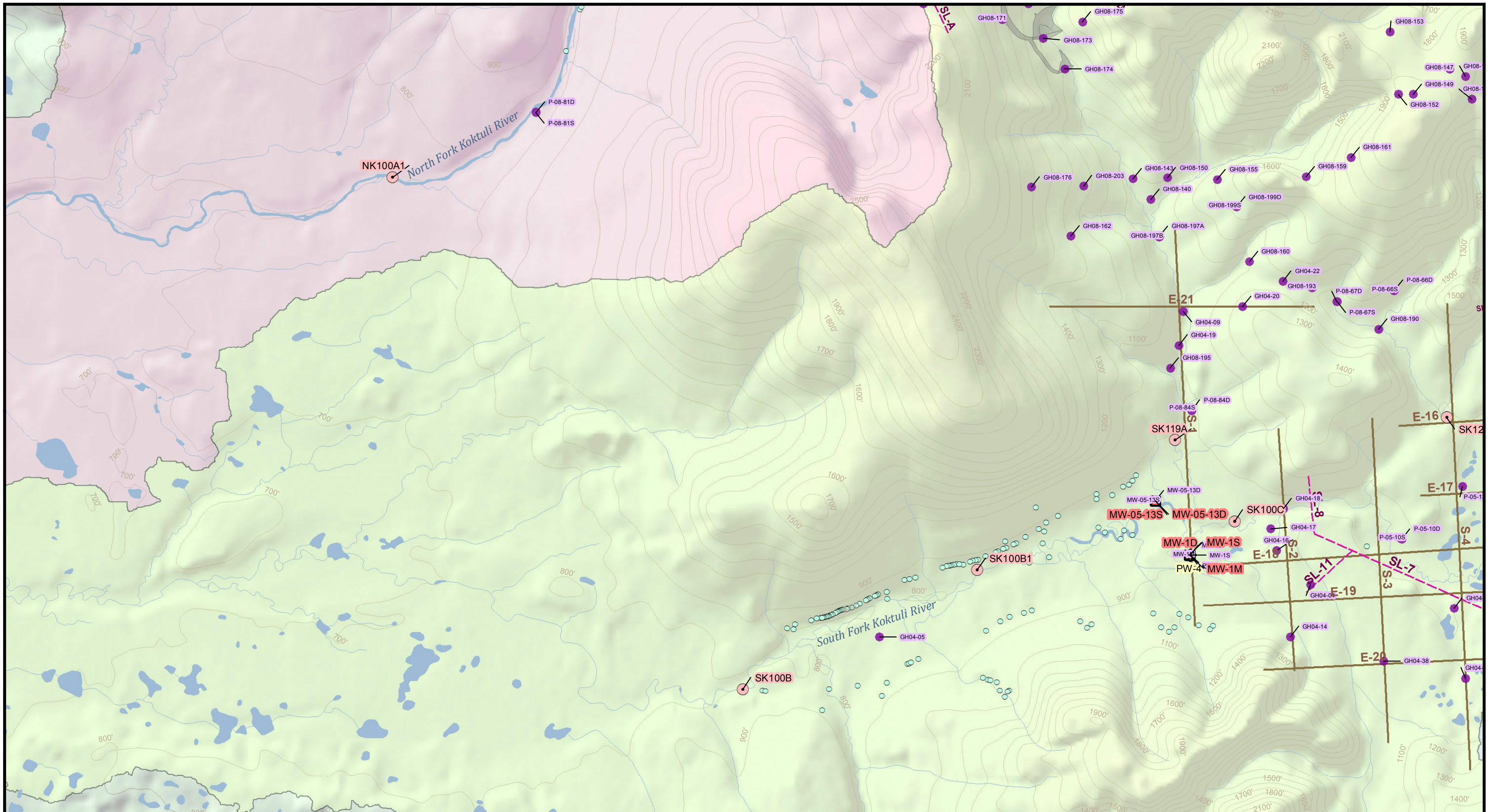
Other Features

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

WELL, PIEZOMETER, AND SEEP LOCATIONS - UTC DRAINAGE NORTH

PEBBLE PROJECT EIS

FIGURE K3.17-1d



Sources: Schlumberger 2011a, Figures 8.1-4 and 9.1-5
Note: Well depths and completions are provided in Table K3.18-17.

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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

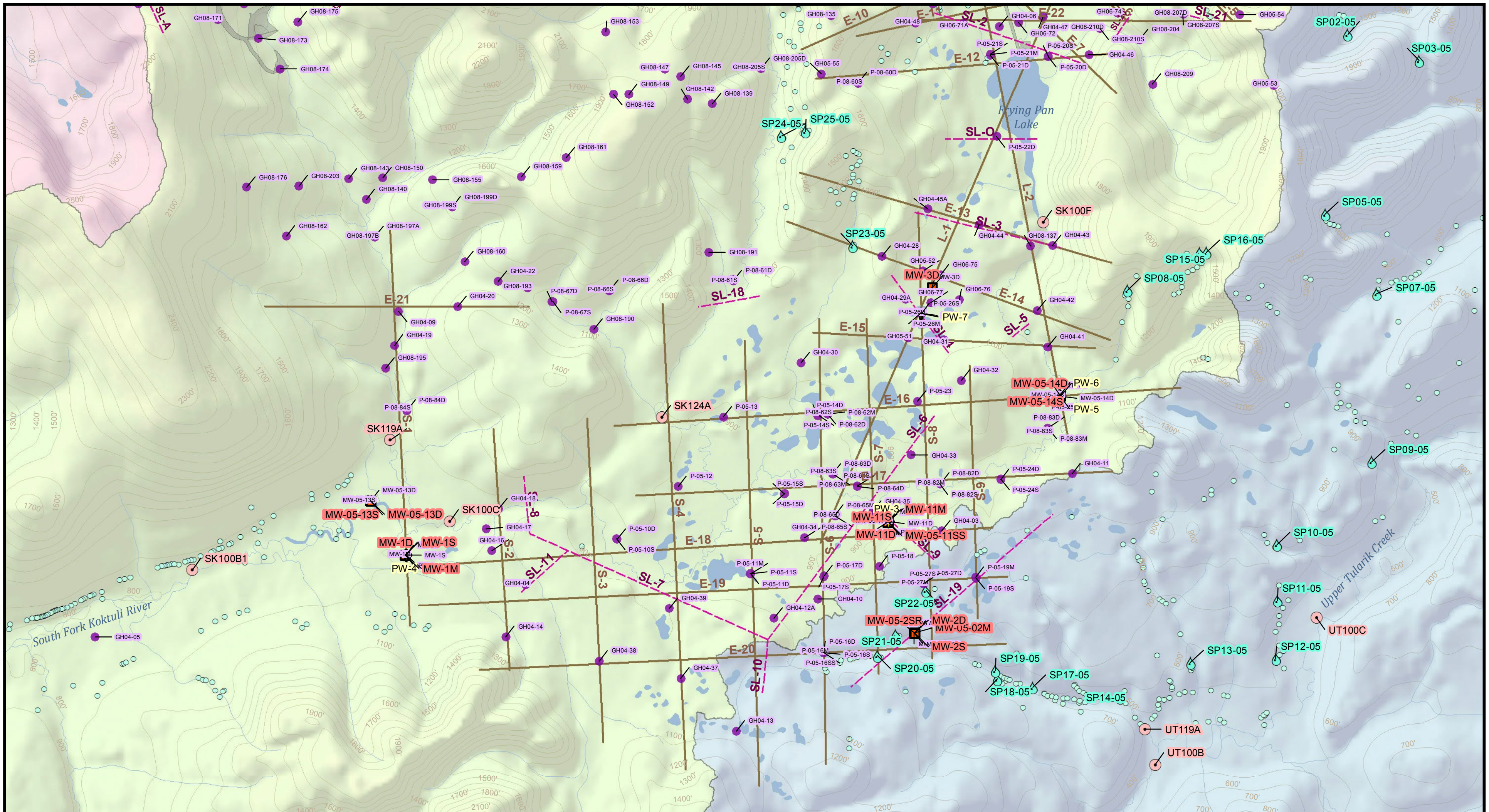
Action Alternative 1
- Mine Site
- Transportation Corridor
- Natural Gas Pipeline

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

WELL, PIEZOMETER, AND SEEP LOCATIONS - LOWER SFK DRAINAGE

PEBBLE PROJECT EIS

FIGURE K3.17-1e



Sources: Schlumberger 2011a, Figures 8.1-4 and 9.1-5
Note: Well depths and completions are provided in Table K3.18-17.

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N

0.5 0 0.5 1
Miles

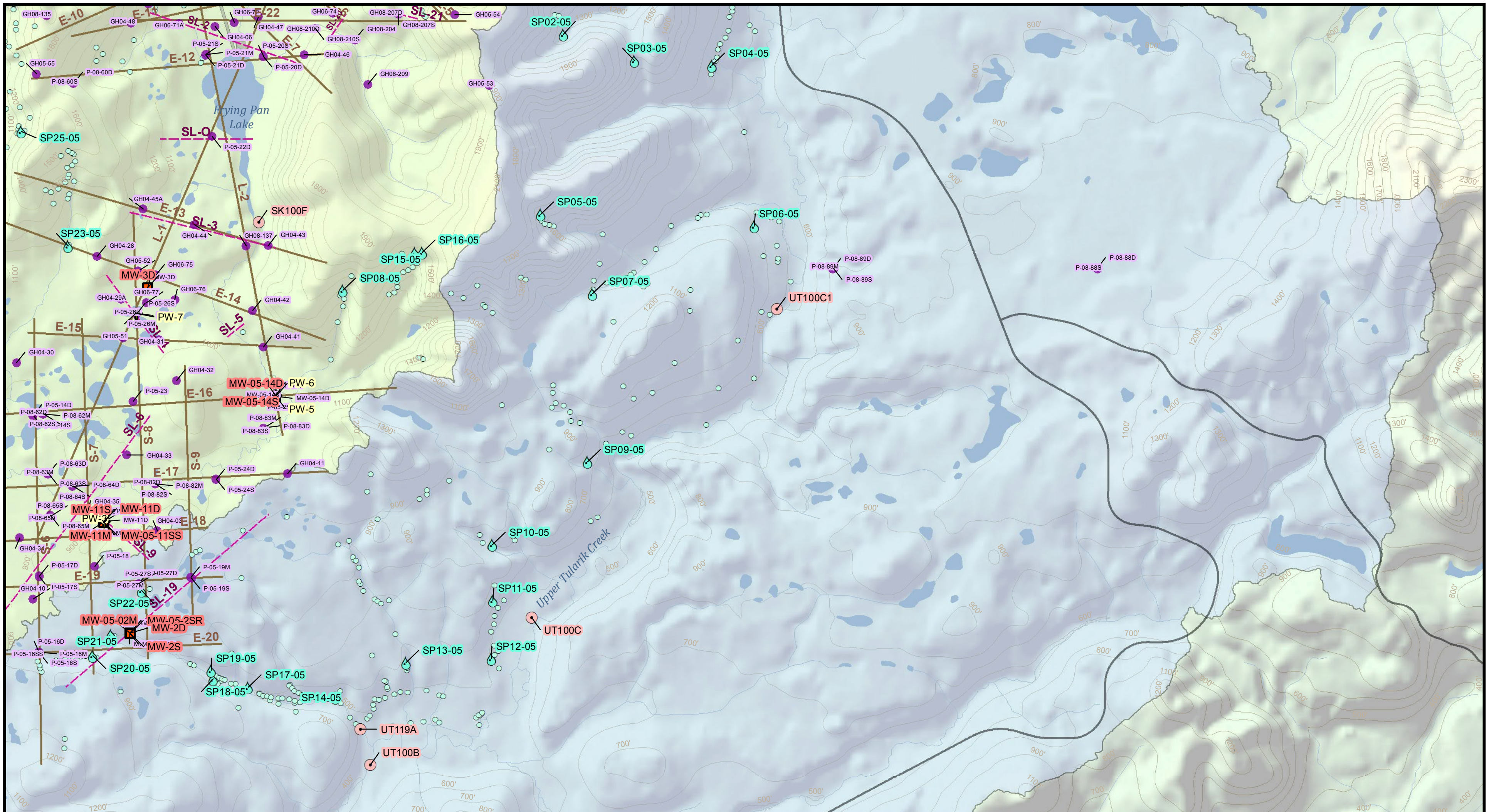
Location Type
- Pumping Well
- Monitoring Well
- Piezometer
- Stream Gaging Station
- Seep Sampling Location
- Seep Location
- 2004-2010 Seismic Line
- Cross Section Line

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

Action Alternative 1
- Mine Site
- Transportation Corridor
- Natural Gas Pipeline

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

WELL, PIEZOMETER, AND SEEP LOCATIONS - UPPER SFK DRAINAGE



Sources: Schlumberger 2011a, Figures 8.1-4 and 9.1-5
Note: Well depths and completions are provided in Table K3.18-17.

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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 Alternative 1
- Mine Site
- Transportation Corridor
- Natural Gas Pipeline

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

WELL, PIEZOMETER, AND SEEP LOCATIONS - UTC DRAINAGE SOUTH

PEBBLE PROJECT EIS

FIGURE K3.17-1g

Single-well response tests were completed by displacing groundwater in the well and monitoring recovery until water levels stabilized. Prior to commencement of each test, static water levels were measured and pressure transducers installed. Falling and rising head slug tests were conducted on monitoring wells and piezometers to determine the hydraulic conductivity of the surrounding overburden or bedrock formations.

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 located 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 site water balance and water quality modeling.

K3.17.2 Aquifers and Confining Units

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)[6]
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 east 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 function as both conduits and barriers to groundwater flow (i.e., compartmentalized flow).	
	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 (from Frying Pan Lake, 5.5 miles downstream along SFK River)	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 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;
			SFK Channel Aquifer	Alluvium and terrace gravels along the channel from downstream of Frying Pan Lake to bedrock high to the east.	

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)[6]
			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).	median of $5x10^{-5}$ m/s
			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 $1x10^{-6}$ m/s; median of $9x10^{-7}$ m/s.
	NFK East - Area E (within Area 12) *(PAG/Pyritic TSF)*	Overburden	Intermediate Aquifer	Sand and gravel.	
		Bedrock	Weathered Bedrock Aquifer	Uppermost portion of bedrock.	
	NFK West - Area G (within	Overburden	Surficial Aquifer	Thin aquifer composed of colluvium, drift, undifferentiated gravel, and undifferentiated drift.	

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)[6]
	drainage Area 14) (*TSF*)	Bedrock	Weathered Bedrock Aquifer	Uppermost portion of weathered and fractured bedrock.	
	North Fork Glacial Outwash Area [3] (aka Area 15) (*TSF Main Embankment Seepage Collection and Sediment Ponds*)	Overburden	North Fork Outwash Aquifer	Sand and gravel.	
			Terrace and Alluvial Deposits	Sand and gravel downstream of North Fork Outwash Aquifer.	
		Bedrock	Weathered Bedrock Aquifer	Uppermost 10 to 50 feet of weathered and fractured bedrock.	
UTC Drainage	Upper Talarik Creek (*East WTP Discharge*)	Overburden	Glacial Outwash Aquifer	Sand and gravel upstream of stream gage UT100E (Section 3.16, Surface Water Hydrology, Figure 3.16-4).	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.
		Bedrock	Weathered Bedrock Aquifer	Uppermost 10 to 50 feet of weathered and fractured bedrock.	
	Talarik Creek Outwash Plain (aka Area 10)	Overburden	Surficial Aquifer	Glacial outwash deposits (sand, gravel), east of UTC. Likely underlain by a low-permeability aquitard.[5]	
			Intermediate Aquifer	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.	
		Bedrock	Weathered Bedrock Aquifer	Uppermost 10 to 50 feet of weathered and fractured bedrock.	

Notes:
[1] Felsenmeer = frost-weathered boulders at the surface.
[2] Numbered tributaries named for stream gaging stations (see Section 3.16, Surface Water Hydrology, Figure 3.16-3).
[3] Outwash – sediments deposited by glacial meltwater
[4] Alluvium – sediments deposited by stream, river, etc.
[5] Aquitard – a low-permeability geologic layer that restricts flow of groundwater from one aquifer to another (e.g., clay layer)
[6] K = Hydraulic conductivity, a measurement of the capacity of the aquifer to transmit water, expressed in meters per second (m/s).
Source: Schlumberger (2011a, 2015a)

SFK River Drainage South of Pebble Deposit. Hydrogeologic cross-section E-10 (Section 3.17, Groundwater Hydrology, Figure 3.17-5), a southwest to northeast trending section, shows the geological layering across the SFK River drainage south of the Pebble deposit and north of Frying Pan Lake. Overburden deposits consist of interbedded gravels, sands, silts, and clays that overlie the underlying weathered bedrock. Groundwater recharge rates in the SFK drainage basin (Areas 2 through 5 and 8, Section 3.17, Groundwater Hydrology, Figure 3.17-1), calculated using the site-wide water balance 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) to depths of at least 600 feet. Groundwater is controlled in the deeper bedrock by cross-cutting fractures and faults. Although fractures and faults are widespread in the deep bedrock, the features are commonly 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 have the potential to create groundwater compartments (compartmentalized flow) in the deeper bedrock, thereby reducing the potential for regional groundwater flow (Knight Piésold 2018l).

Cross-section L-1 (Section 3.17, Groundwater Hydrology, Figure 3.17-6) trending northeast-southwest, shows 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 the overburden of sand and gravel.

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

Numerous vertical groundwater gradients have been measured in this area as shown on Figure K3.17-2, Figure K3.17-3, Figure K3.17-4, and Figure K3.17-5 (Schlumberger 2015a, Figures 8.1F1 through F4). During seasonal low periods of the year, 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 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 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-section L-1 (Section 3.17, Groundwater Hydrology, Figure 3.17-6) Several overburden aquifers have been identified in this area and overburden thickness under Frying Pan Lake is about 150 feet thick. 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.

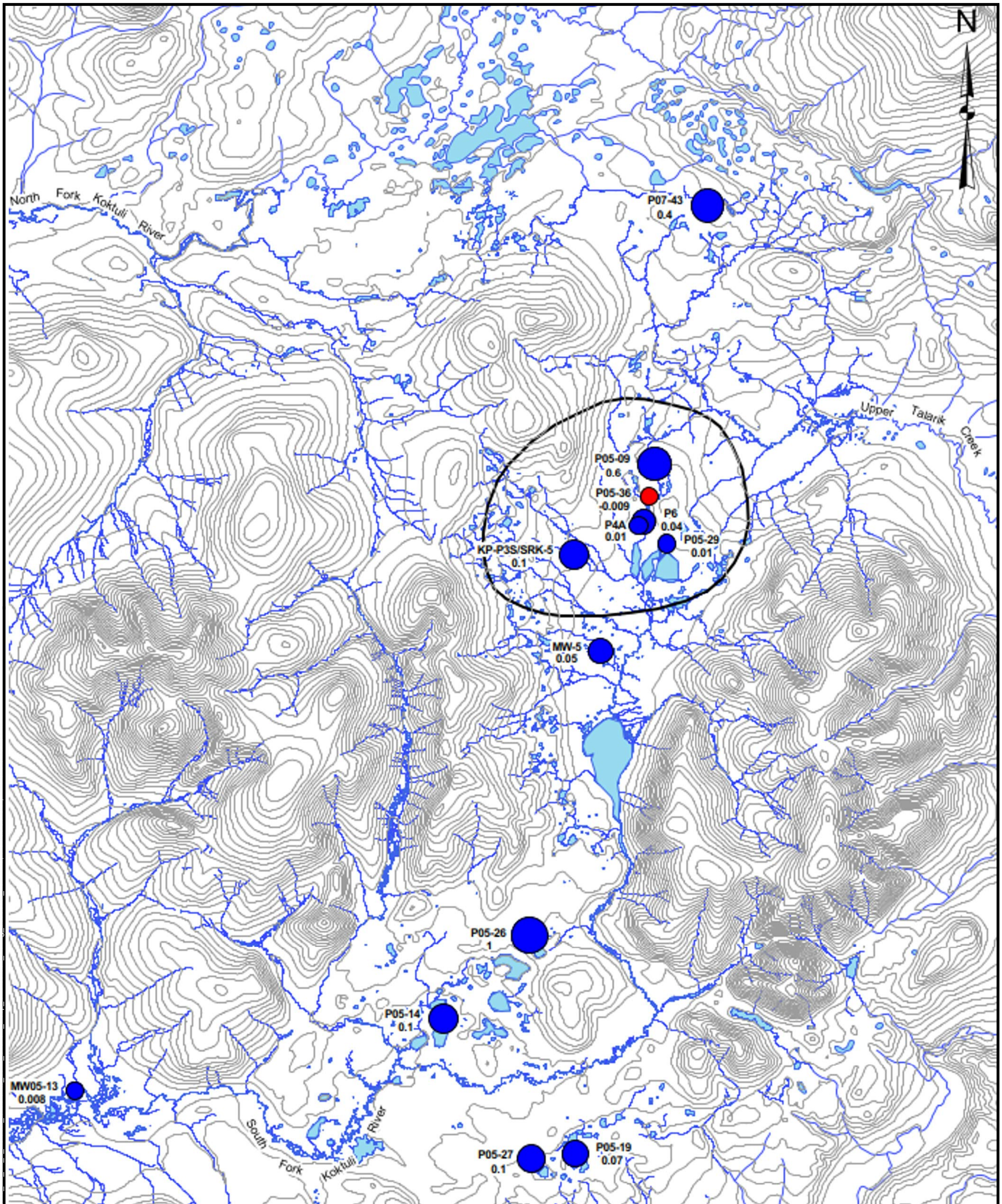
South of Frying Pan Lake, silty layers are absent along the SFK River where overburden consists of sand and gravel. Overburden is relatively thin as compared to beneath the lake and is permeable beneath most valley floors, with valley walls dominated by colluvium (coarse material originating from the slopes, such as angular pieces of bedrock) and shallow weathered and fractured shallow bedrock, with the exception of some local thin till deposits (a mixture of many grain size gradations, deposited by glacial ice).

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 dry 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.

[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.

[3] An area where the bedrock is higher than the surrounding bedrock surface, similar to a hill in surface topography.



Sources: Schlumberger 2015a, Figure 8.1F-1

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Legend

- SO-CZ/BR Upward Gradient
- SO-CZ/BR Downward Gradient
- 50-ft Contour Interval
- Rivers
- Lakes

DO = Deep Overburden
SO = Shallow Overburden
P = Piezometer
KP-P = Knight-Piesold Piezometer
MW = Monitoring Well
SRK = Steffan Robertson Kirsten

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

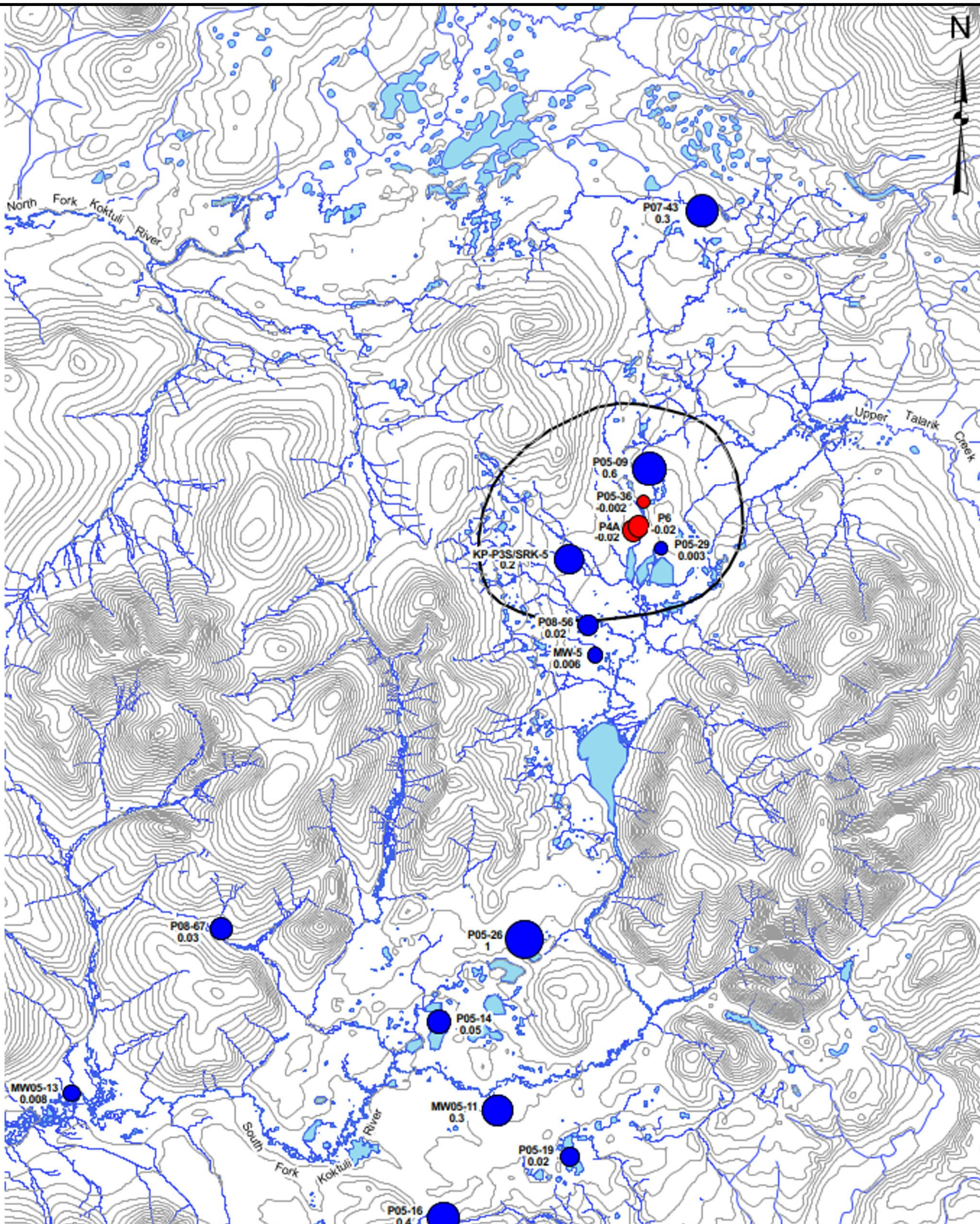
Feet: 0, 2,500, 5,000, 7,500, 10,000
Meters: 0, 1,000, 2,000, 3,000, 4,000

Scale 1:60,000

Alaska State Plane Zone 5 (units feet)
1983 North American Datum

VERTICAL GRADIENTS BETWEEN SHALLOW OVERBURDEN AND DEEP OVERBURDEN DURING SEASONAL LOW MAY, 2008

PEBBLE PROJECT EIS **FIGURE K3.17-2**



Sources: Schlumberger 2015a, Figure 8.1F-2

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Legend

- SO-CZ/BR Upward Gradient
- SO-CZ/BR Downward Gradient
- 50-ft Contour Interval
- Rivers
- Lakes

DO = Deep Overburden
SO = Shallow Overburden
P = Piezometer
KP-P = Knight-Piesold Piezometer
MW = Monitoring Well
SRK = Steffan Robertson Kirsten

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

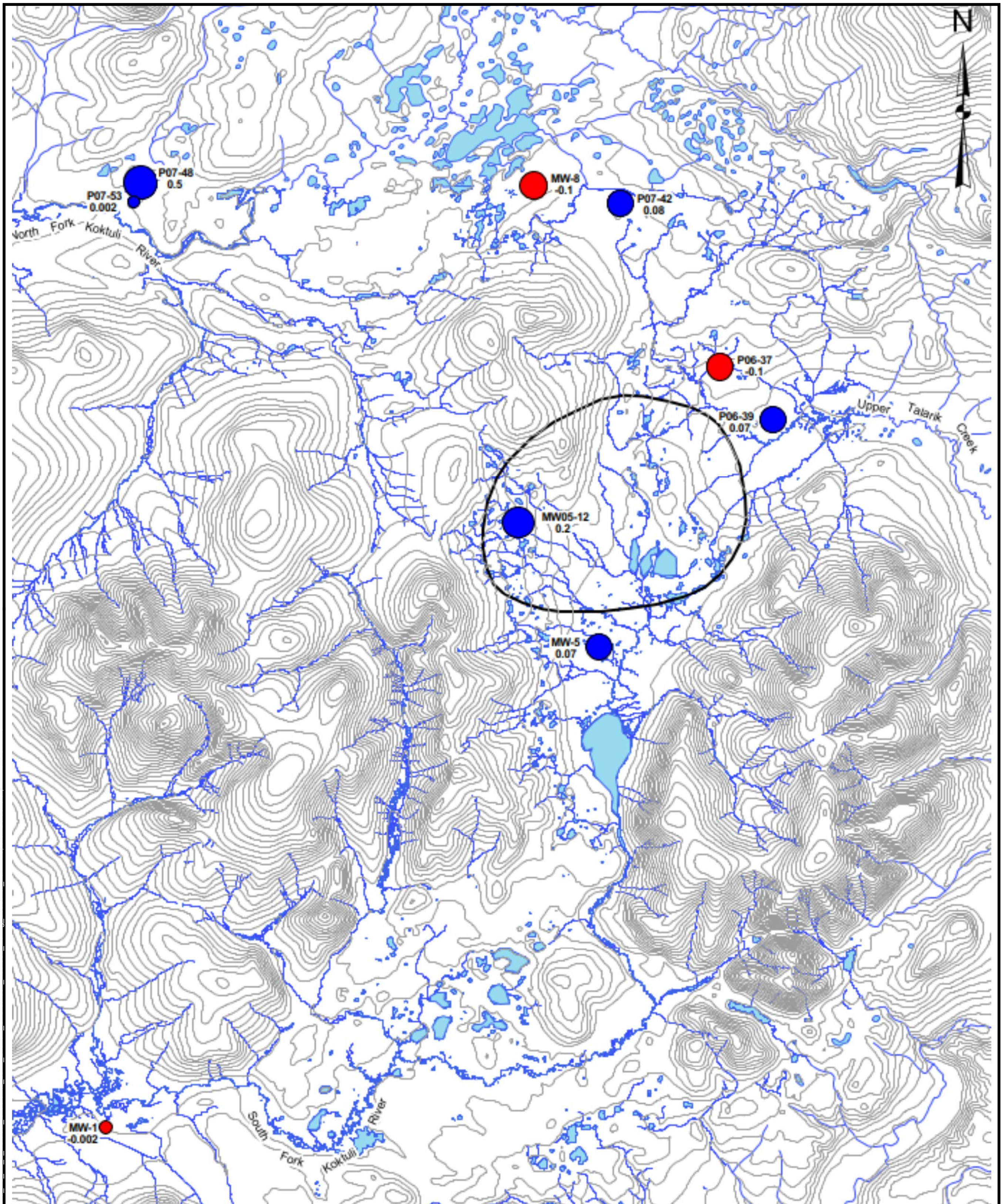
Feet: 0, 2,500, 5,000, 7,500, 10,000
Meters: 0, 1,000, 2,000, 3,000, 4,000

Scale 1:60,000

Alaska State Plane Zone 5 (units feet)
1983 North American Datum

VERTICAL GRADIENTS BETWEEN SHALLOW OVERBURDEN AND DEEP OVERBURDEN DURING SEASONAL HIGH JUNE, 2008

PEBBLE PROJECT EIS **FIGURE K3.17-3**



Sources: Schlumberger 2015a, Figure 8.1F-3

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Legend

- SO-CZ/BR Upward Gradient (red circle)
- SO-CZ/BR Downward Gradient (blue circle)
- 50-ft Contour Interval
- Rivers
- Lakes

DO = Deep Overburden
SO = Shallow Overburden
P = Piezometer
KP-P = Knight-Piesold Piezometer
MW = Monitoring Well
SRK = Steffan Robertson Kirsten

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

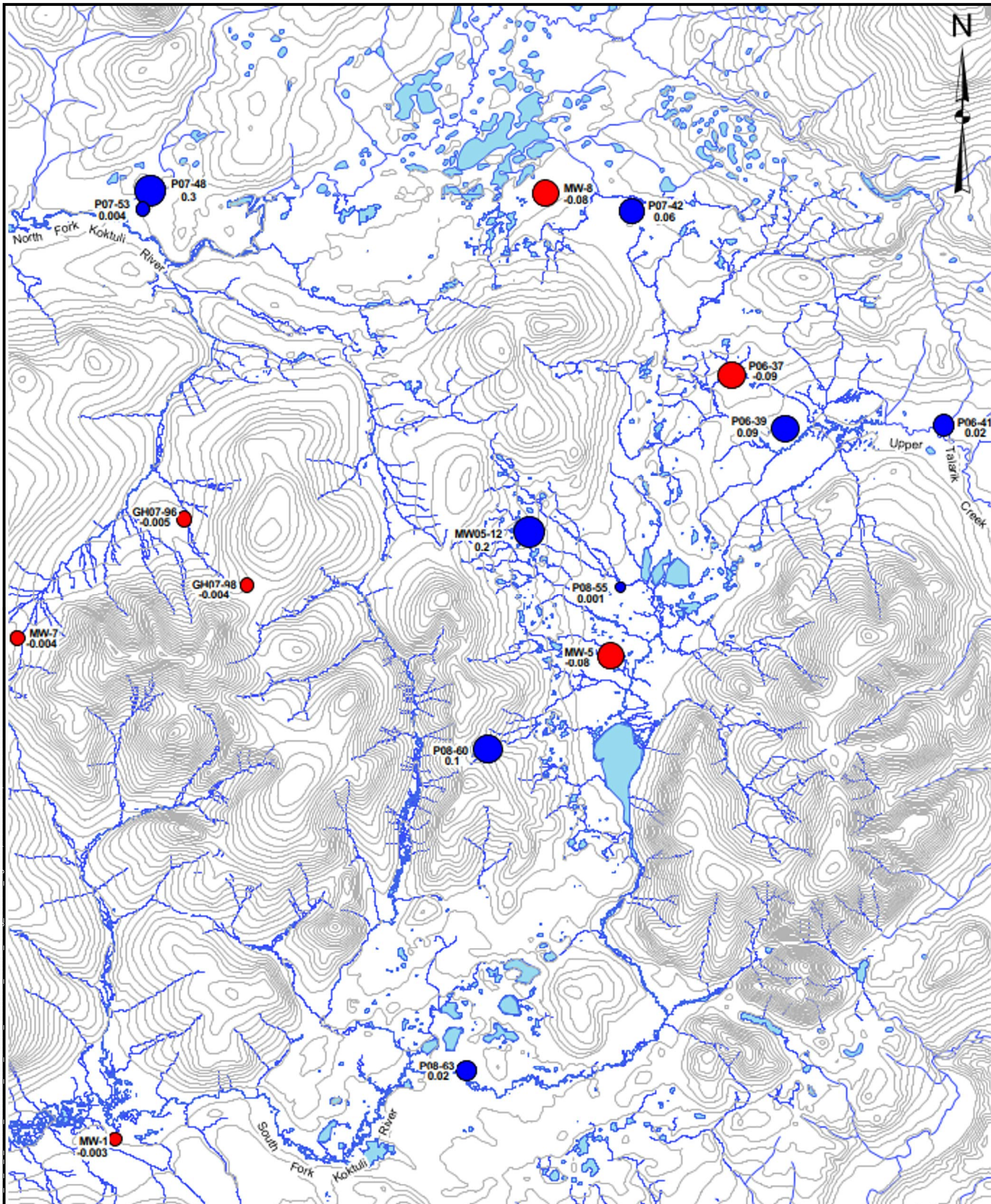
2. Diameter of circle is logarithmically proportional to the magnitude of the gradient

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

Feet: 0, 2,500, 5,000, 7,500, 10,000
Meters: 0, 1,000, 2,000, 3,000, 4,000
Scale 1:60,000
Alaska State Plane Zone 5 (units feet)
1983 North American Datum

VERTICAL GRADIENTS BETWEEN SHALLOW OVERBURDEN AND BEDROCK DURING SEASONAL LOW MAY, 2008

PEBBLE PROJECT EIS **FIGURE K3.17-4**



Sources: Schlumberger 2015a, Figure 8.1F-4

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Legend

- SO-CZ/BR Upward Gradient
- SO-CZ/BR Downward Gradient
- 50-ft Contour Interval
- Rivers
- Lakes

DO = Deep Overburden
SO = Shallow Overburden
P = Piezometer
KP-P = Knight-Piesold Piezometer
MW = Monitoring Well
SRK = Steffan Robertson Kirsten

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

Feet: 0, 2,500, 5,000, 7,500, 10,000

Meters: 0, 1,000, 2,000, 3,000, 4,000

Scale 1:60,000

Alaska State Plane Zone 5 (units feet)
1983 North American Datum

VERTICAL GRADIENTS BETWEEN SHALLOW OVERBURDEN AND BEDROCK DURING SEASONAL HIGH JUNE, 2008

PEBBLE PROJECT EIS **FIGURE K3.17-5**

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. Section 3.17, Groundwater Hydrology, Figure 3.17-10 depicts the divergent groundwater flow along SFK River to UTC in the deep groundwater aquifer. The divergent groundwater flow pattern occurs during seasonal low and high water periods.

SFK River Discharge Area. Hydrogeologic cross-section S-1 (Section 3.17, Groundwater Hydrology, Figure 3.17-7) 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 (Area 5). At times when the groundwater level is high, groundwater might discharge to the streambed near the boundary between Areas 5 and 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 run-on from adjoining slopes.

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 (Section 3.17, Groundwater Hydrology, Figure 3.17-8) 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. This drainage, sometimes referred to as Area G or Drainage Area 14, and would contain the bulk tailings storage facility and main seepage collection pond (Section 3.17, Groundwater Hydrology, Figure 3.17-1 and Figure 3.17-2). 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 (Section 3.17, Groundwater Hydrology, Figure 3.17-2), with 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 Section 3.16, Surface Water Hydrology, 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 and is sometimes referred to as Area E or Drainage Area 12 (Section 3.17, Groundwater Hydrology, Figure 3.17-1 and Figure 3.17-2). 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 (Section 3.17, Groundwater Hydrology, 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 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 recharge is locally recharged on the hilltops and hillsides of weathered bedrock. Upstream of UT100E, UTC and tributaries contribute additional recharge to groundwater (losing streams). 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 depicted on Section 3.17, Groundwater Hydrology, Figure 3.17-10.

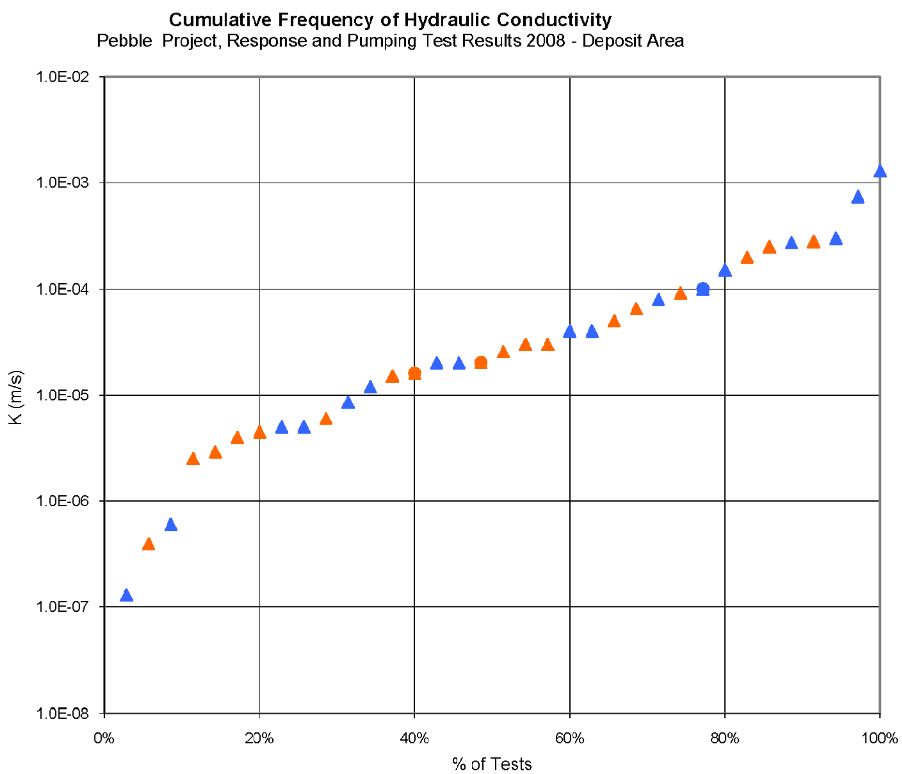
K3.17.3 Aquifer Properties – Hydraulic Conductivity and Storativity

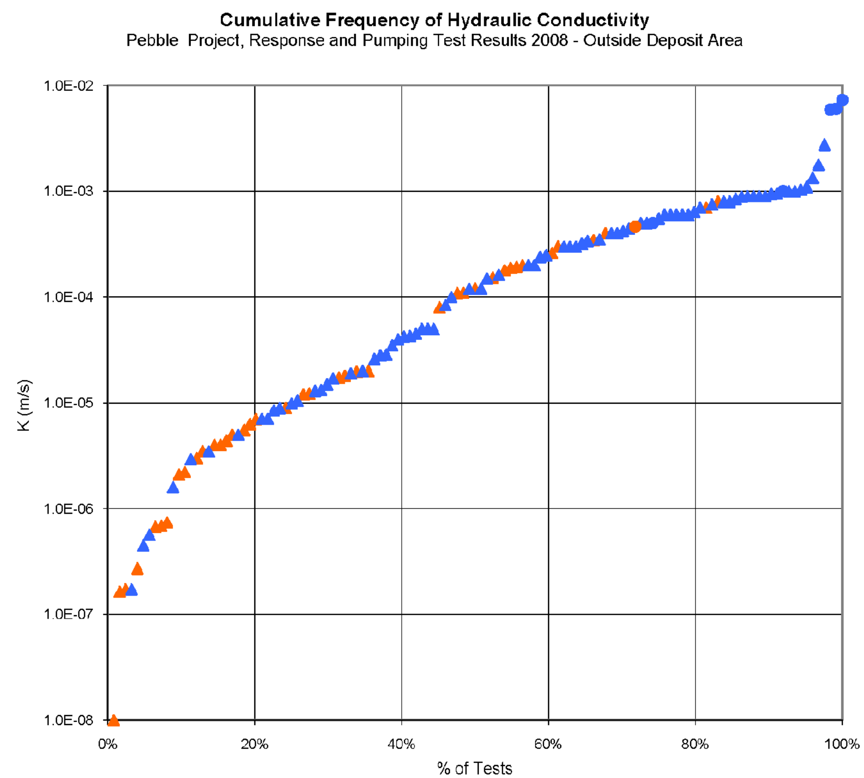
Table K3.17-2 and Figure K3.17-6 through Figure K3.17-9 provide a summary of hydraulic conductivity testing conducted at the mine site, based on individual testing results presented in Schlumberger (2015a).

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}

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





Sources: Schlumberger 2015a, Figure 8.1-9b

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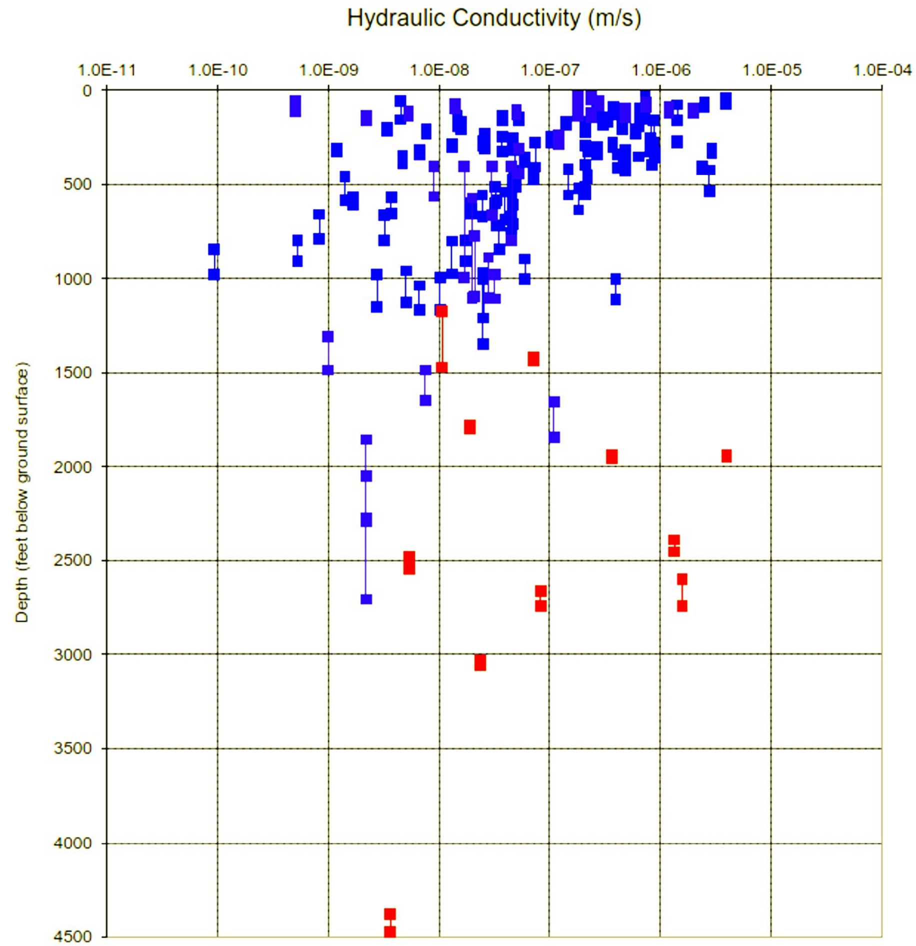
Legend:

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

CUMULATIVE FREQUENCY OF HYDRAULIC CONDUCTIVITY MEASUREMENTS FROM PUMBING AND RESPONSE TESTS



Sources: Schlumberger 2015a, Figure 8.1-11a

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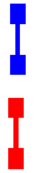
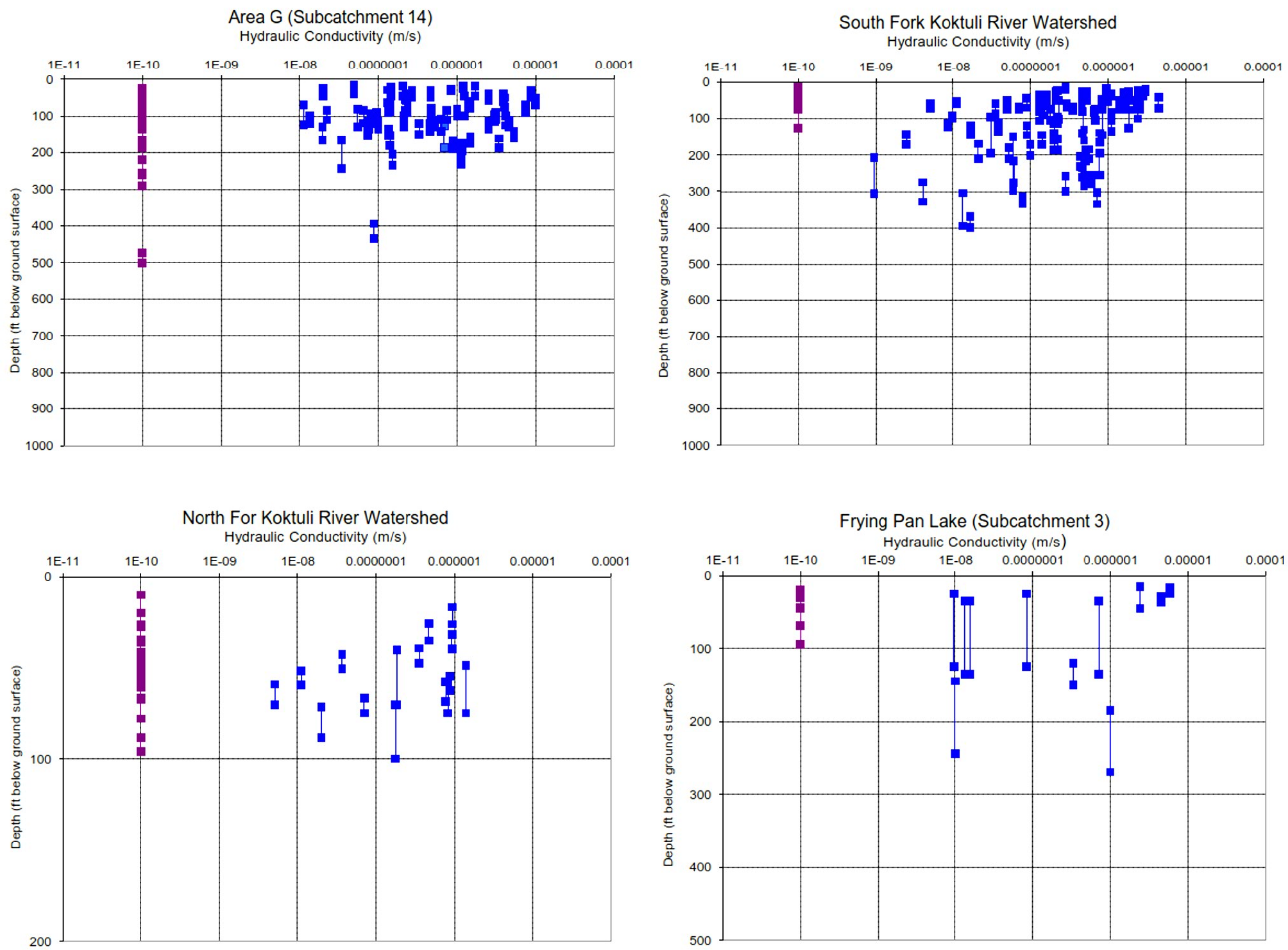
Legend



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

Packer Testing Interval Collected by SLR

HYDRAULIC CONDUCTIVITY IN BEDROCK VS. DEPTH IN PEBBLE DEPOSIT AREA FROM PACKER TESTS



Sources: 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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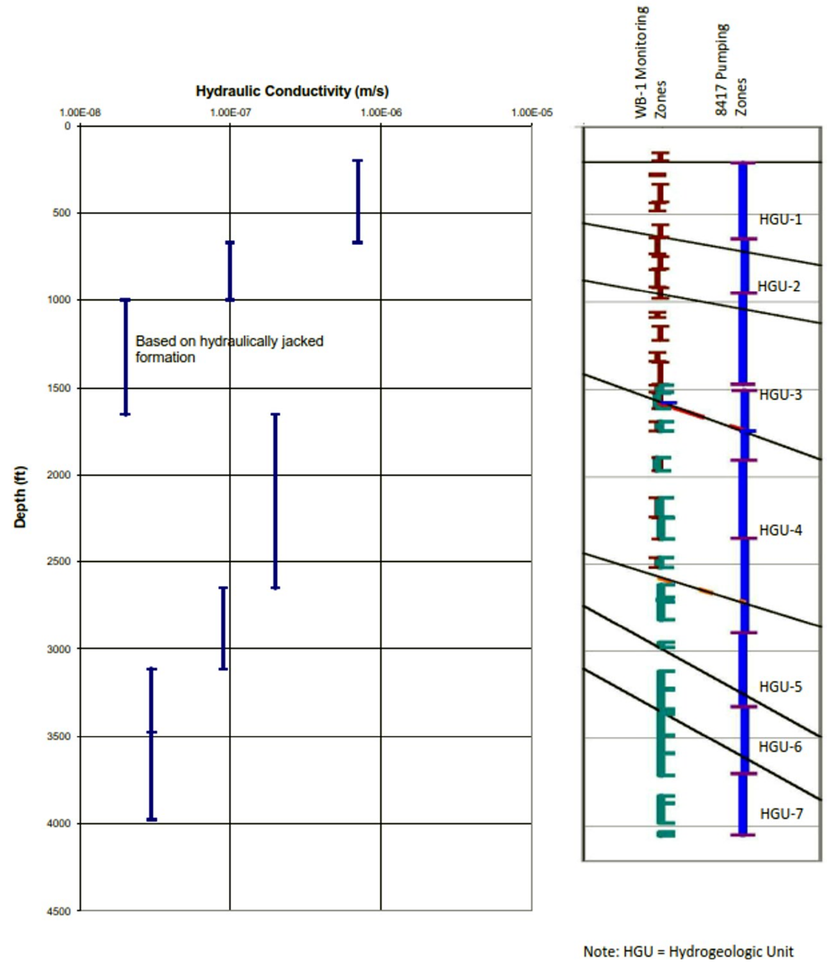
HYDRAULIC CONDUCTIVITY IN BEDROCK VS. DEPTH OUTSIDE THE PEBBLE DEPOSIT AREA FROM PACKER TESTS



Sources: Schlumberger 2015a, Figure 8.1-11c

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HYDRAULIC CONDUCTIVITY PROFILE FOR DEEP BEDROCK

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FIGURE K3.17-9

Based on a total of 110 response tests, the hydraulic conductivity of overburden ranges from 7.8×10^{-9} to 1.78×10^{-3} m/s in the mine site. The hydraulic conductivity of overburden is similar throughout the mine site, with geometric mean values between 1.05×10^{-5} m/s and 1.0×10^{-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 9.4×10^{-9} to 3.0×10^{-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 9.7×10^{-7} and 2.0×10^{-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.

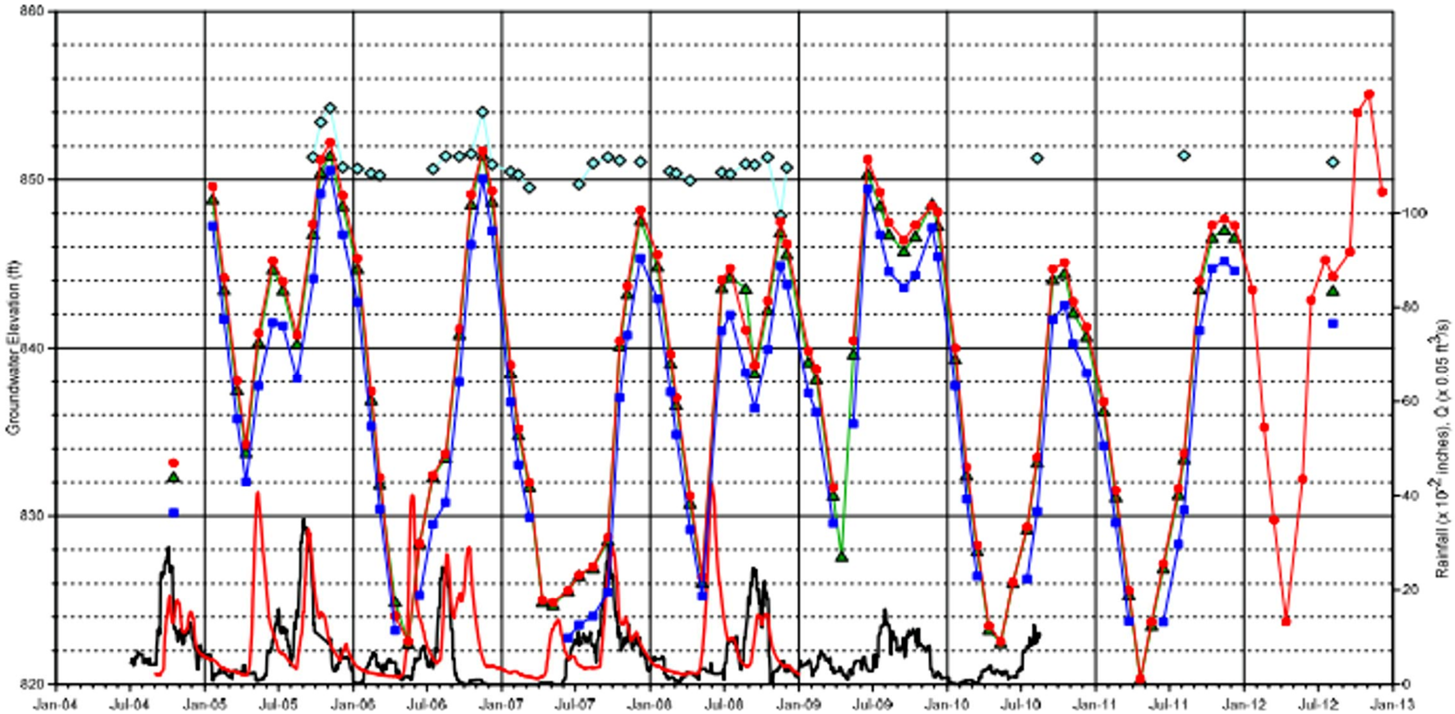
Larger-scale hydraulic conductivity values were also assessed by conducting nine pumping tests, and found that the hydraulic conductivity of overburden was almost 10 times higher than values derived from response tests (Schlumberger 2011a). Pumping rates ranged from approximately 10 to 356 gallons per minute (gpm); although seven of the nine tests reported well yields between 45 and 85 gpm. Water level responses were observed at monitoring wells located 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 8.0×10^{-5} to 1.1×10^{-1} m^2/s, indicating the aquifers are capable of conveying moderate to large quantities of groundwater. Calculated storativity values ranged from 1×10^{-5} to 2.5×10^{-2} m^2/s, 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 response testing underestimates 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. Overall, bedrock hydraulic conductivity values are lower at depth than shallow bedrock in the deposit area.

K3.17.4 Groundwater Flow Seasonality

Hydrographs of monitoring wells (MW) MW-11 (SFK Flats area) and MW-5 (Pebble deposit area) are presented on Figure K3.17-10 and Figure K3.17-11 to illustrate seasonal and vertical groundwater level fluctuations. These examples show groundwater levels from three to four different screened intervals 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 in 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 in both 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.



Sources: Schlumberger 2015a, Figure 8.1-13a

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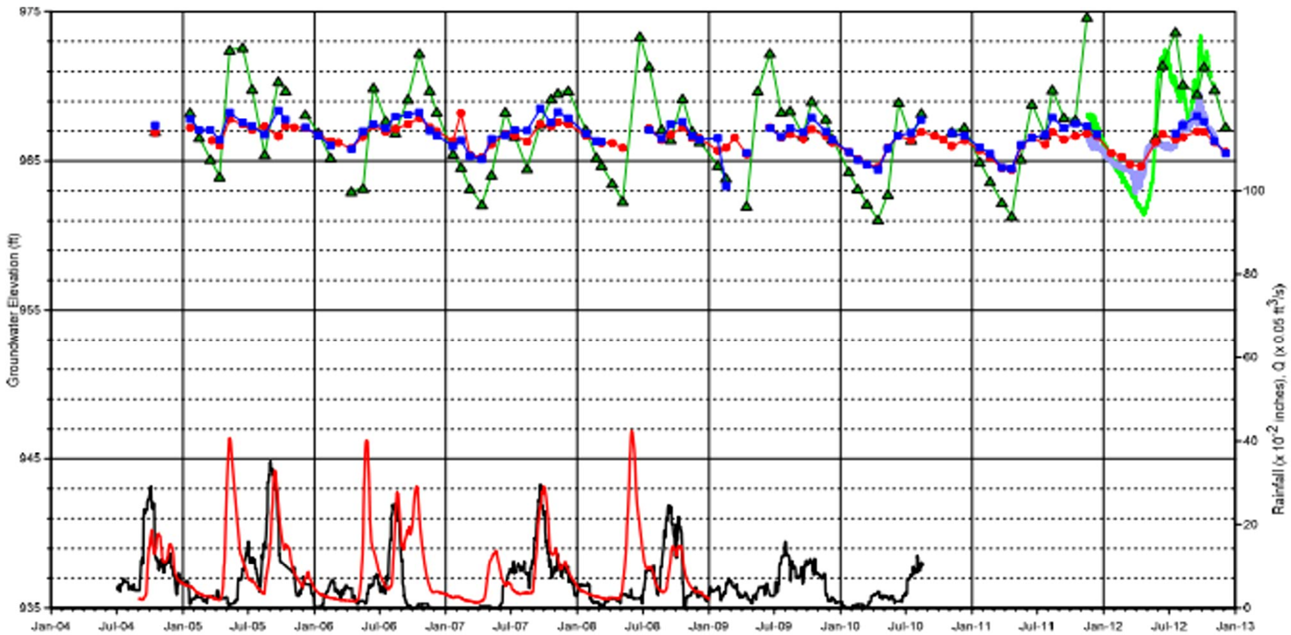
TIME SERIES OF PIEZOMETRIC ELEVATIONS, SOUTH FORK KOKTULI FLATS AREA, 2004-2009



Sources: Schlumberger 2015a, Figure 8.1-13b

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

Based on the results of tritium analysis, the majority of the groundwater in mine site aquifers 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 in response to rainfall and snowmelt.

K3.17.5 Site Water Balance Model

A detailed description of the site baseline WBM is provided in Schlumberger (2011a: Appendix 8.1I). The model was also 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 WBM 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 within the same drainage, with the exception of the inter-catchment transfer of approximately 6 inches per year that occurs between the SFK River and UTC drainages.

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

The baseline 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). The approach to developing and parameterizing the original 2008 version of the model is described in Schlumberger (2011a: Appendix 8.1J). In 2017 to 2018, updates were incorporated to better simulate rates of inter-watershed flow and groundwater discharge for the analysis of site-wide flow reduction effects (Piteau Associates 2018a; Knight Piésold 2018n). The latest version of the model was used for the effects analysis discussed in Section 4.17, Groundwater Hydrology. Model calibration and predictions will be updated based on ongoing hydrogeologic investigations and as mine design progresses (Piteau Associates 2018a).

The finite difference code MODFLOW-SURFACT (MFST) 3.0 (Hydrogeologic, Inc. 1996) was used to implement the three-dimensional groundwater 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. MFST minimizes cell wetting and drying problems and mathematical instability that often occur in groundwater models in steep areas (Schlumberger 2011a).

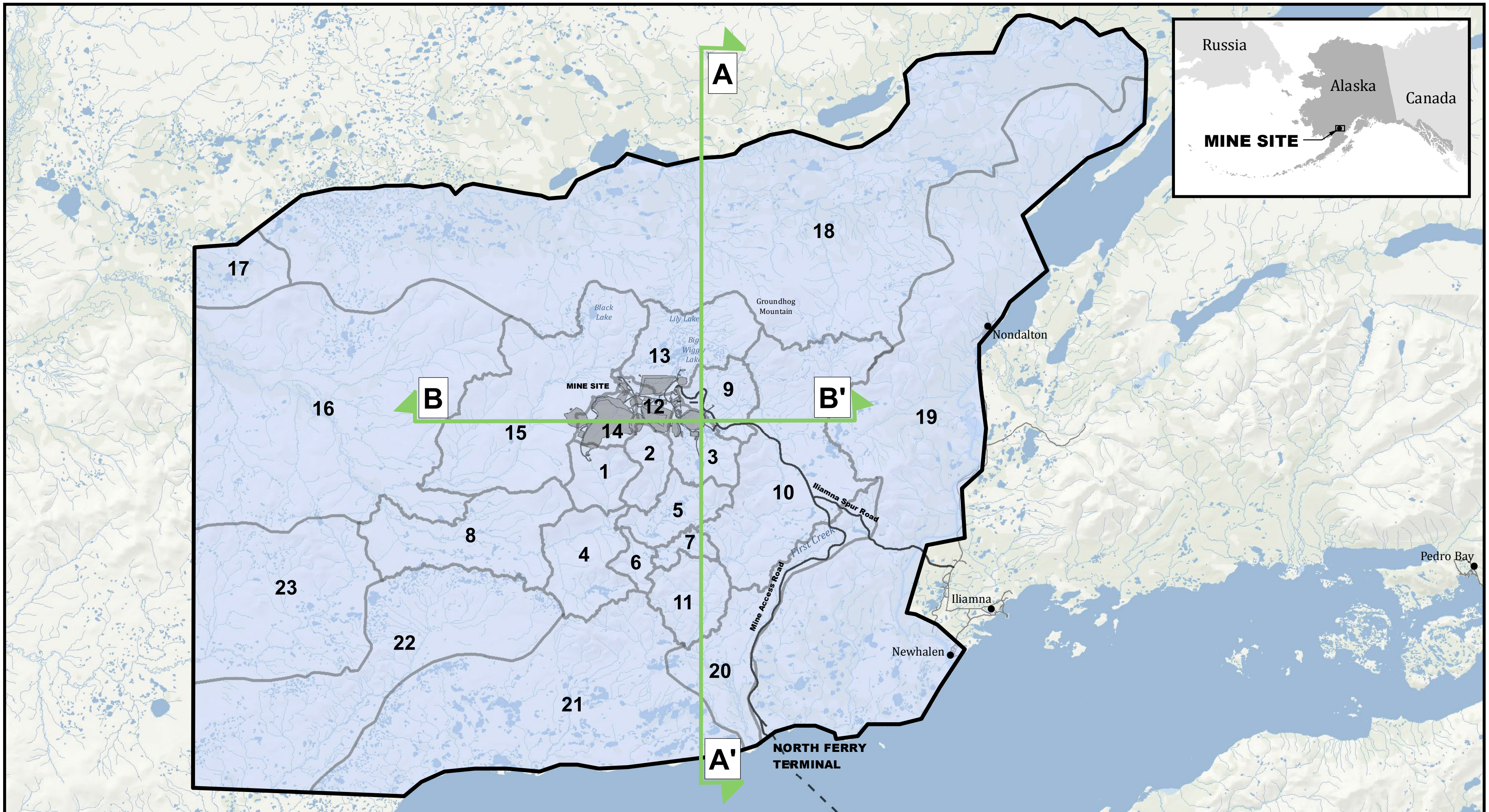
The model domain encompasses a total area of about 1,400 square miles, and includes the majority of the mine site and subcatchments that were included in the WBM (Figure K3.17-12 and Figure K3.17-13). A uniform grid consisting of 223 rows and 272 columns, with cells 1,000 feet on a side, were used to discretize the model domain. The complex site geology was translated into the groundwater model using a five- to 10-layer structure, depending on watershed and year of update. The initial model contained three layers to represent variably thick overburden units, the fourth layer to represent the uppermost 50 feet of fractured and weathered bedrock, and the fifth layer for the underlying bedrock to an elevation of -200 feet above mean sea level. The current version expanded the deep bedrock layer (layer 5) to a total of six layers (layers 5-10) and currently contains 10 layers as shown in Knight Piésold (2018n: Figures 1 through 10) extending to a simulated depth of 5,500 feet (PLP 2019-RFI 109, Figure 1a.1). Some predictive simulations of the pit area were performed with a smaller "pit area model" that is a subset of the regional model (PLP 2019-RFI 109).

Boundary conditions that characterize groundwater inflows and outflows were defined using the following MODFLOW packages: rivers, lakes, and streams were represented using the RIVER package; seeps or springs using the DRAIN package; meteoric recharge using the RECHARGE package. Inflow and outflow at the domain edges were represented with constant-head boundaries (Schlumberger 2011a). Recharge values were assigned to individual grid cells based on site-specific precipitation and infiltration conditions, and ranged from about 5 to 65 inches per year (Knight Piésold 2018n: Figure 9).

Hydrogeologic units in the model domain were represented by several hundred different hydraulic conductivity zones based on aquifer material type and position within each sub-catchment (e.g., uplands versus valley floor) and calibration results. Geologic cross-sections such as those shown in Section 3.17, Groundwater Hydrology, Figure 3.17-5 through Figure 3.17-8 were used to define areas of similar aquifer materials within each model layer (Knight Piésold 2018n: Figures 1 through 7). 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 (Schlumberger 2011a: Appendix 8.1J, Tables 4.2 and 4.3; Knight Piésold 2018n: Figures 10 and 11; PLP 2019-RFI 109c).

Because groundwater levels and flow exhibit strong seasonality, the model was developed as a transient model with an initial simulation period of 37 months, from December 2004 to December 2007, to coincide with the WBM. The primary objective was to simulate the behavior of the groundwater flow system in the upper reaches of the SFK River, the UTC tributary UT1.190, and the upper reaches of the NFK River. The calibration effort was focused on the SFK River area, where data are most abundant. The calibration results discussed below were mostly derived from the five-layer model (Schlumberger 2011a); a comprehensive calibration report for the current 10-layer model is not available, although some updated calibration information has been provided (PLP 2018-RFI 019c; Knight Piésold 2018n; PLP 2019-RFI 109; PLP 2019-RFI 109a; PLP 2019-RFI 109b; and PLP 2019-RFI 109c).

The calibrated groundwater model produced water table (hydraulic head) elevations that follow the same general pattern as field measurements, and also calculated inter-catchment flows between the SFK River catchment and UTC catchment UT1.190 that tracked well with field-based estimates. A total of 220 piezometers, with up to 35 measurements prior to 2008 each, were used to calibrate hydraulic heads and calculate hydraulic head residuals to evaluate the calibration of the model. The model was also calibrated to aquifer stresses observed during pumping tests.



Sources: PLP 2018; Sclumberger 2011a: Figures 8.1-16 and App. 8.1J Figure 4.10

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4 0 4 8
Miles

A A' Model Cross-Sections Shown on Figure K3.17-13

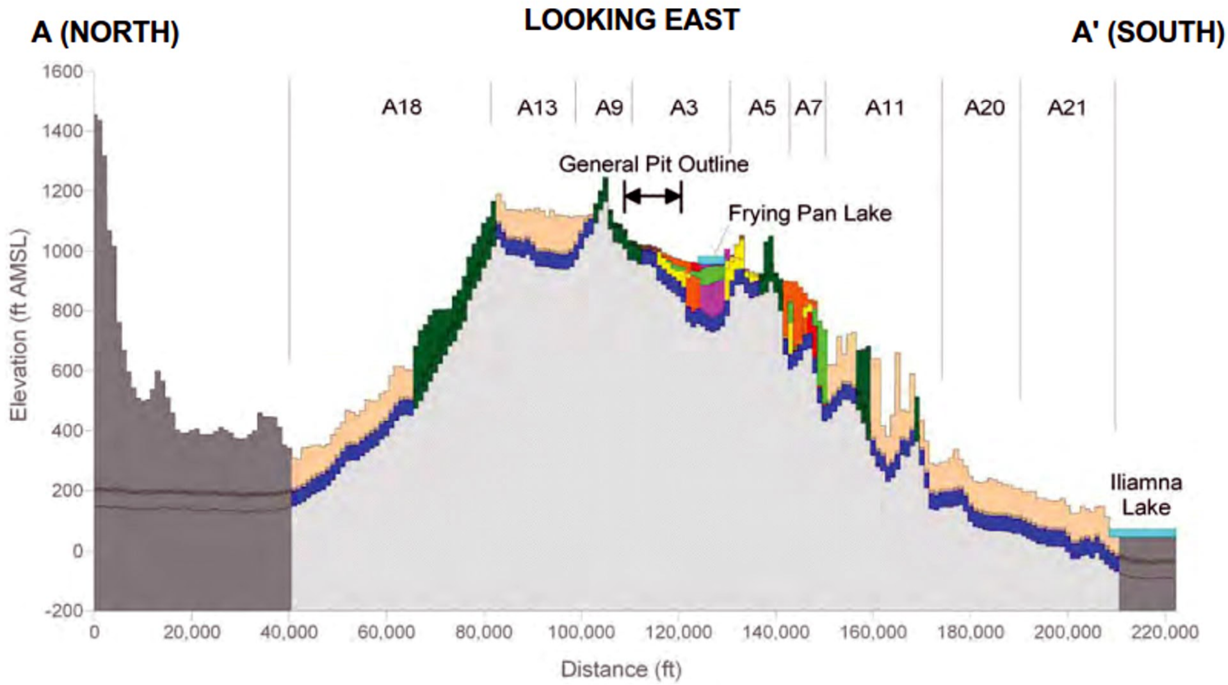
Alternative 1
- Transportation Corridor
- Natural Gas Pipeline
- Mine Site

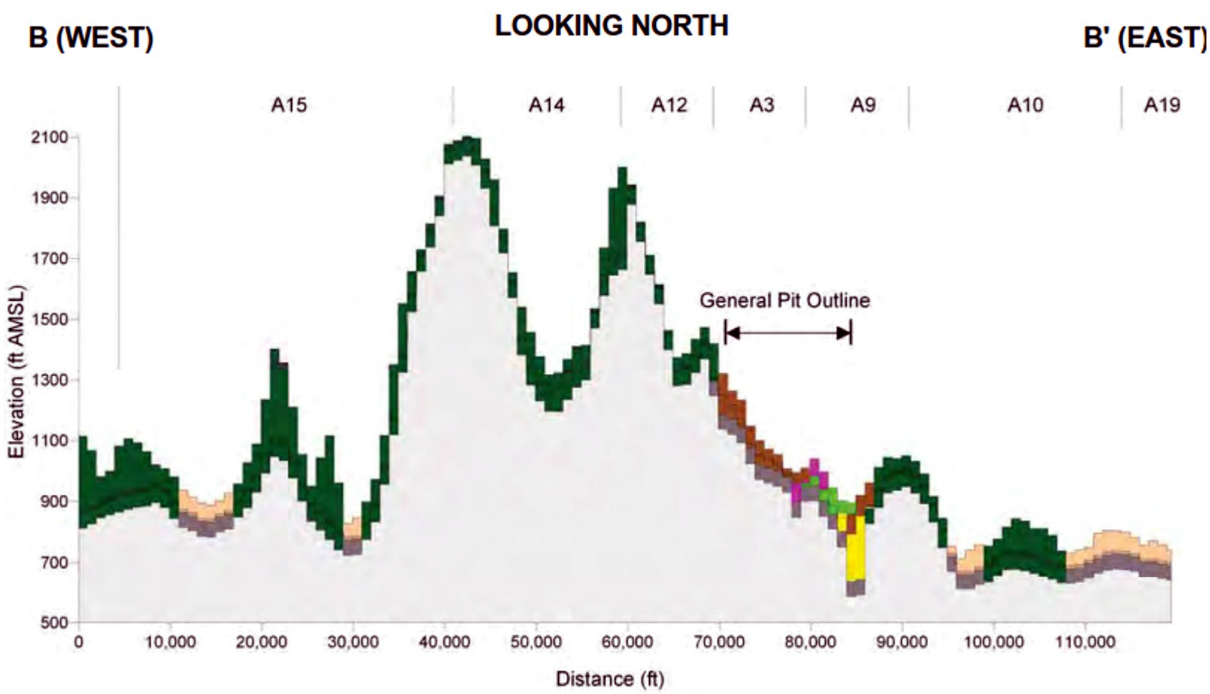
Other Features
- Sub-catchment
- Model Boundary
- Local Roads

GROUNDWATER MODEL DOMAIN

PEBBLE PROJECT EIS

FIGURE K3.17-12





Sources: Schlumberger 2011a, Appendix 8.1J, Figures 4.10 and 4.11

Note: Cross-section locations shown on Figure K3.17-12

Legend

Modeled Hydrostratigraphic Units:

- gravel, gravelly sand
- gravel, gravelly sand with sand, silty sand
- gravel, gravelly sand with clay/silt aquitards
- sand, silty sand
- sand, silty sand with clay/silt lenses
- clay, silty clay
- General bedrock
- General overburden
- weathered bedrock
- non-weathered bedrock
- inactive

A7 = Area 7, Watershed Number

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GROUNDWATER MODEL CROSS-SECTIONS

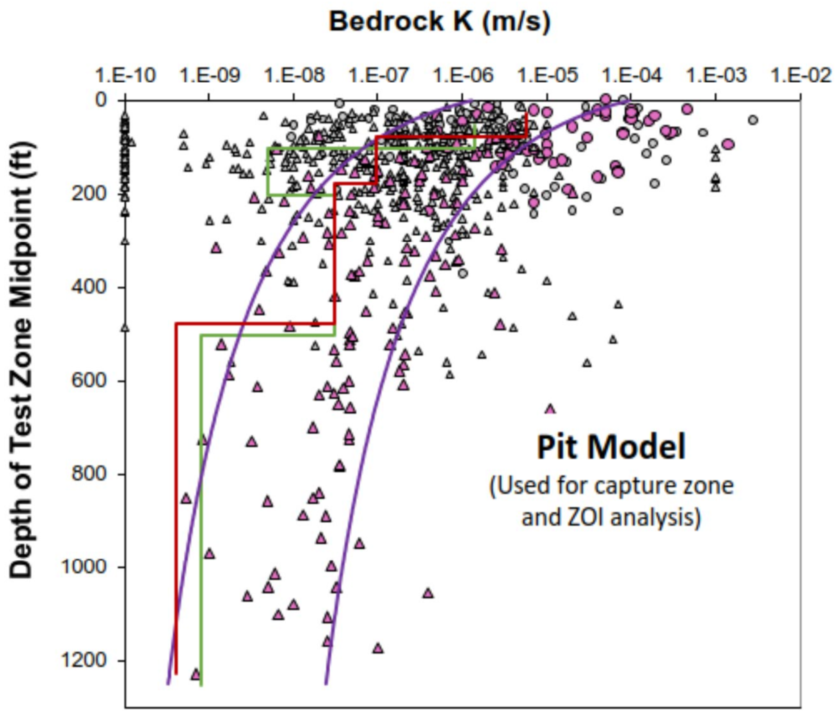
Figure K3.17-14 shows a comparison of modeled values of hydraulic conductivity in bedrock with field-measured values for the 10-layer model. In general, pit model values are lower than or near the low end of the range of field-measured values.

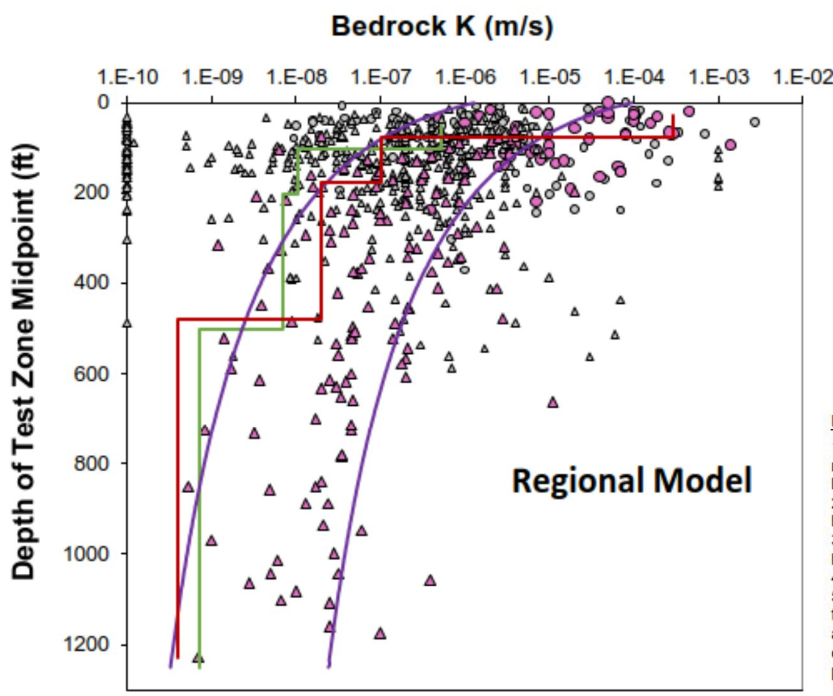
Simulated groundwater elevations in the five-layer model were very similar to measured groundwater elevations, as shown in Schlumberger (2011a: Figure 8.1-20), whereby an ideal calibration is represented by equivalent modeled and measured hydraulic heads to produce a straight line. Hydraulic heads in bedrock beneath upland areas are predicted to be slightly lower by the model than measurements. When plotted over time, hydraulic head residuals continually increased in some areas, highlighting opportunities for model refinement; while in other areas, the model produced uniform residuals over the simulation period.

Calculated calibration statistics run for the 2008 model (Schlumberger 2011a) produced a root mean squared error (RMSE) of 3 percent, with values ranging between 4 and 12 percent for the focus areas of calibration, suggesting that calibration could be improved in the SFK discharge and tributary UT1.190 areas. RMSE values ranged from 5 to 25 percent for areas in the model domain that were not the focus of calibration. Lower RMSE values generally indicate a good match between the model and actual field data. The largest errors at the mine site typically occurred in the bedrock layers. The model was generally able to reproduce measurements of groundwater elevations over time, but was unable to reproduce the range of measured seasonal hydraulic head fluctuations near Frying Pan Lake, where fine sediments may not be adequately reflected in the numerical groundwater model. Although the average direction of vertical flow between overburden and bedrock was well simulated by the model, the seasonality of vertical hydraulic head differences was not well replicated by the model.

Recharge and discharge rates estimated by the 2008 groundwater model agreed fairly well with estimates calculated in the WBM. The groundwater model simulates the exchange of water between streams and groundwater, and model estimates were compared with streamflow measurements during periods of time when flows were low, and primarily groundwater-derived. Overall, the groundwater model was able to reproduce measured hydraulic head calibration targets, and was in general agreement with recharge rates, inter-catchment flows, and local groundwater discharge rates estimated by the WBM with a reasonable degree of accuracy.

In order to assess model uncertainty, a Null Space Monte Carlo analysis (Doherty 2015) was conducted. This analysis involved the generation of 96 realizations of the model using input parameters that were randomly generated and slightly adjusted within user-defined bounds (PLP 2019-RFI 109b). The input parameters were slightly adjusted in order to make sure that each realization met calibration criteria. This methodology differs from standard sensitivity analyses in which model realizations frequently exceed calibration criteria, meaning that the scenarios simulated may not be physically credible compared to existing field data (PLP 2019-RFI 109b). This process results in simulation of a relatively modest range of hydraulic conductivity values in bedrock (Knight Piésold 2018n), for example, compared to the broad range of field-measured values (Figure K3.17-14).





Notes:

1. Each step in the K profile of the model represents a model layer. The profile includes layers 4 to 7.
2. Tests flagged as "No Take" were assigned a hydraulic conductivity of 1 x 10^{-10} m/s.
3. Tests flagged as high flow were assigned a hydraulic conductivity of 1 x 10^{-3} m/s.
4. Tests flagged with dashes were not plotted.
5. Considering that four deep holes (1000 to 3000 ft) in proximity to the proposed pit had negligible air-lift yield, the bulk bedrock hydraulic conductivity may be lower than indicated by the packer tests.

Sources: PLP 2019-RFI 109c

- Response Test - Pebble Deposit Area
- Response Test - All Other Areas
- Packer Test - Pebble Deposit Area
- Packer Test - All Other Areas
- GW Model - Upper Talarik Headwater
- GW Model - Pit Area
- K vs Z (Wei et al.)

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BEDROCK HYDRAULIC CONDUCTIVITY VS. DEPTH