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Pebble Project EBD
Groundwater Hydrology Overview

Presented by R. Smith

January 31, 2012

Groundwater Hydrology Team

- Schlumberger Water Services (formerly Water Management Consultants).
- SLR Consulting Limited.
- Knight Piesold Consulting.
- HDR Inc.
- Pebble Limited Partnership.

EBD Study Area

- Focused on an area surrounding the deposit.
- Included headwaters of Upper Talarik Creek (UTC), North Fork Koktuli River (NFK) and South Fork Koktuli River (SFK).
- More detailed studies closer to deposit area.

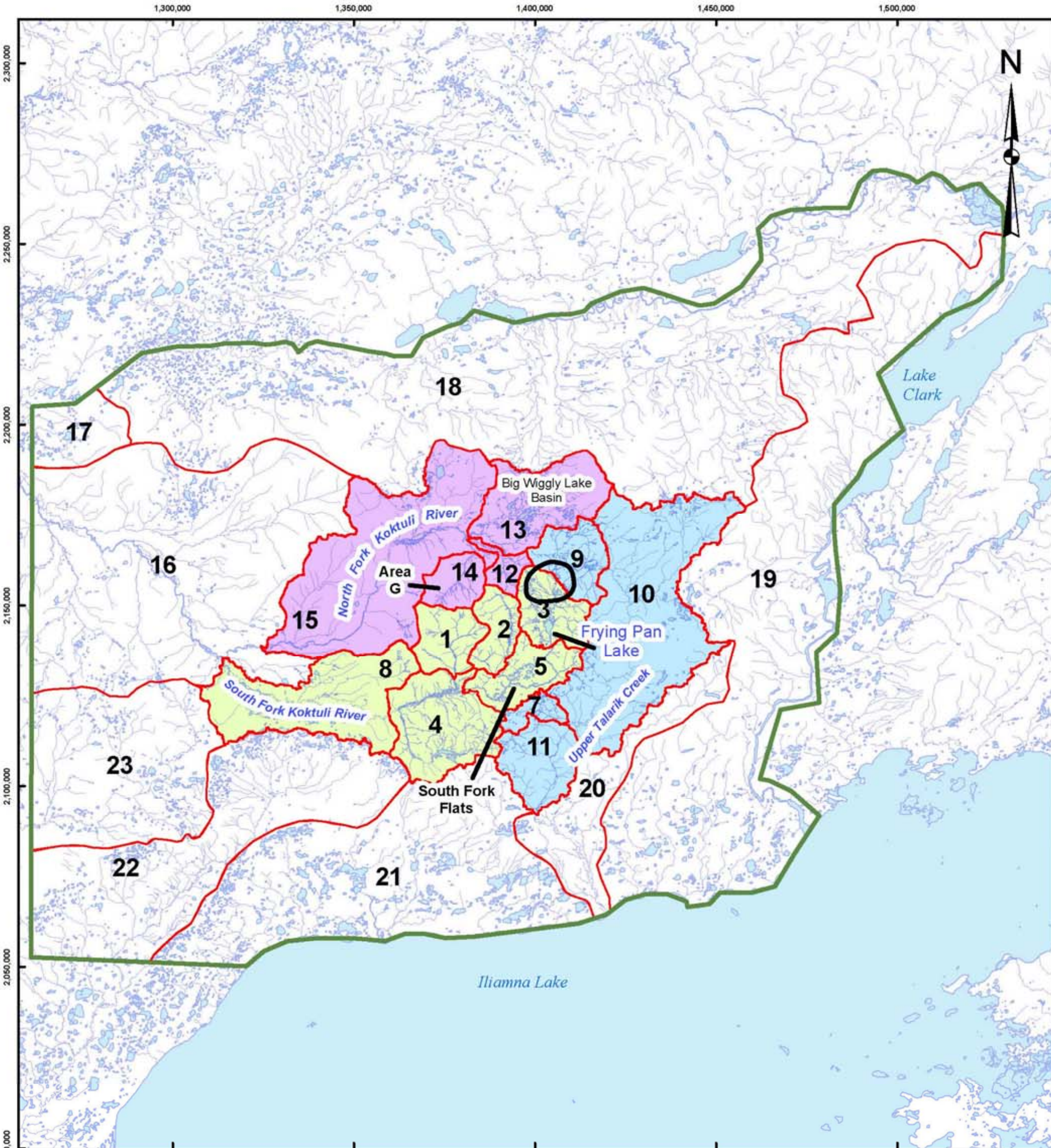

Figure 8.1-1b
Mine Hydrogeology Study Area - Detailed

Legend

- General Deposit Location
- Groundwater Model Boundary
- Subcatchment Areas
- Rivers
- Lakes

Watershed

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

Feet: 0, 20,000, 40,000, 60,000, 80,000

Meters: 0, 5,200, 10,400, 15,600, 20,800, 26,000

Scale 1:500,000

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

Project No: 7126	Author: SWS-KB
Version: 1	Date: April, 2011

Z:\Pebble_7126_2010\GIS\MXDs\T3914\Figure 8-1-1b Mine Hydrogeology Study Area Detailed.mxd

EBD Objectives

- **Characterize the existing groundwater flow regime and define how the local regime interacts with the regional groundwater system.**
- **Evaluate the interaction between groundwater and surface water, and the potential for cross basin transfer of groundwater.**
- **Develop baseline water flow.**
- **Support aquatic, fish resource, and wetlands habitat assessment.**

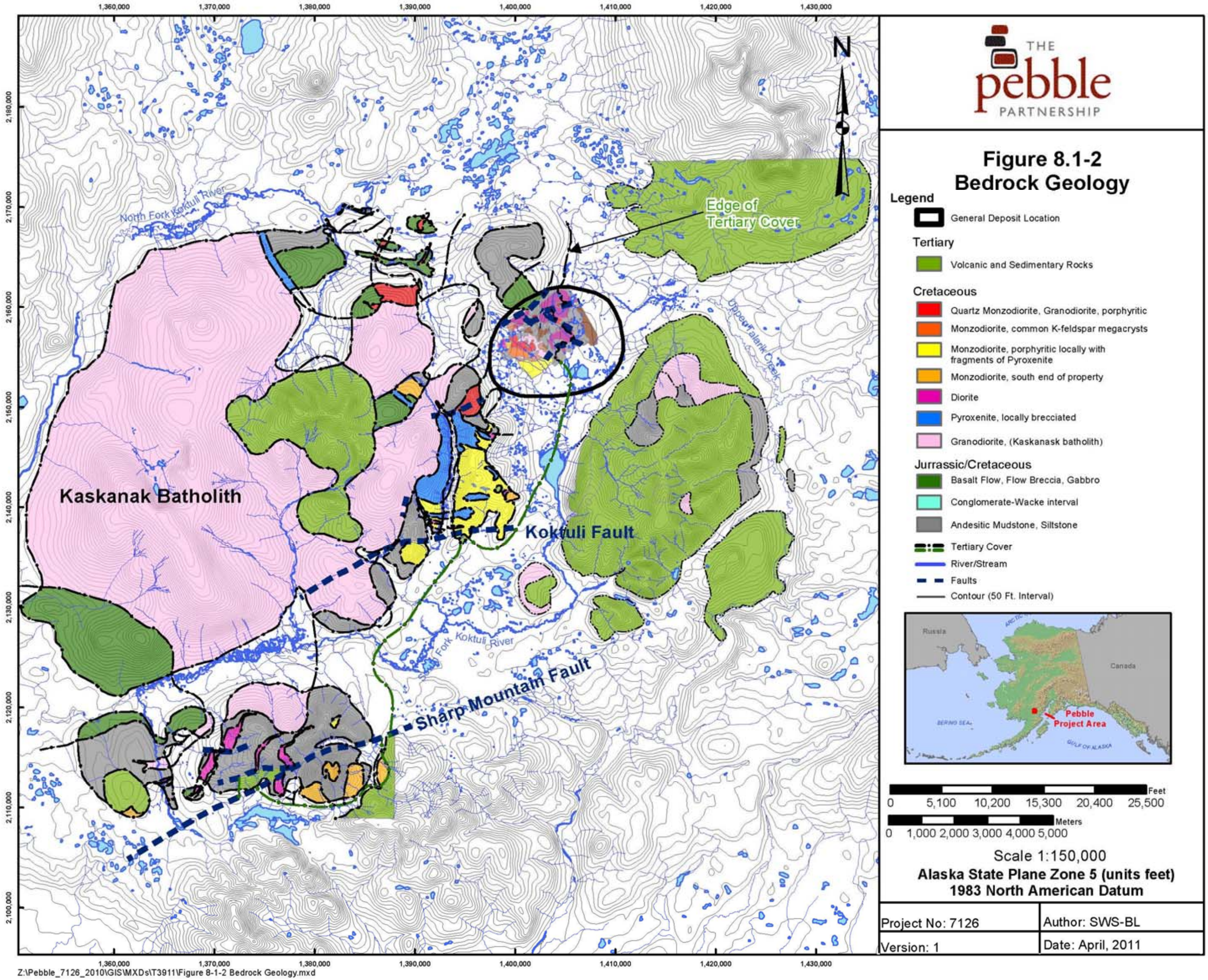
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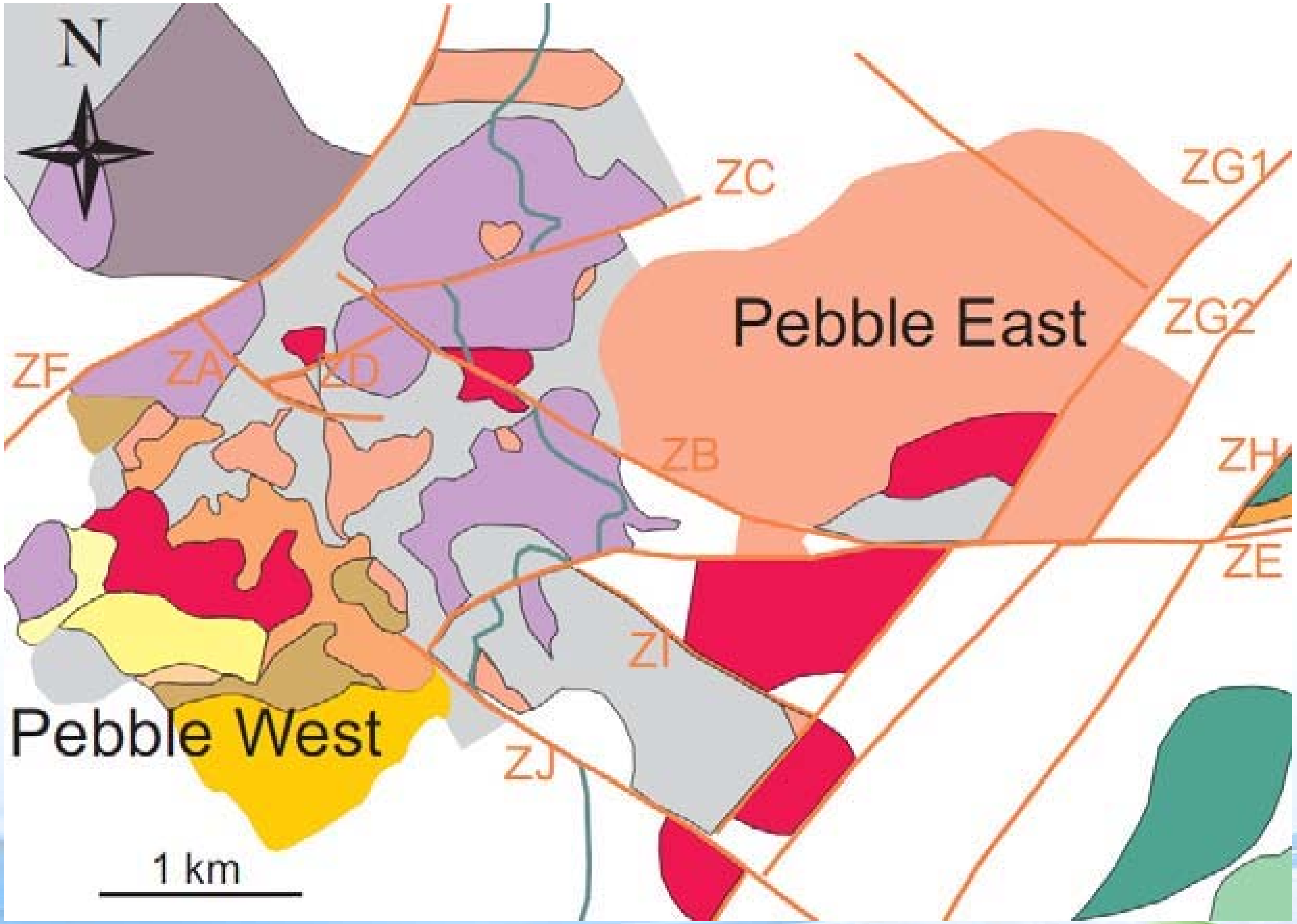
Figure 8.1-2
Bedrock Geology
Legend
General Deposit Location
Tertiary
Volcanic and Sedimentary Rocks
Cretaceous
Quartz Monzodiorite, Granodiorite, porphyritic
Monzodiorite, common K-feldspar megacrysts
Monzodiorite, porphyritic locally with fragments of Pyroxenite
Monzodiorite, south end of property
Diorite
Pyroxenite, locally brecciated
Granodiorite, (Kaskanask batholith)
Jurrassic/Cretaceous
Basalt Flow, Flow Breccia, Gabbro
Conglomerate-Wacke interval
Andesitic Mudstone, Siltstone
Tertiary Cover
River/Stream
Faults
Contour (50 Ft. Interval)
Russia
Canada
BERING SEA
GULF OF ALASKA
Pebble Project Area
Feet
0 5,100 10,200 15,300 20,400 25,500
Meters
0 1,000 2,000 3,000 4,000 5,000
Scale 1:150,000
Alaska State Plane Zone 5 (units feet)
1983 North American Datum
Project No: 7126
Author: SWS-BL
Version: 1
Date: April, 2011
N
Kaskanak Batholith
Koktuli Fault
Sharp Mountain Fault
Edge of Tertiary Cover
North Fork Koktuli River
Koktuli River
Upper Talarik Creek
1,360,000
1,370,000
1,380,000
1,390,000
1,400,000
1,410,000
1,420,000
1,430,000
2,180,000
2,170,000
2,160,000
2,150,000
2,140,000
2,130,000
2,120,000
2,110,000
2,100,000
Z:\Pebble_7126_2010\GIS\MXDs\T3911\Figure 8-1-2 Bedrock Geology.mxd

Bedrock Structures

- Structural fabric broadly defined by northeast trending faults related to the Lake Clark Fault, about 10 km to the east.
- Seven major fault zones in deposit area (ZA to ZG).
- ZG fault borders a graben on the east side of the deposit area, with vertical displacement of at least 3000 ft.

Bedrock Structures



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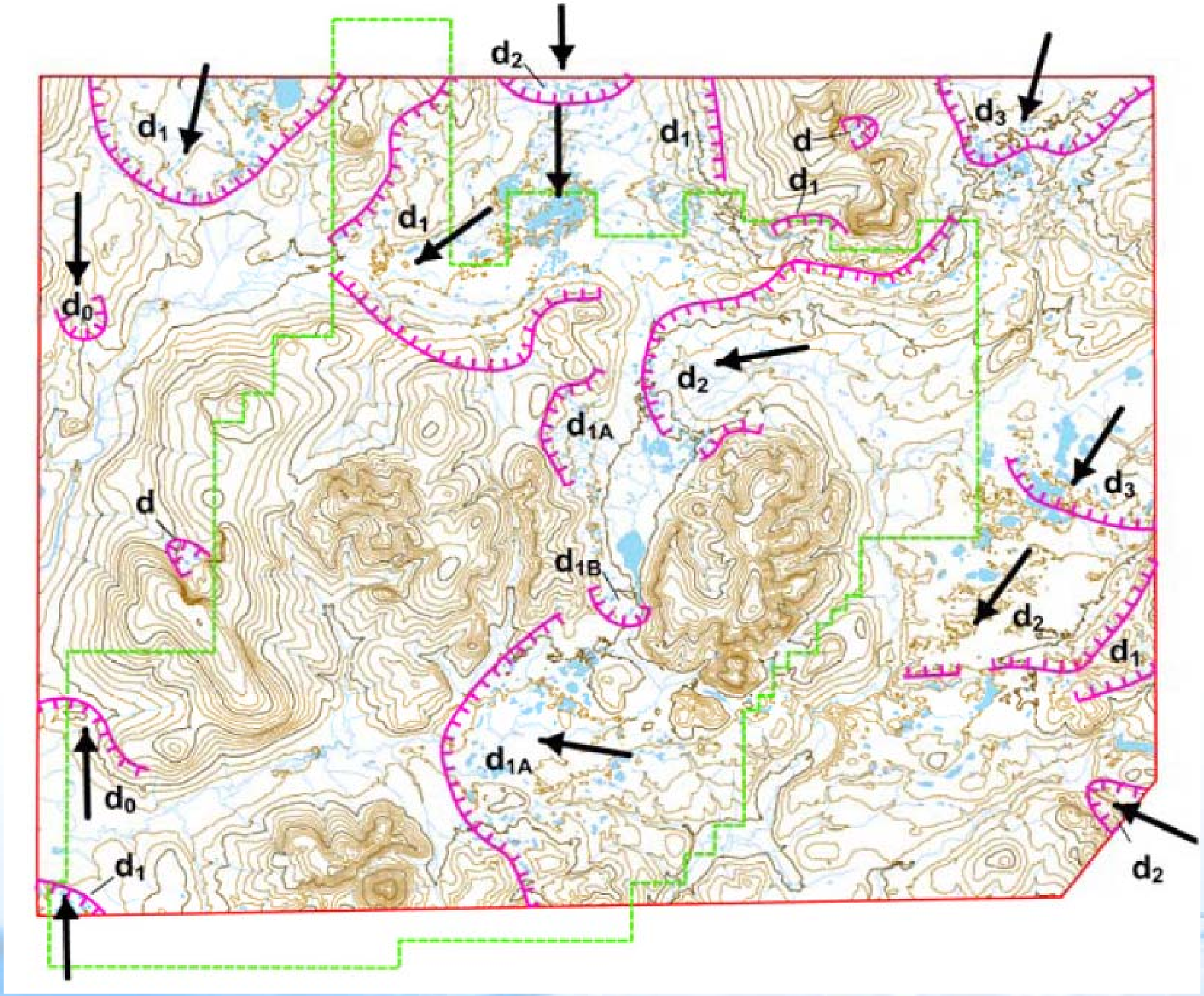
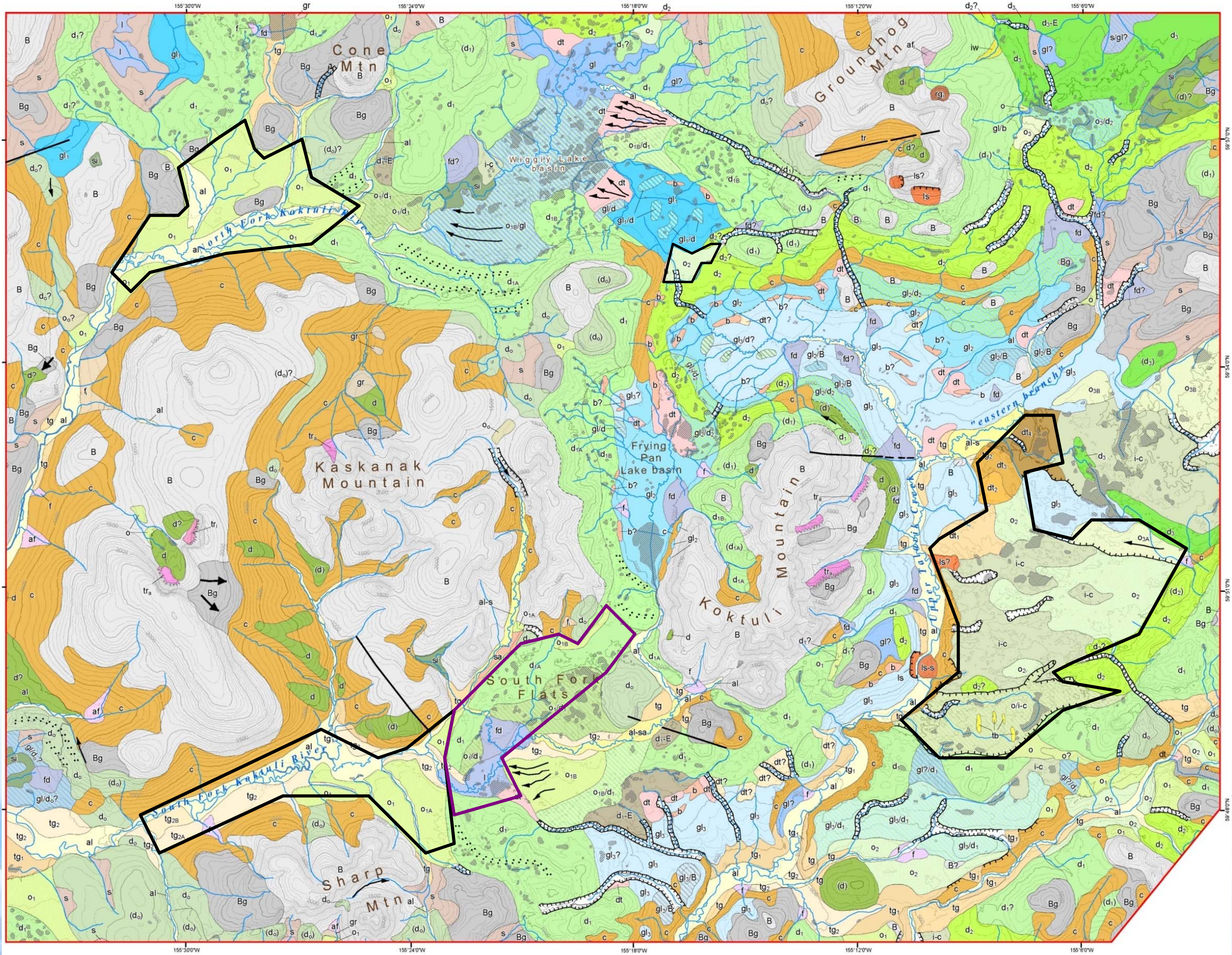
Study Area Overburden

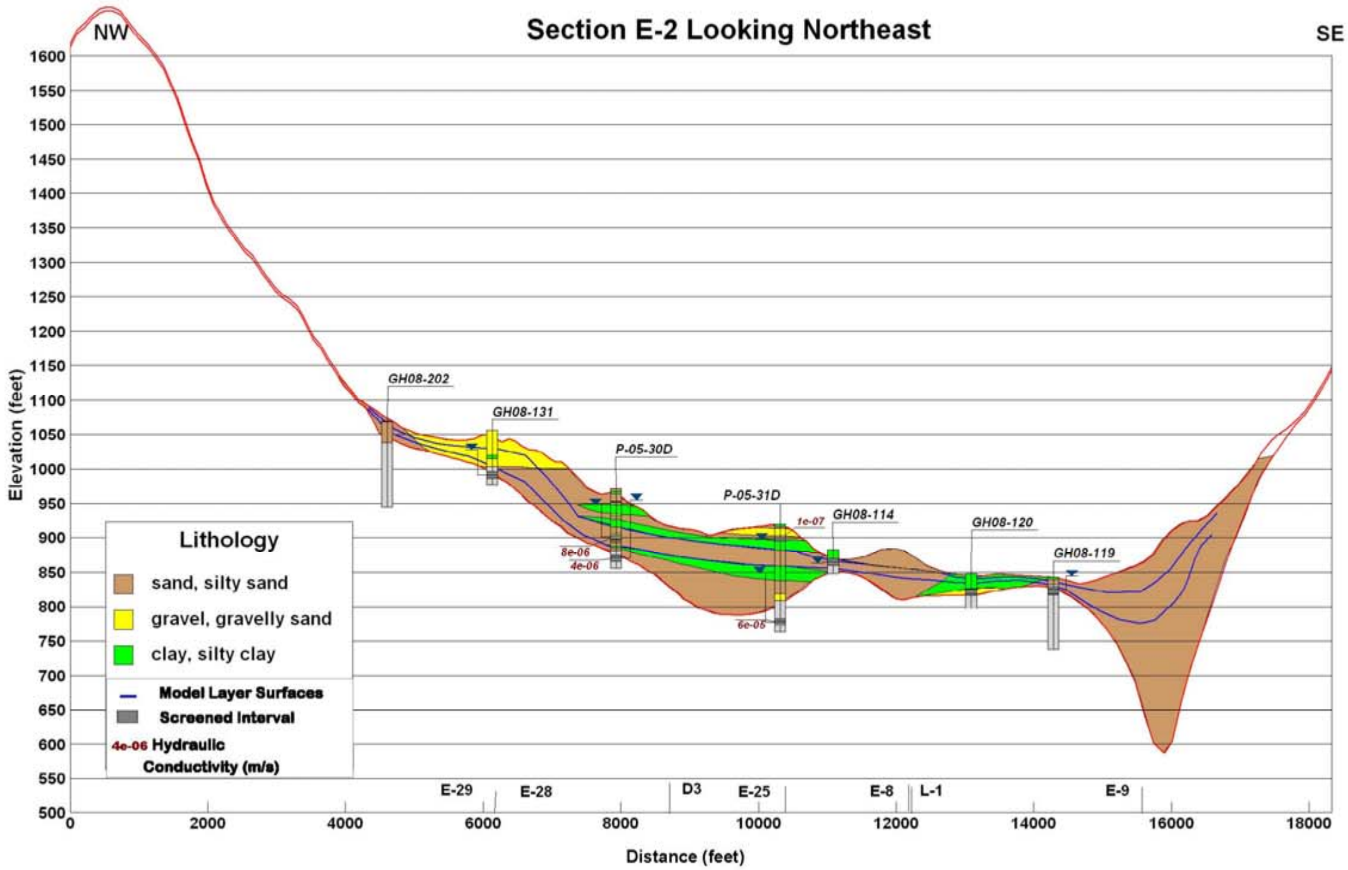
- Mapping by Tom Hamilton.
- Overburden geology dominated by glacial deposits.
- Alluvial and colluvial deposits present.

Study Area Overburden





155°30'0"W
155°24'0"W
155°18'0"W
155°12'0"W
155°6'0"W
59°57'0"N
59°54'0"N
59°51'0"N
59°48'0"N
Cone Mtn
Groundhog Mtn
Wiggly Lake basin
North Fork Koktuli River
Kaskanak Mountain
Frying Pan Lake basin
Koktuli Mountain
"eastern branch"
Upper Talarik Creek
South Fork Flats
South Fork Koktuli River
Sharp Mtn



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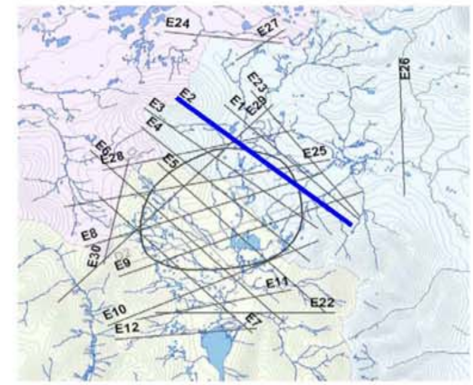
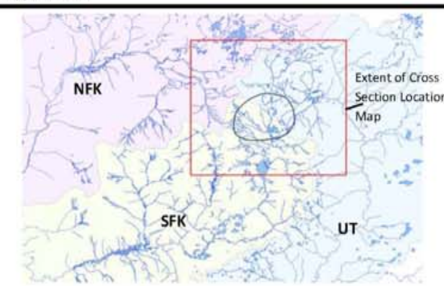
Appendix 8.1B
Geologic Cross Sections

Cross Section Location Map



Notes:

1. Water levels measured October, 2008
2. Drill hole logs for the KP, MW and P series drill holes are in Appendix 8.1A
3. Drill hole logs for the GH series are included in Knight Piesold 2004, 2005, 2005a, 2006, 2007, 2008
4. Water levels are plotted as time series in Appendix 8.1G



Project No: 7126	Section E-2
Author: SWS-PP	Date: December 20, 2010

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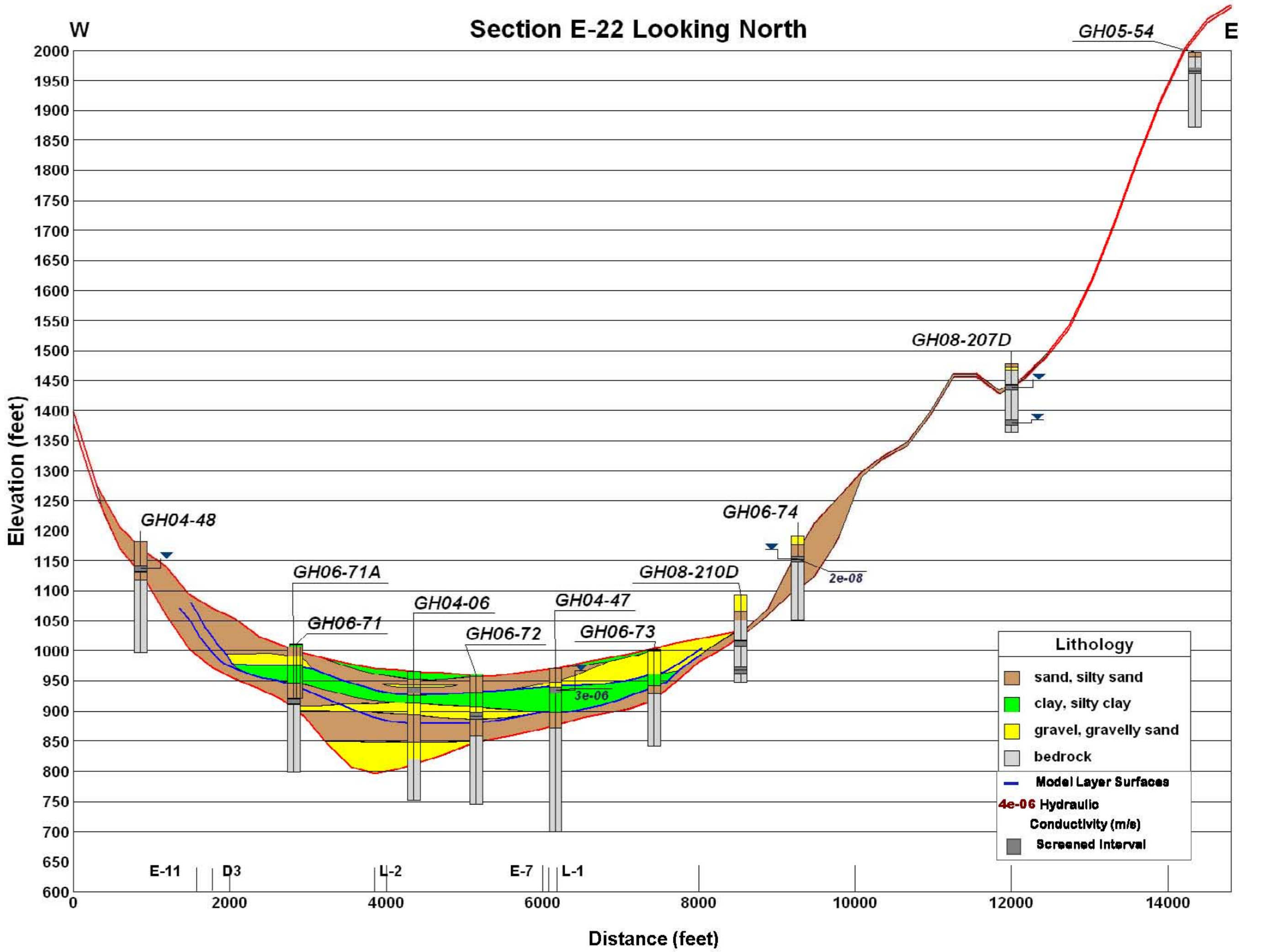

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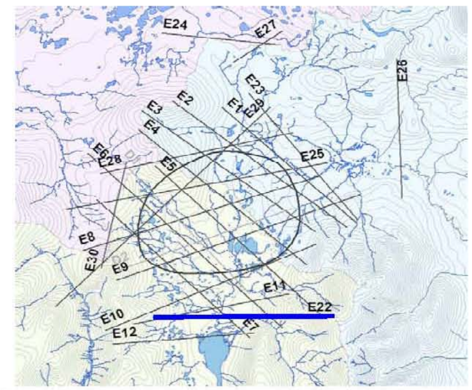
Geologic Cross Sections

Cross Section Location Map



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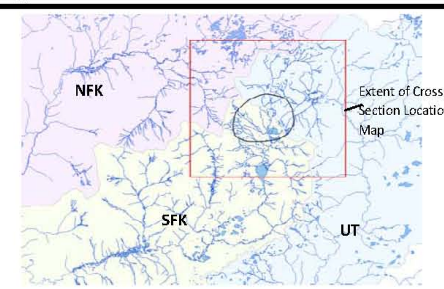

Project No: 7126	**Section E-22**
Author: SWS-PP	Date: December 20, 2010

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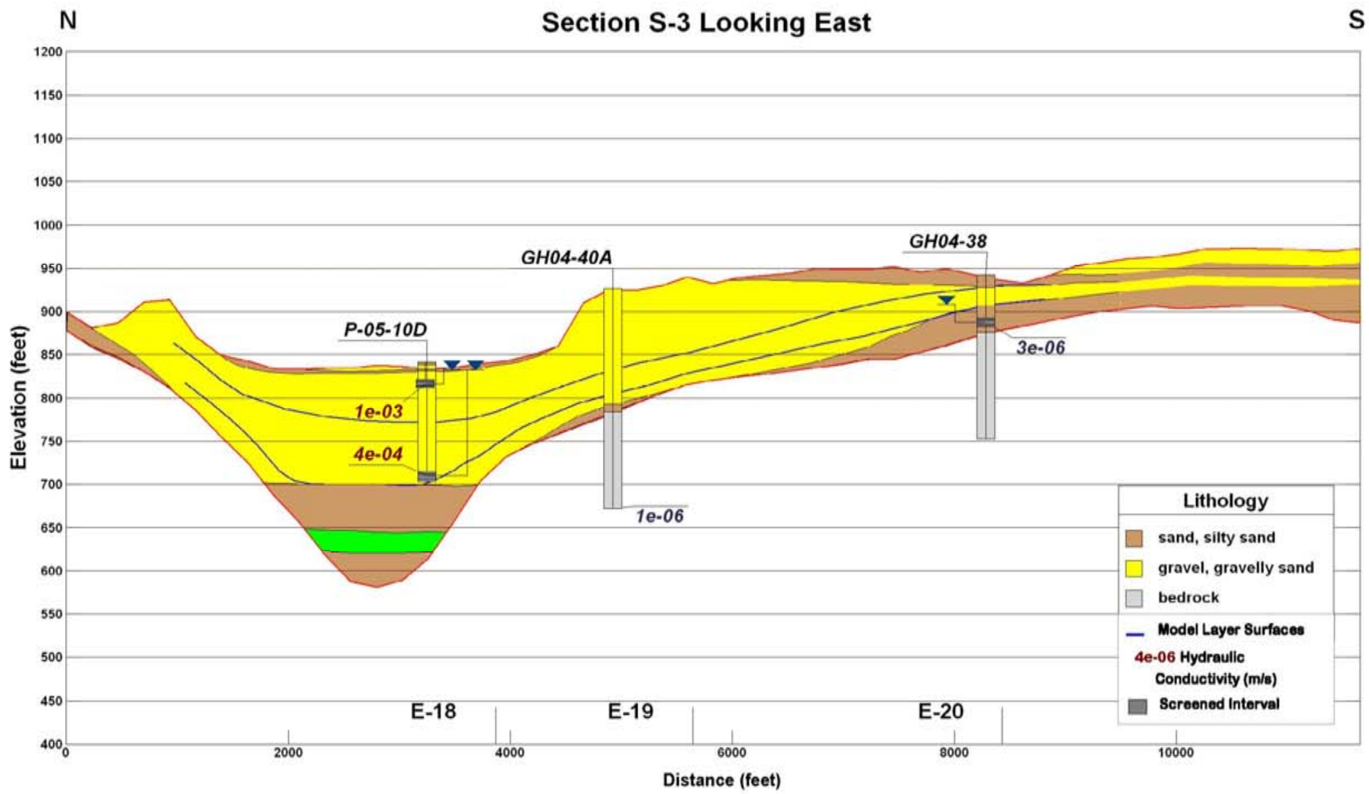
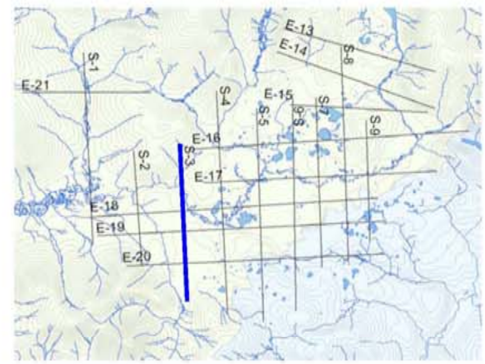
Appendix 8.1B
Geologic Cross Sections



Cross Section Location Map



Notes:
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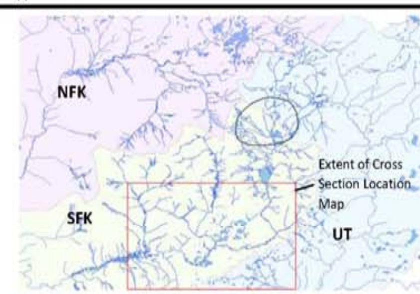


Project No: 7126	Section S-3
Author: SWS-PP	Date: December 20, 2010

Geology Summary

- Faults present in deposit area provide groundwater pathways and blockages.
- Freeze thaw activity particularly through glacial periods has resulted in a thin (10 to 50 ft) disturbed zone at top of rock.
- Glacial outwash sand and gravel and ice contact deposits have left extensive permeable deposits.
- One large glacial moraine is composed of permeable sand and gravel.

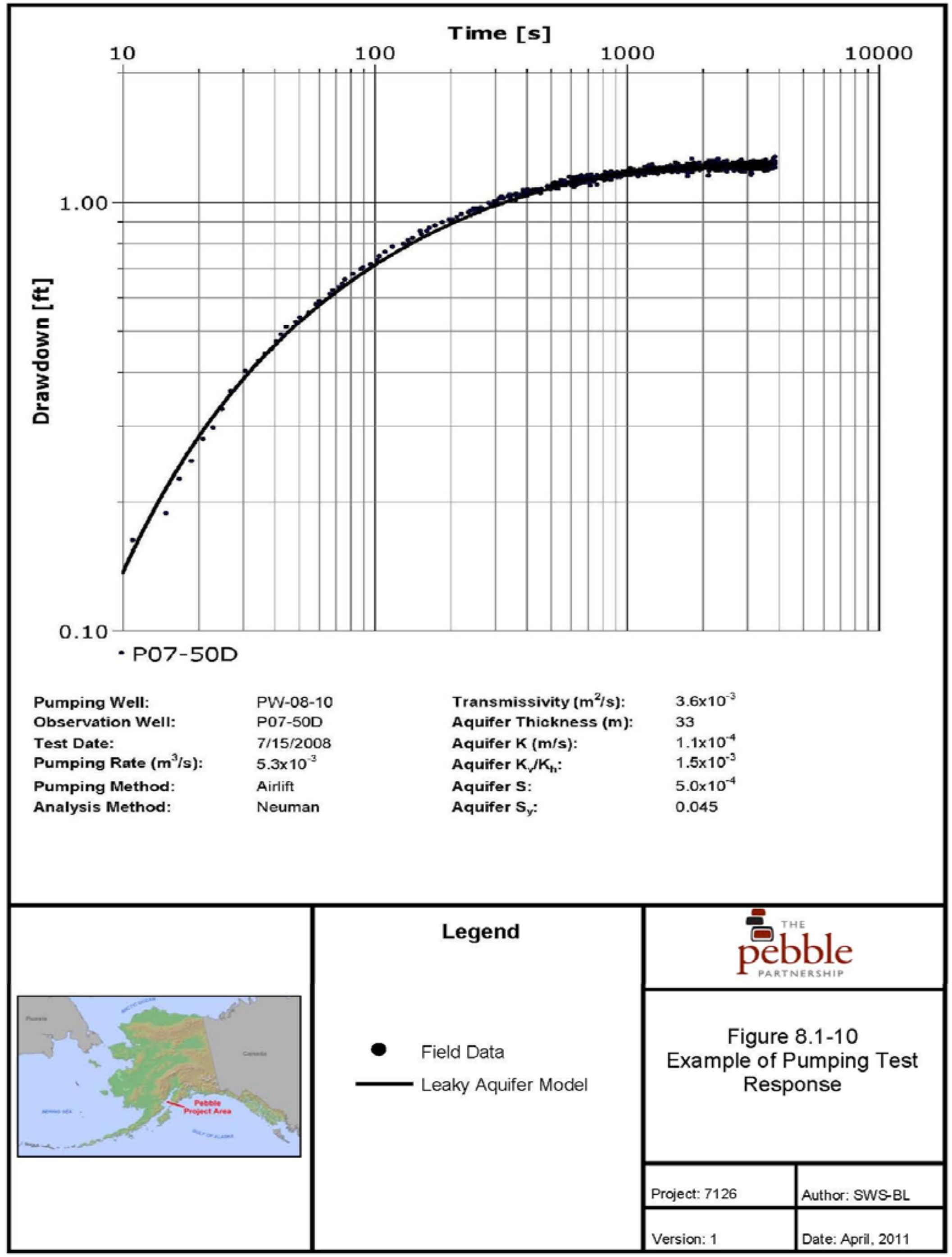
Geology Summary

- Glacial lakes have left extensive low permeability materials in all three drainage areas.
- Terminal, recessional and lateral moraines are mostly composed of a low permeability silt, sand and gravel.

Hydrogeologic Testing

- Pumping tests. Pumped with air lift method and monitored in adjacent piezometers.
- Slug or response single well tests.
- Packer testing during drilling in bedrock.
- Multiple depth cross hole tests to a depth of 4,000 ft.

Pumping Test



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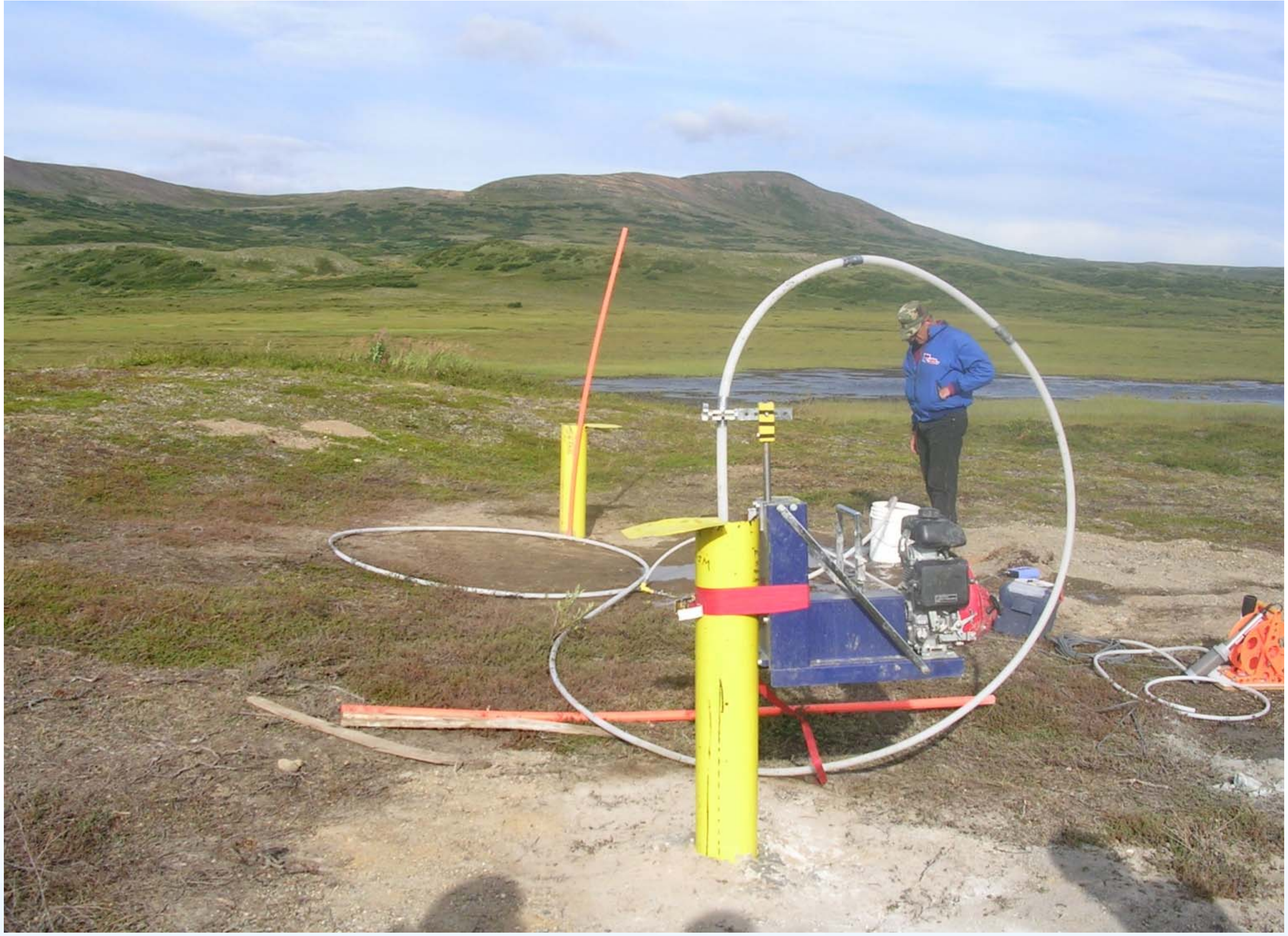
Hydrogeologic Testing

Well development prior to response test at MW-5



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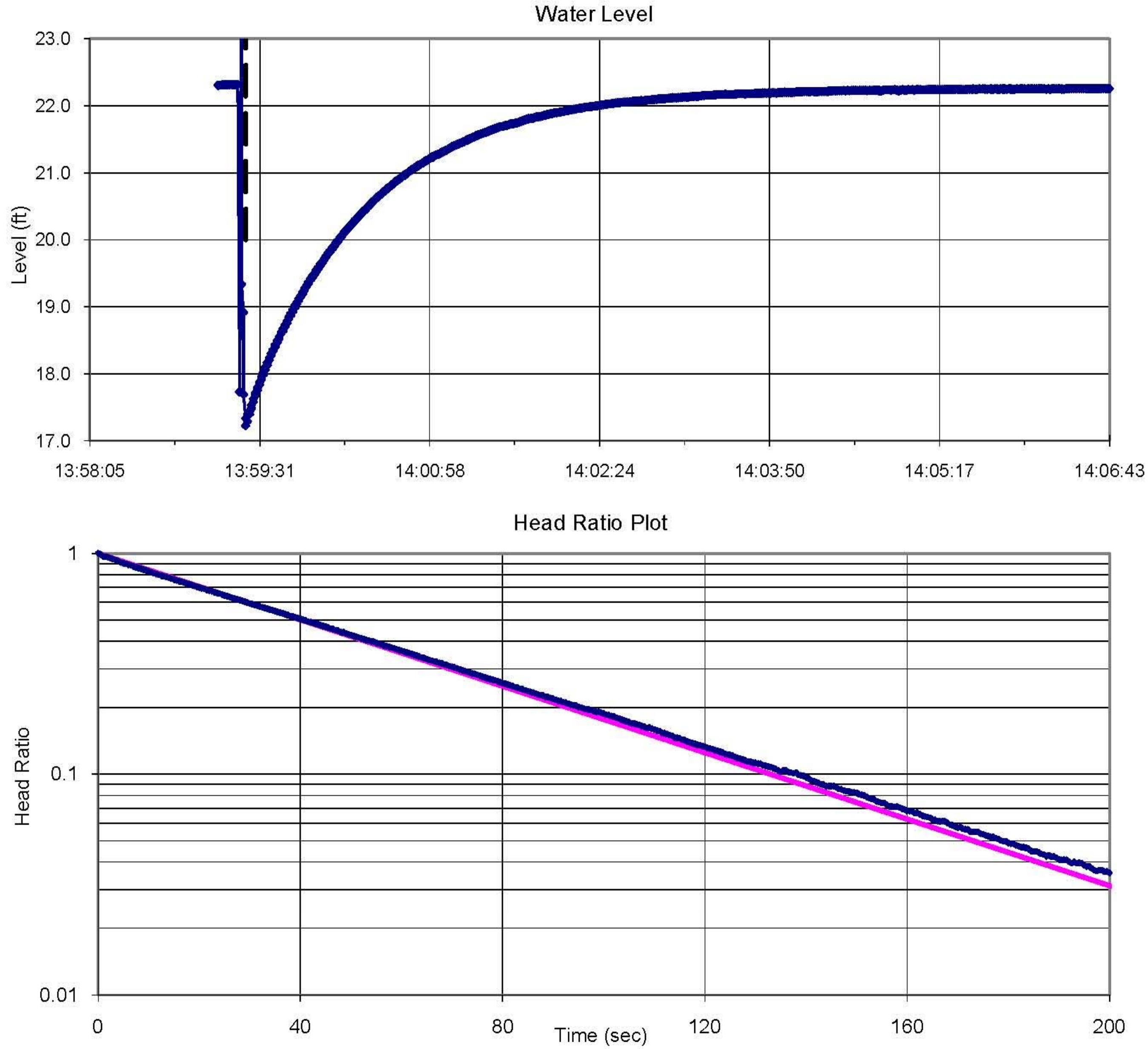

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Figure 8.1-8b
Overdamped Response Test
P-08-55D

Legend

Data

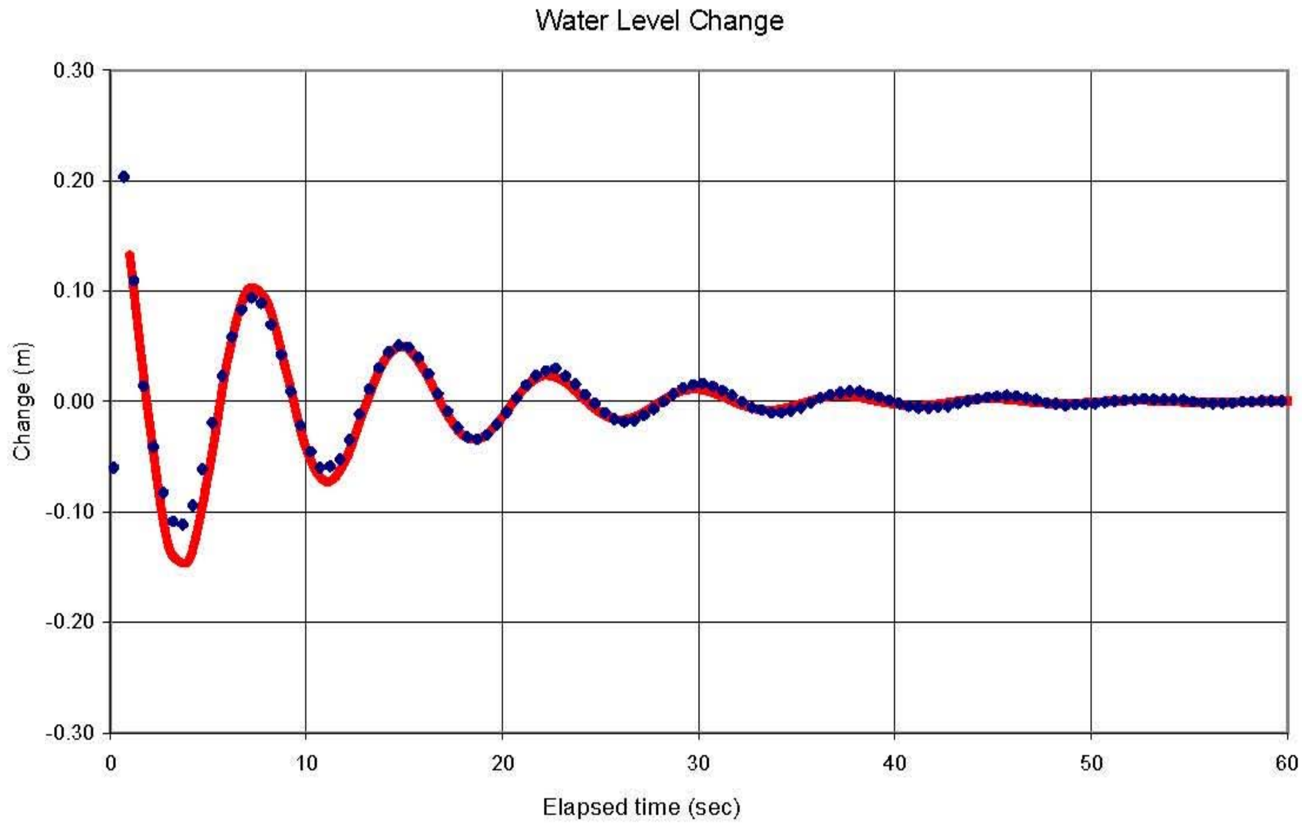
Hvorslev Plot

Test Start

Project No: 7126	Author: SWS-KB
Version: 1	Date: April, 2011

Z:\Pebble_7126_2010\GIS\MXDs\T3919\Figure 8.1-8b Overdamped Response Test P-08-55D.xlsx

Figure 8.1-8a
Underdamped Response Test
P-08-62M



Legend

Data

Calculated Response

Project No: 7126	Author: WMC-AUB
Version: 1	Date: May 25, 2010

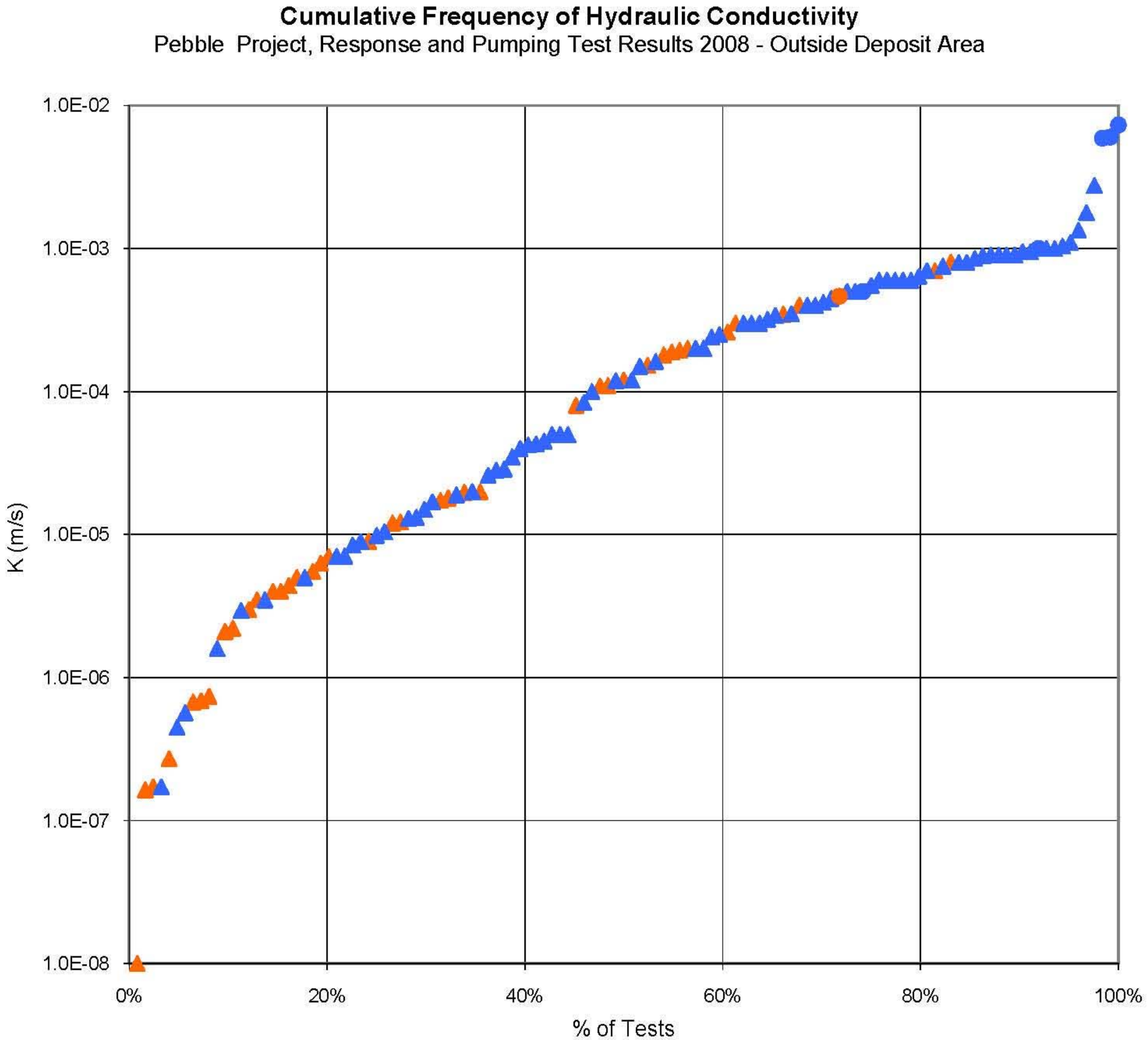


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Figure 8.1-9c
Cumulative Frequency of Calculated Hydraulic Conductivity Outside of General Pebble Deposit Area

Legend:

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

Project No: 7126	Author: WMC-LC
Version: 1	Date: April, 2011

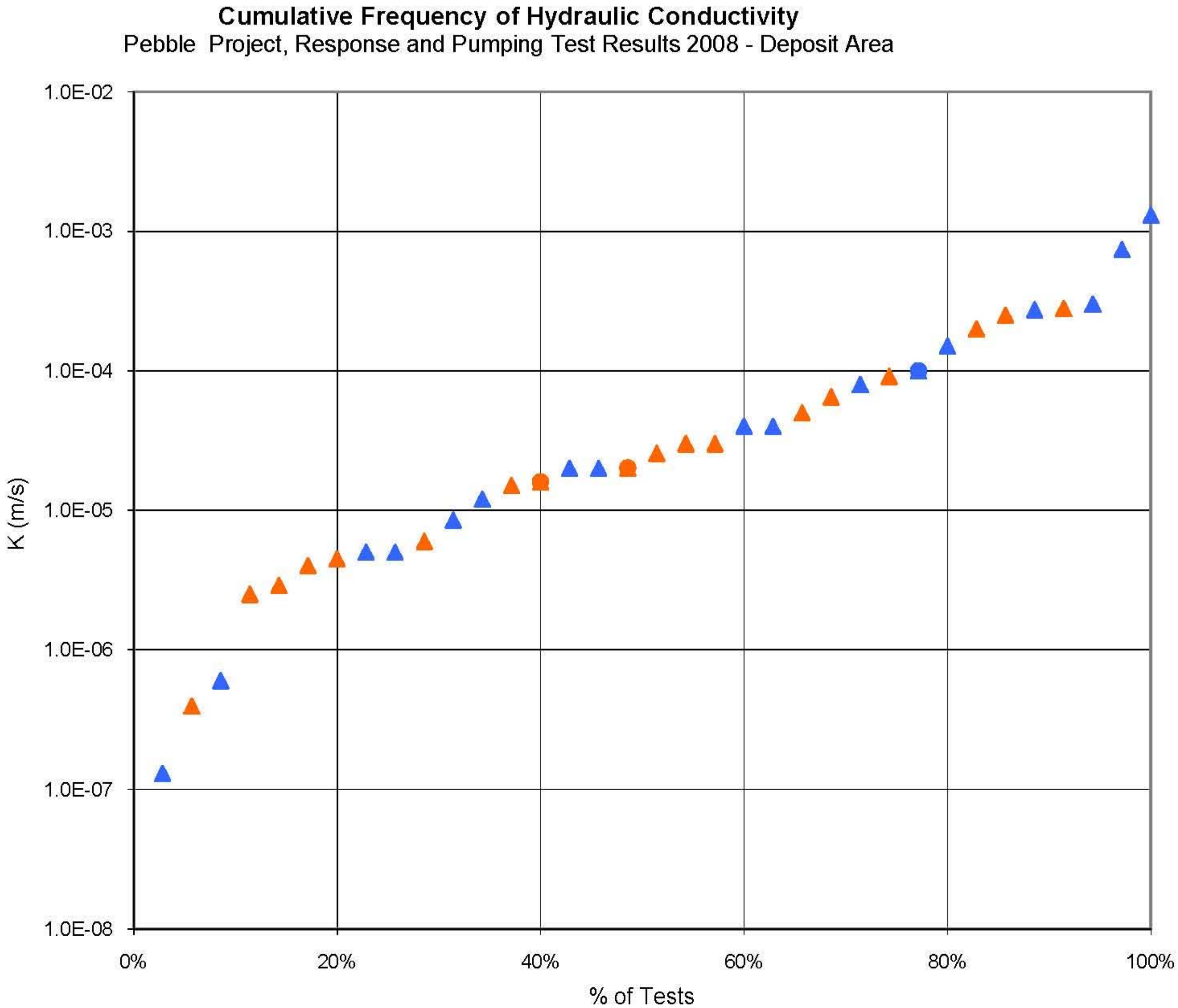

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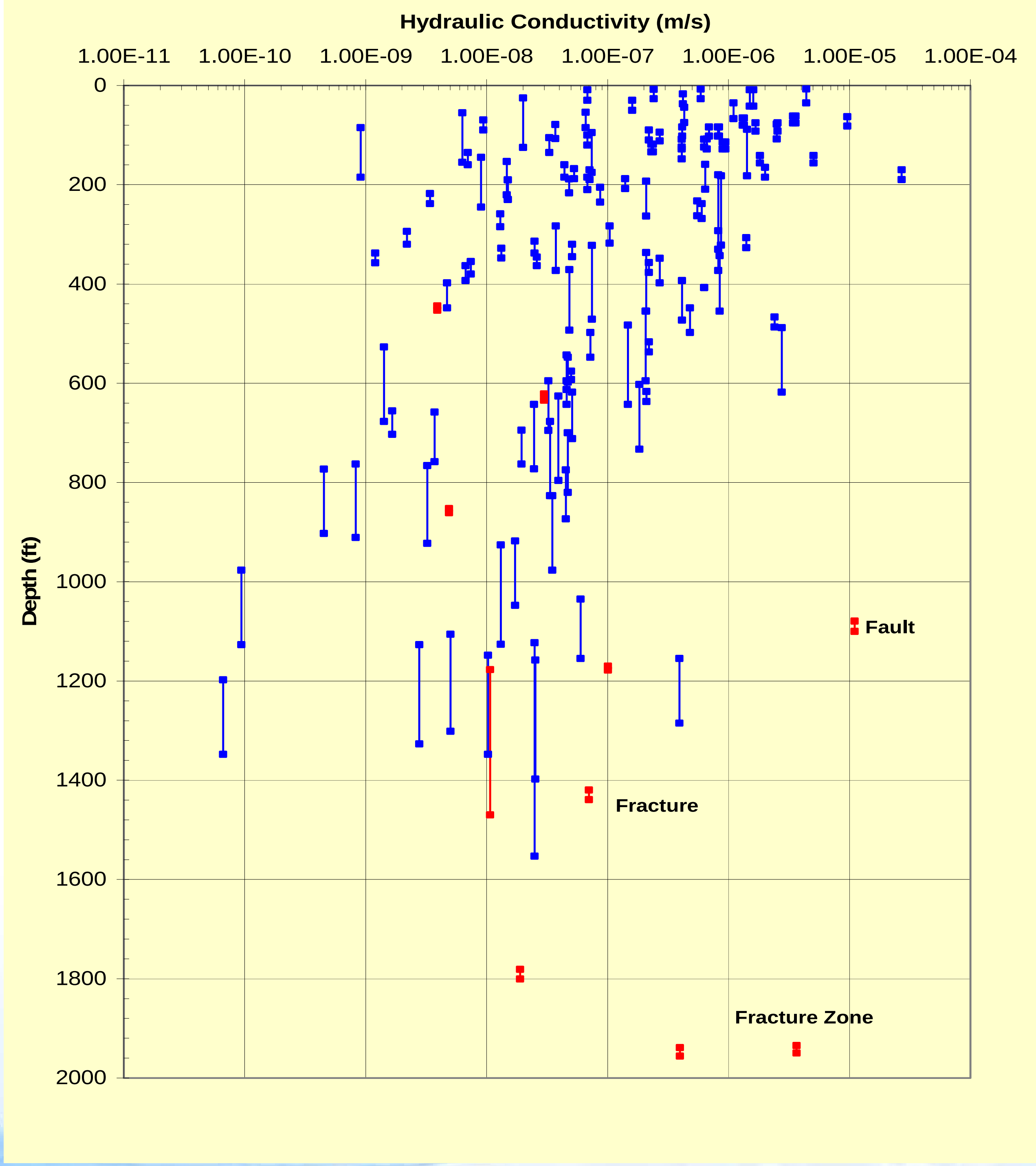
Figure 8.1-9b
Cumulative Frequency of Calculated Hydraulic Conductivity in General Pebble Deposit Area

Legend:
- Pumping test - bedrock
- Pumping test - overburden
- Response test - bedrock
- Response test - overburden

Project No: 7126	Author: WMC-LC
Version: 1	Date: April 2011

Packer testing hydraulic conductivity results with depth in deposit area



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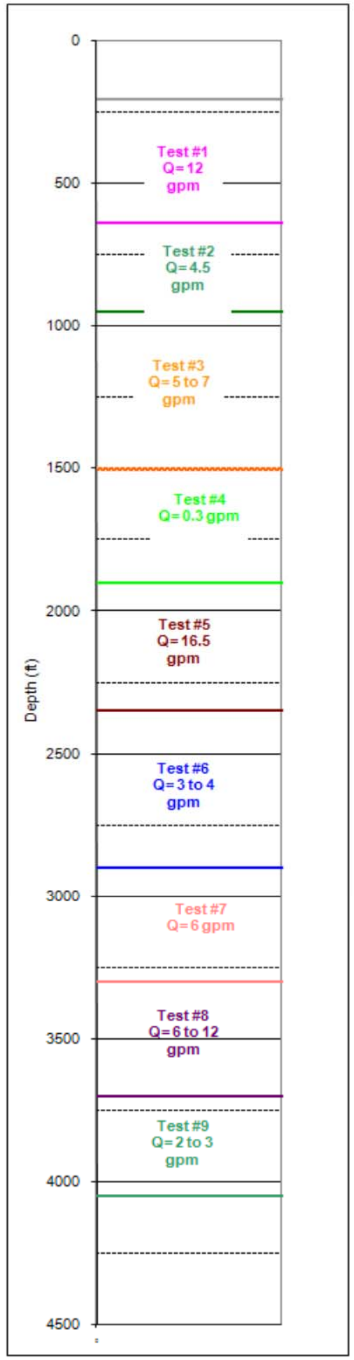
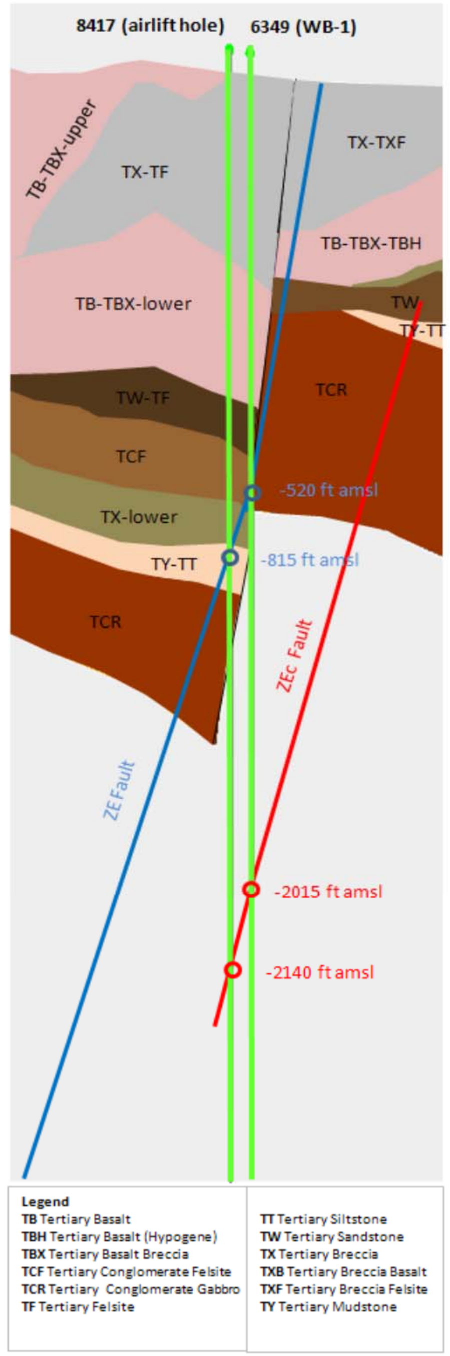
Westbay Deep Cross Hole Test

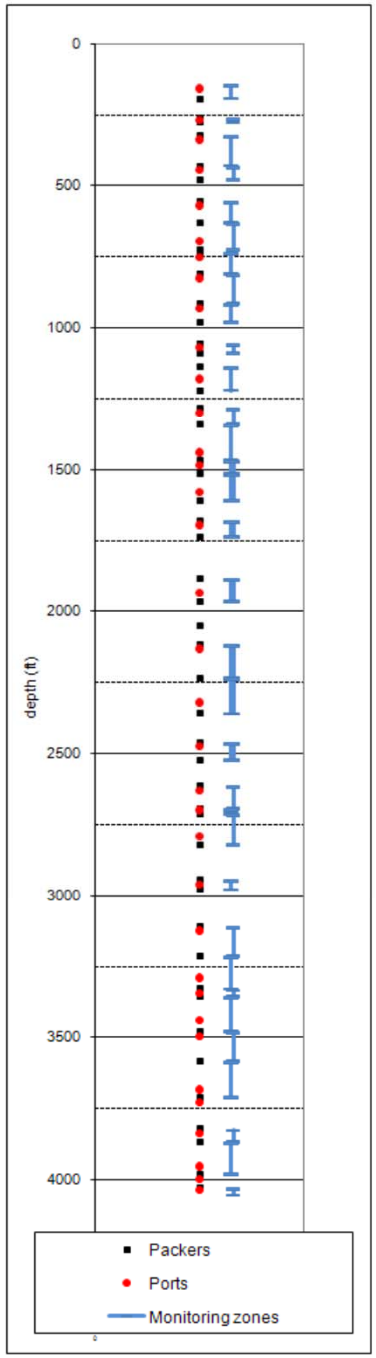
Legend For Tertiary
TB - Basalt
TBH - Basalt (Hypogene)
TBX - Basalt Breccia
TCF - Conglomerate Felsite
TCR - Conglomerate Gabbro
TF – Felsite
TT – Siltstone
TW - Sandstone
TX – Breccia
TXB – Breccia Basalt
TXF – Breccia Felsite
TY - Mudstone

8417 (airlift)





6349 (WB-1)



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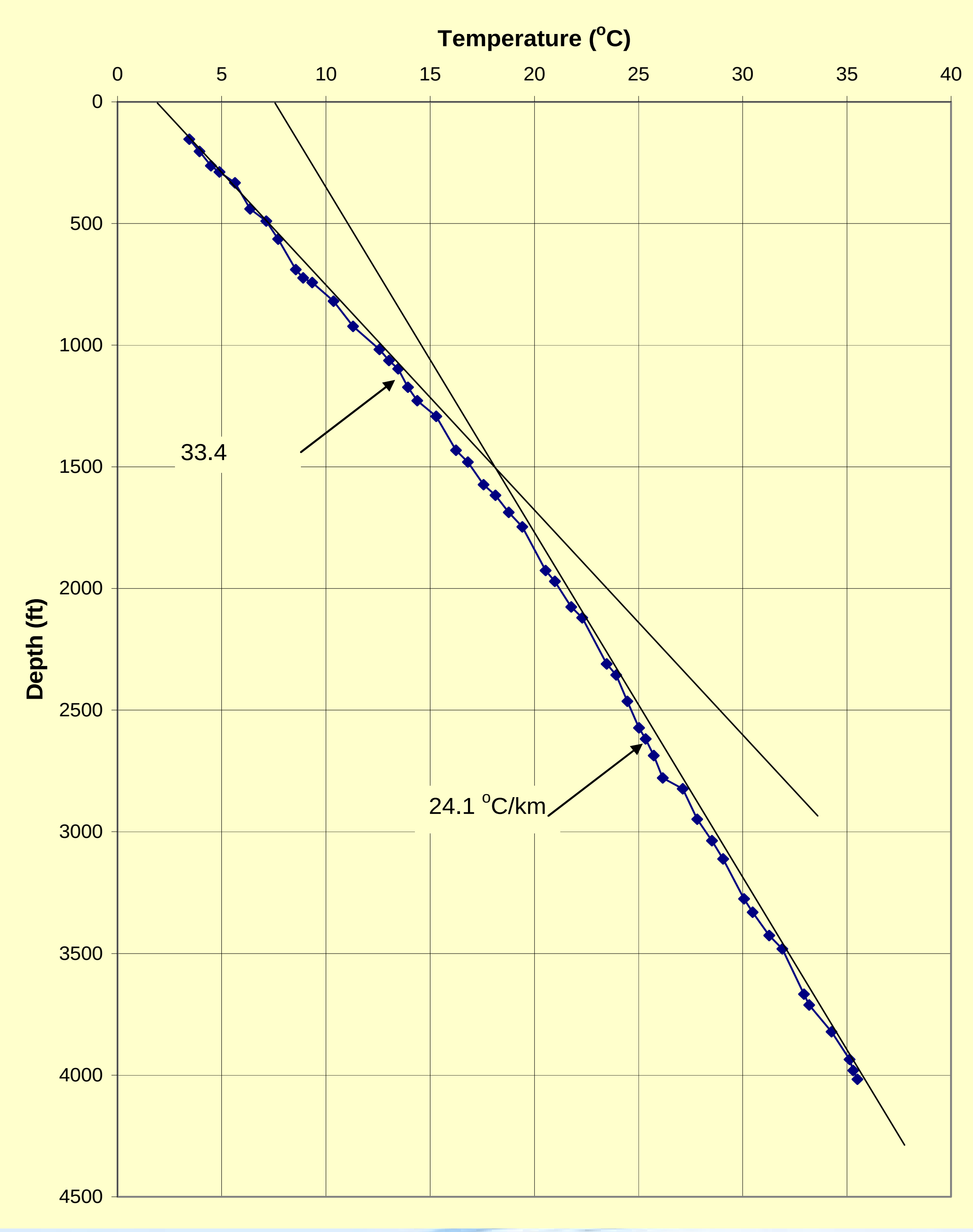
Westbay Deep Cross Hole Test



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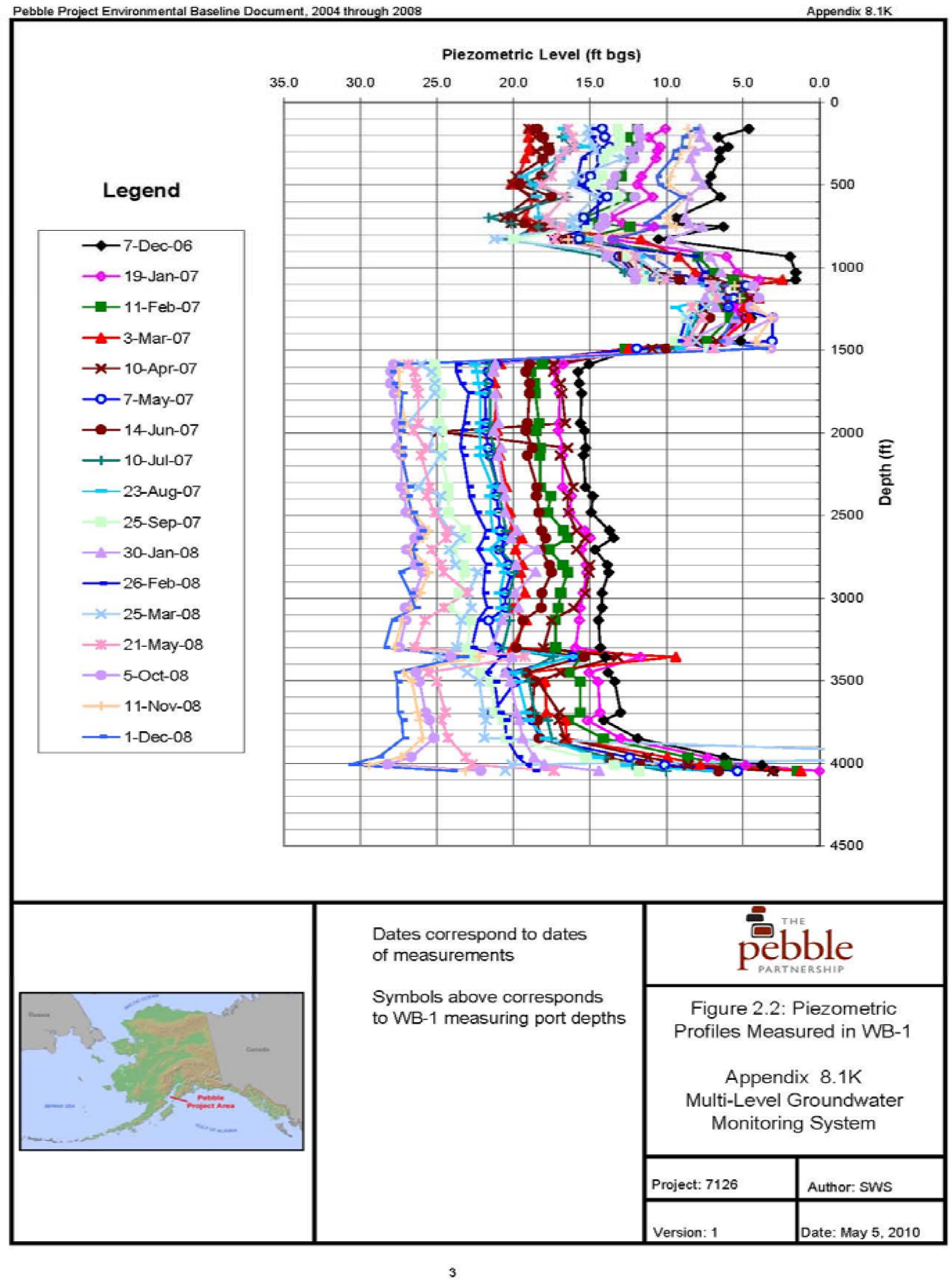
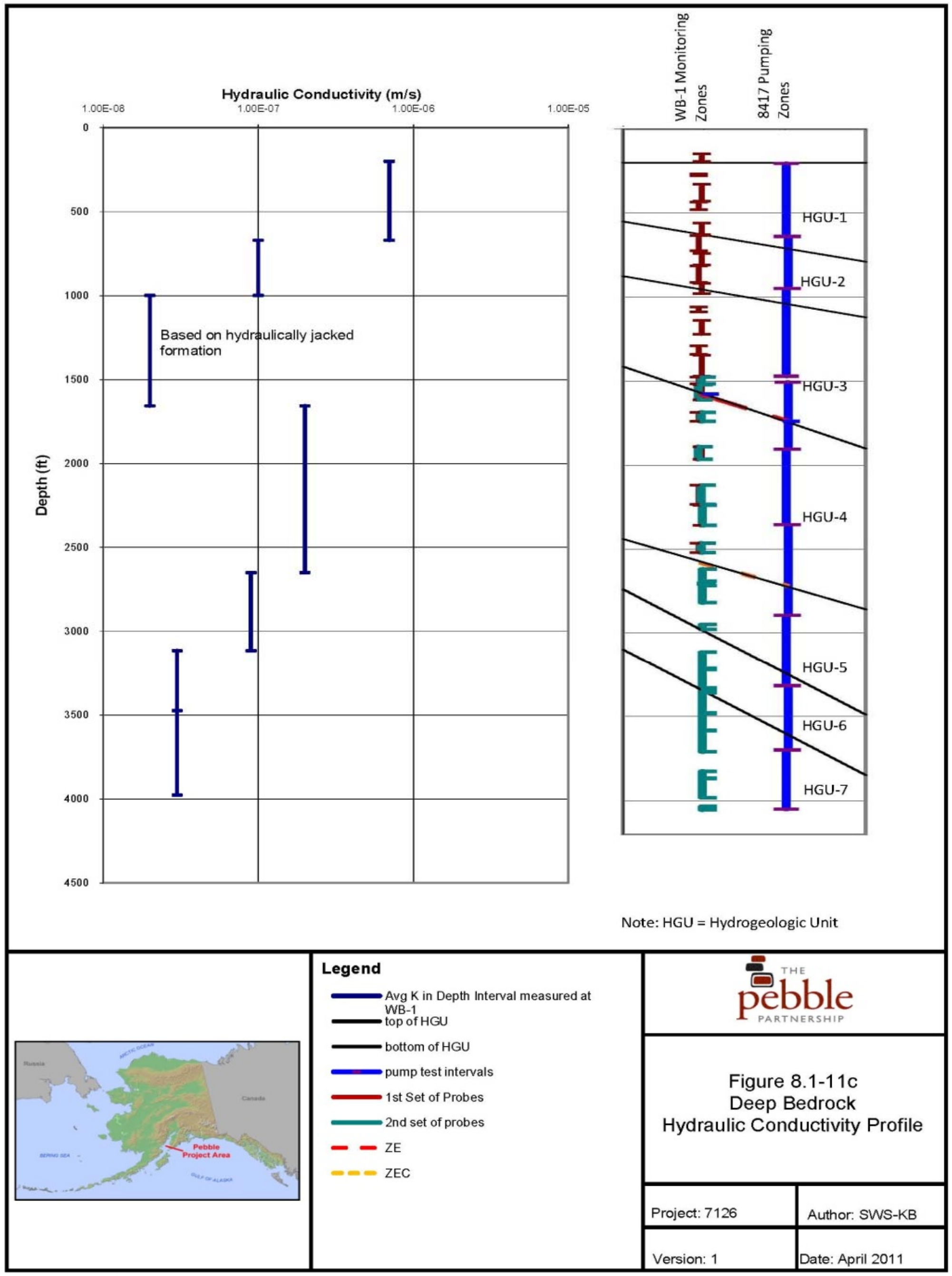
Deep Cross Hole Testing



Deep Cross Hole Testing



Z:\Pebble_7126_2010\GIS\MXDs\T3929\Figure 8.1-11c Deep Bedrock Hydraulic Conductivity Profile.xlsx

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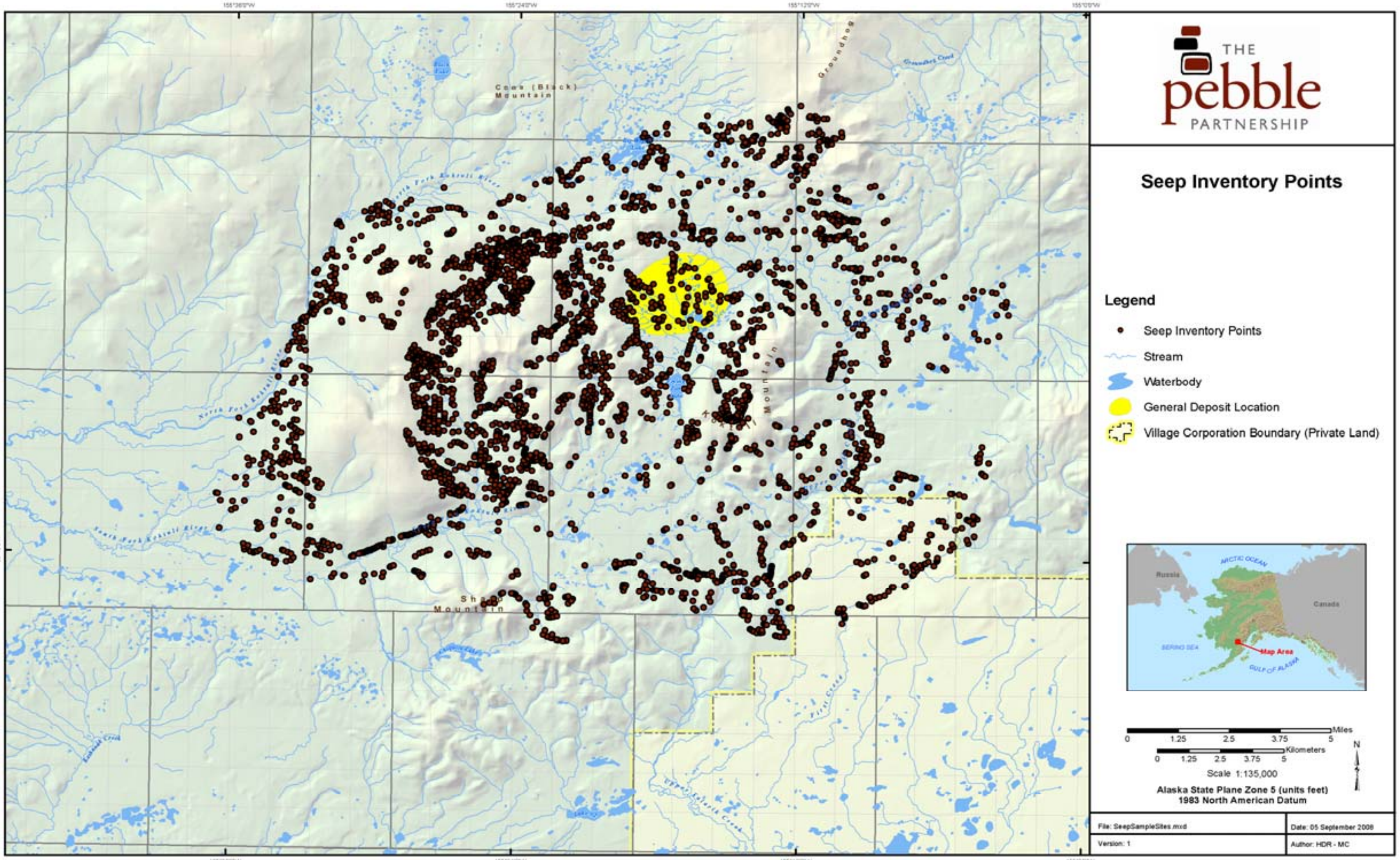
Westbay Deep Hole Testing

- Upper 600 ft of bedrock is responsive to seasonal recharge events and changes in barometric pressure.
- Response to surface declines rapidly below 600 ft, but response to earth tides observed.
- Hydraulic conductivity decreases with depth down to the base of the Tertiary. The Tertiary basal conglomerate has very low permeability.
- The base of the Tertiary is defined by the ZE fault, where there is a sudden change in piezometric levels.
- Below the ZE fault the hydraulic conductivity increases and then again decreases with depth. The slow recovery of drilling and installation induced pressures is indicative of a system compartmentalized by faulting systems.

Spring and Seep Inventory and Sampling

- Seep inventory of an extensive area completed by helicopter.
- A high density of springs and seeps identified.
- Many of the springs and seeps were high on valley slopes indicating high groundwater table.
- Some springs mapped along stream banks.
- Dominance of seeps and springs indicative of relatively high recharge rates and relatively low hydraulic conductivity.
- A selection of springs sampled for water quality and flow rate.

Spring and Seep Inventory and Sampling



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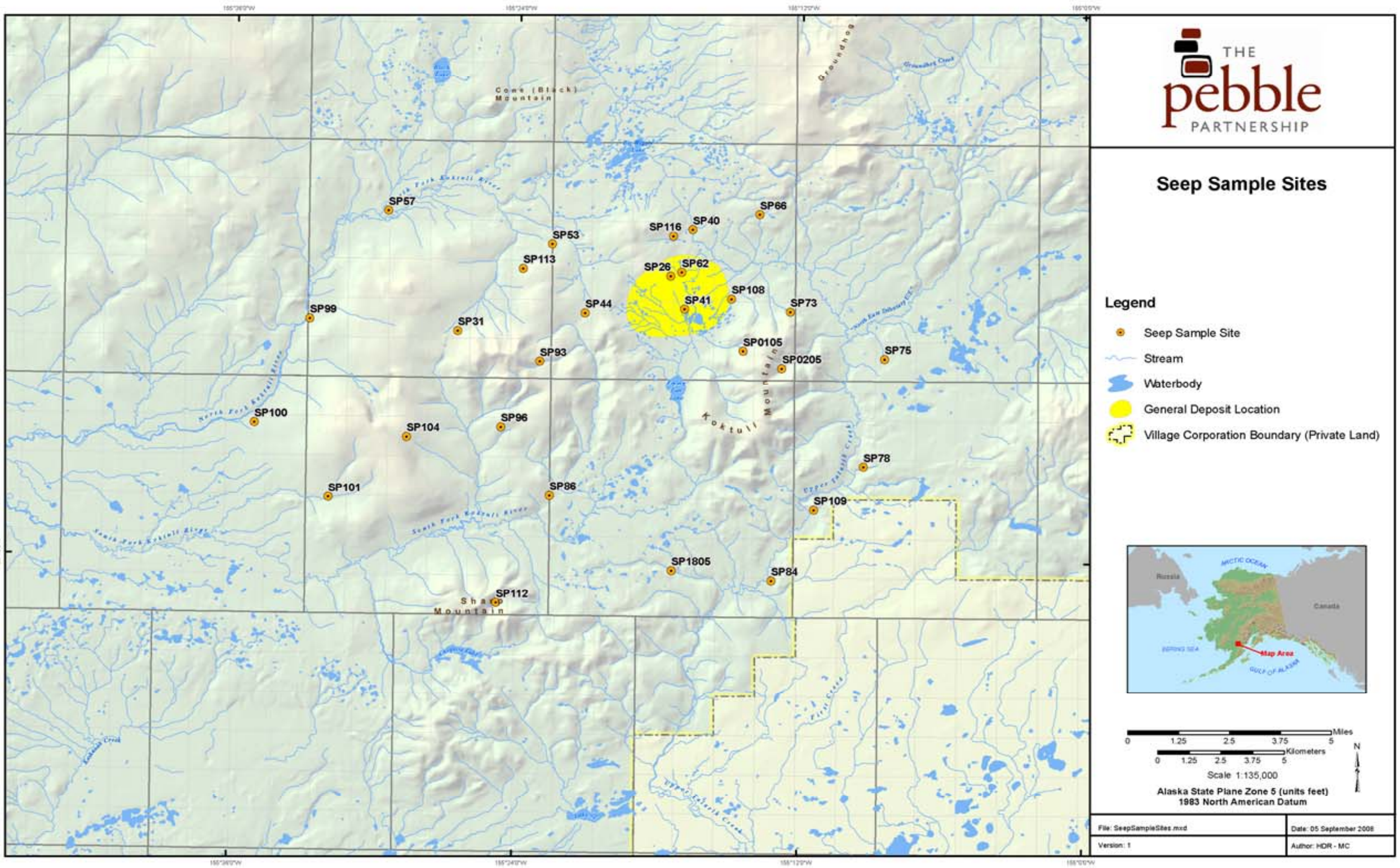
Spring and Seep Inventory and Sampling



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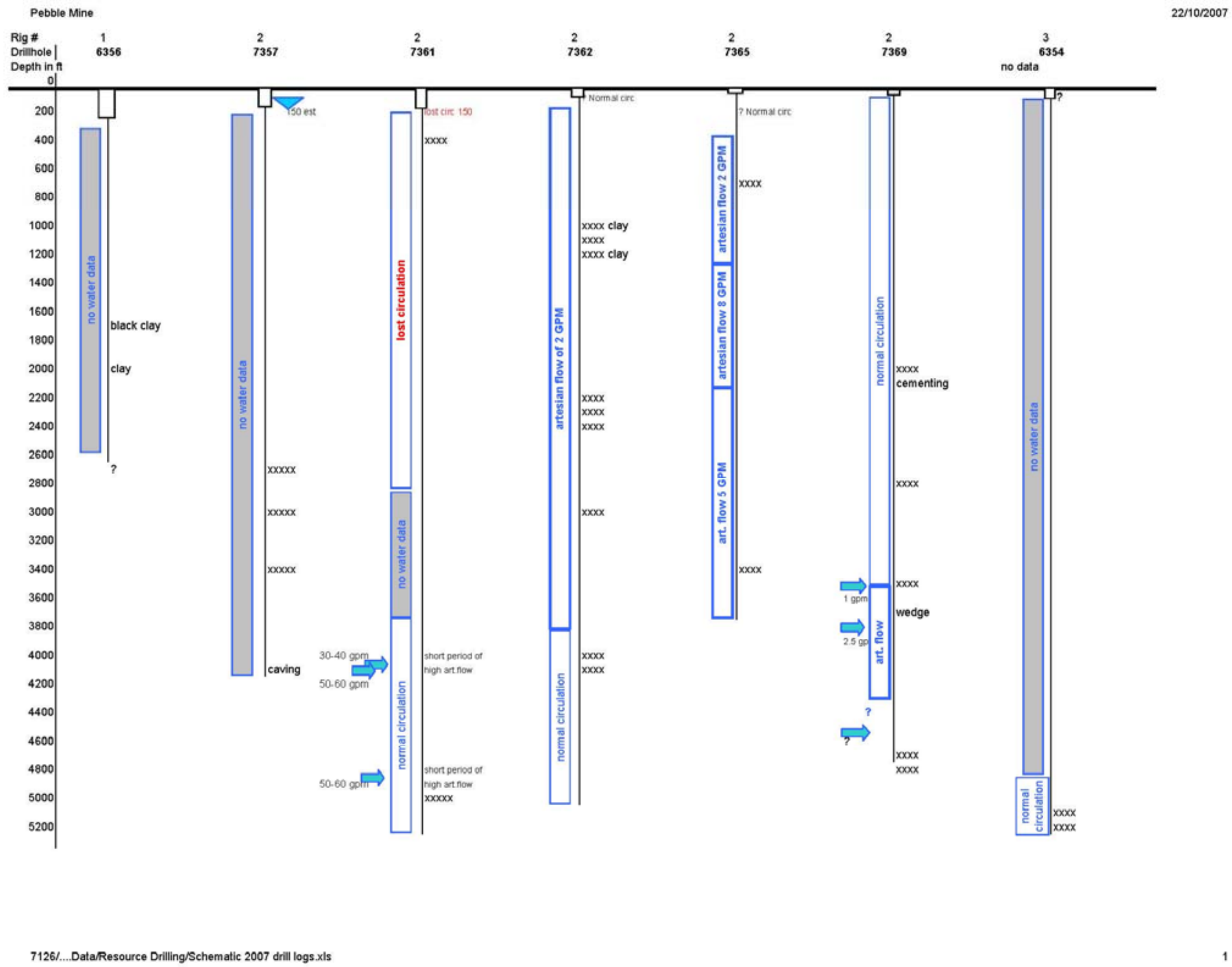
Drill Circulation Monitoring



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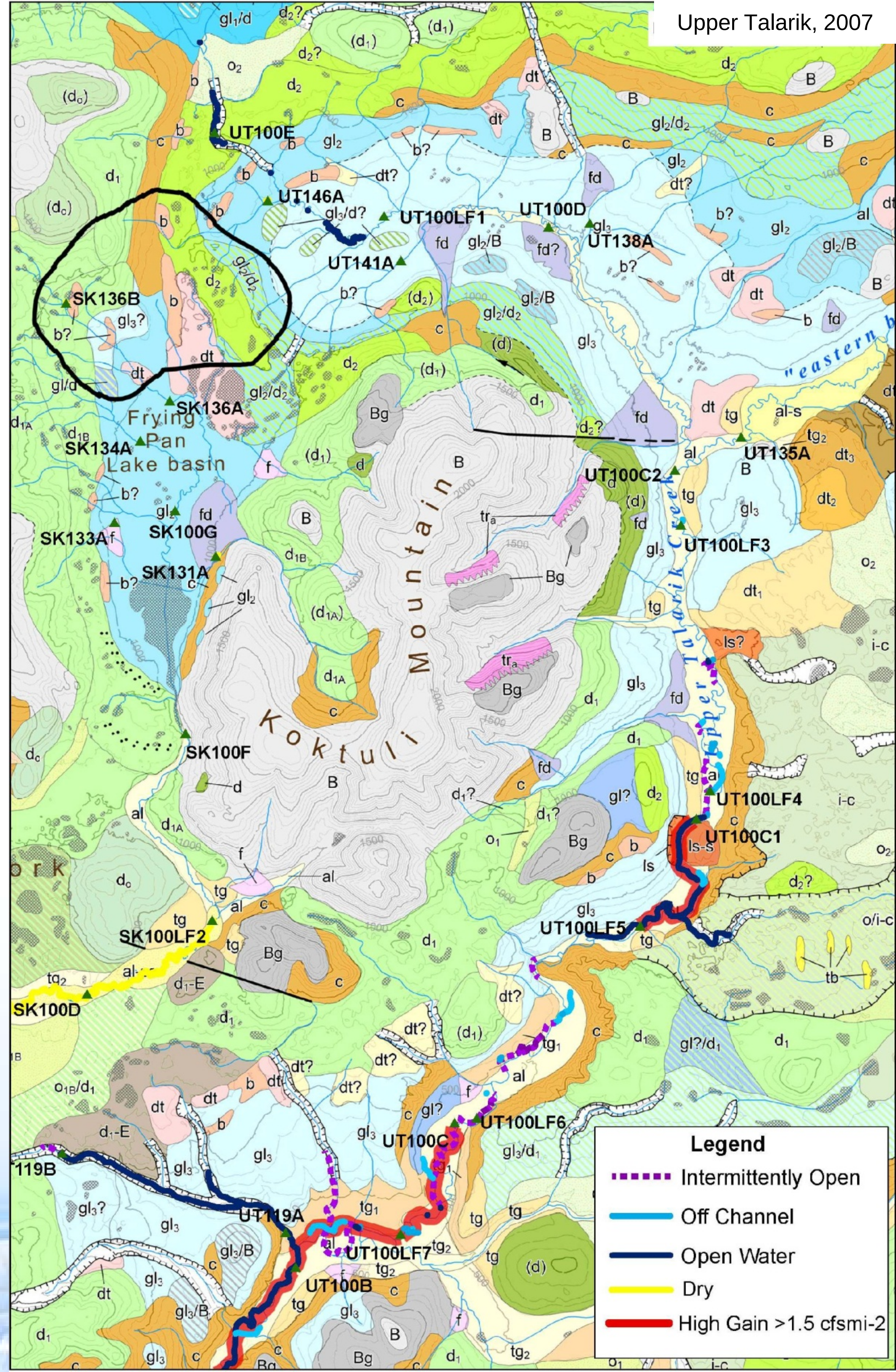
Drill Circulation Monitoring

- During drilling programs, drill crews are requested to note drill circulation losses and gains.
- These notes provide a qualitative indication of the presence of permeable horizons for consideration in ongoing investigations.

Low flow stream gaging

- Stream flows during dry season supplied almost entirely by groundwater discharge.
- Low flows are therefore a primary source of data for documentation of the groundwater flow system.
- Low flow gaging was carried out at continuous gaging sites as well as intermediate low flow sites.
- Stream reaches with winter open water were documented.

Upper Talarik Creek low flow stream gaging



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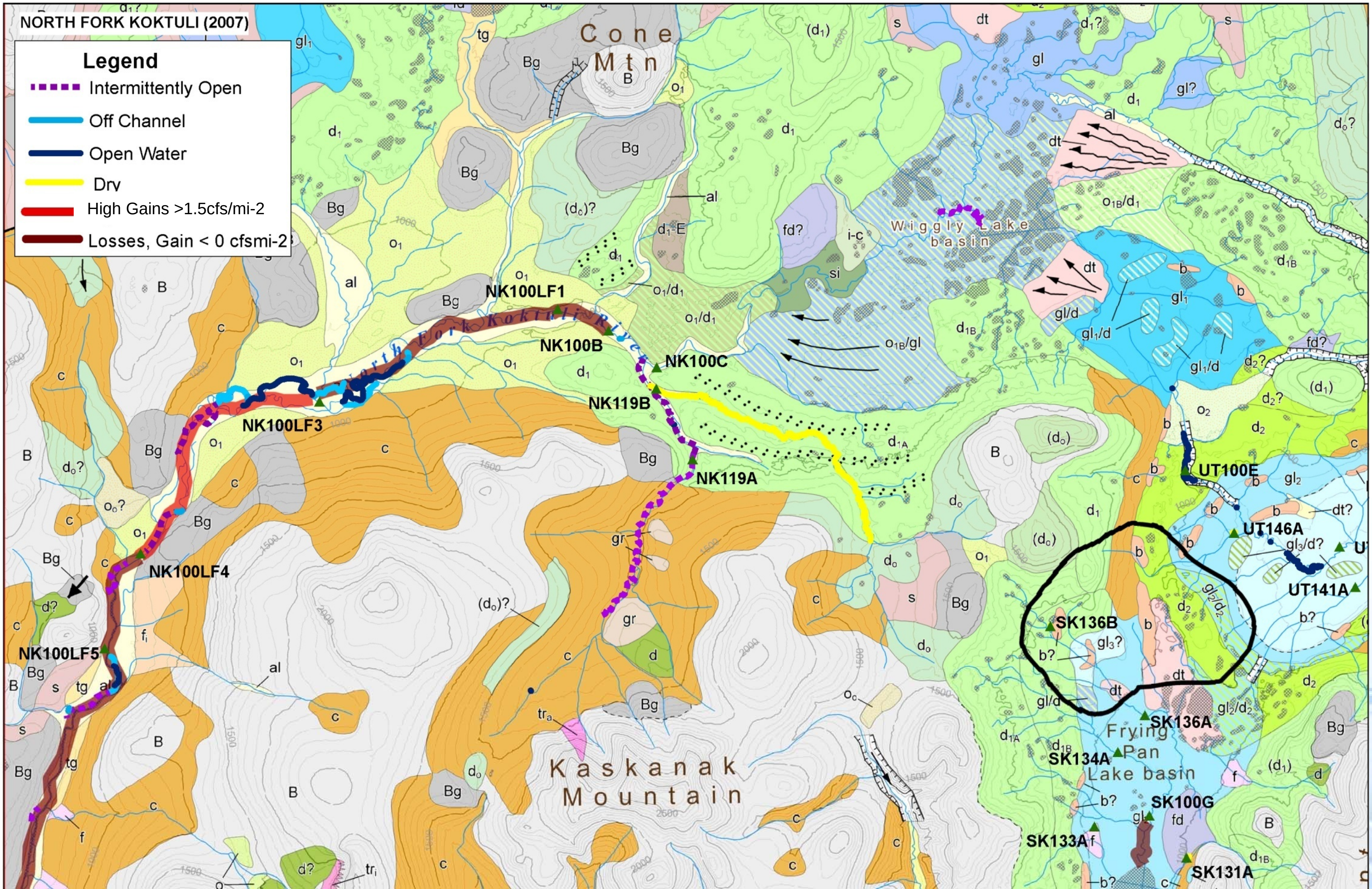
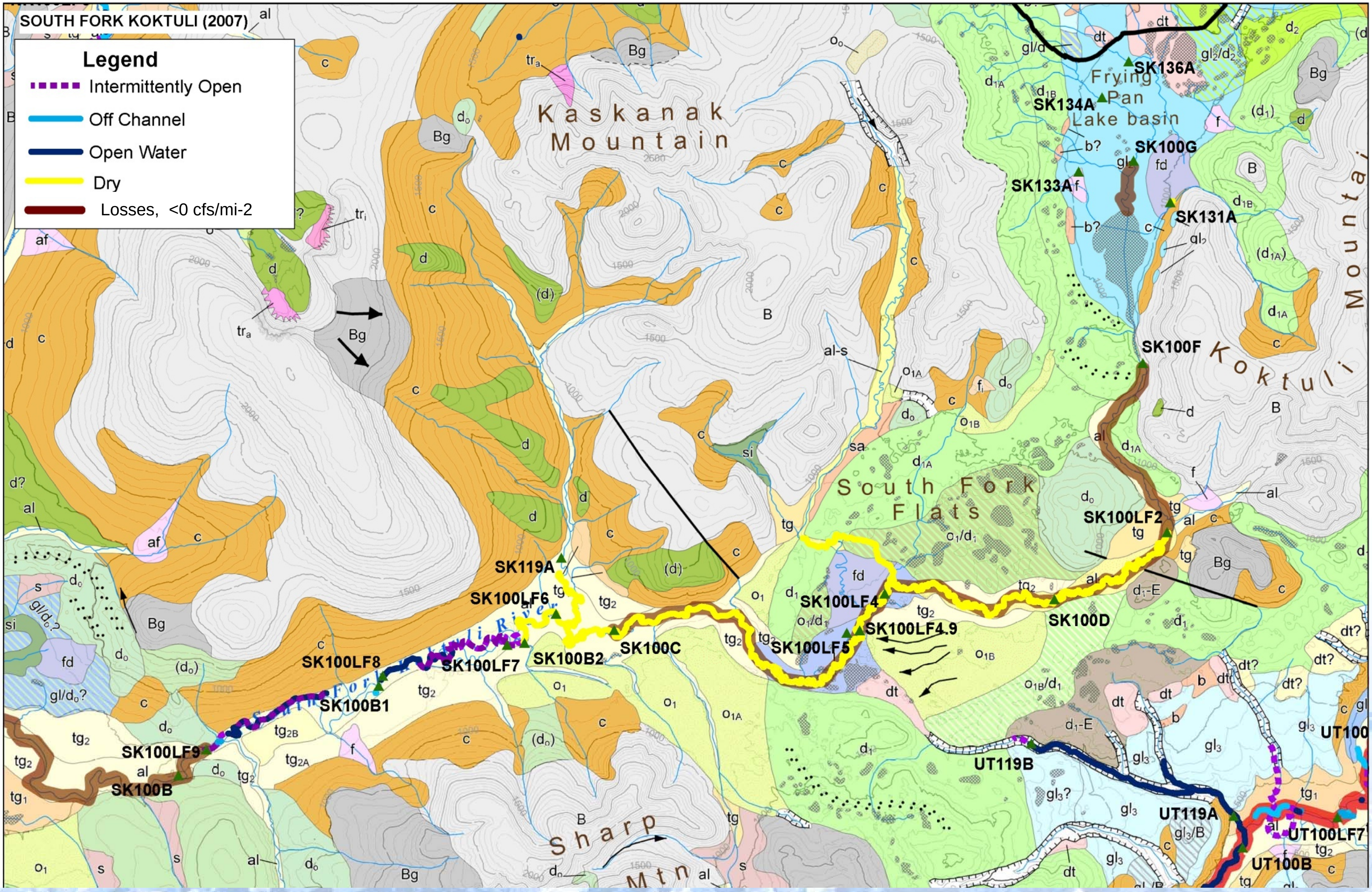
North Fork Koktuli River low flow stream



South Fork Koktuli River low flow stream

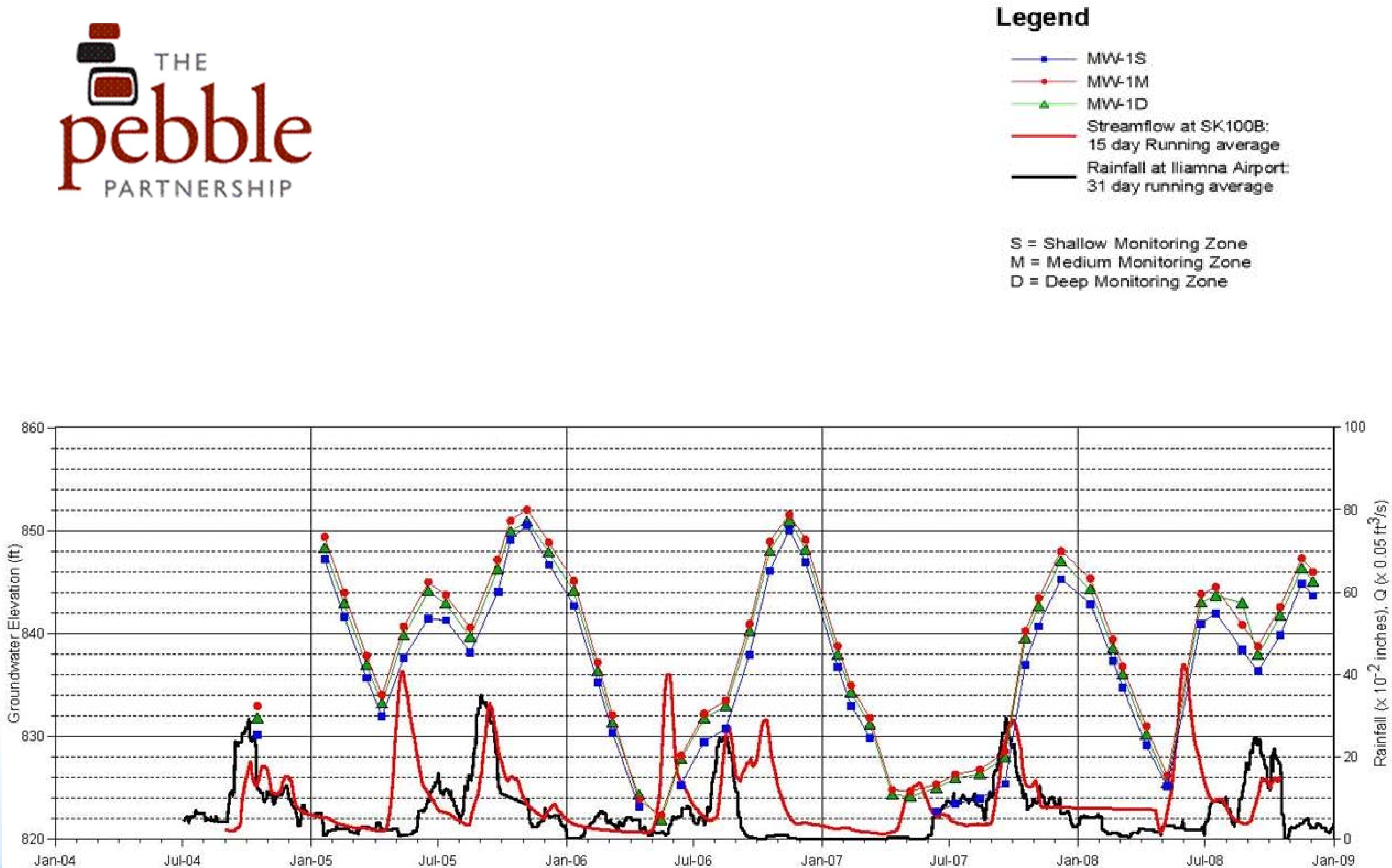


Groundwater Levels

- Groundwater levels measured in geotechnical holes with installed standpipe piezometers.
- Standpipe installed specifically for groundwater monitoring.
- Drive pipe installations for wetland pond studies.
- Vibrating wire piezometers grouted in place in some locations.
- Westbay multi-port installation.
- Groundwater levels implied from seeps, springs and surface water bodies.

Groundwater Levels

- Groundwater level database used to:
  - Develop snapshots of piezometric levels to assist with defining groundwater flow directions and rates as well as aquifer continuity.
  - Develop patterns of vertical groundwater gradients.
  - Develop seasonal responses of groundwater levels.
  - Assist with understanding the groundwater recharge locations.
  - Define the location of groundwater divides.
  - Establish the depth to the water table.


Legend
MW-1S
MW-1M
MW-1D
Streamflow at SK100B:
15 day Running average
Rainfall at Iliamna Airport:
31 day running average
S = Shallow Monitoring Zone
M = Medium Monitoring Zone
D = Deep Monitoring Zone
Groundwater Elevation (ft)
Rainfall (x 10^-2 inches), Q (x 0.05 ft^3/s)
860
850
840
830
820
100
80
60
40
20
0
Jan-04
Jul-04
Jan-05
Jul-05
Jan-06
Jul-06
Jan-07
Jul-07
Jan-08
Jul-08
Jan-09

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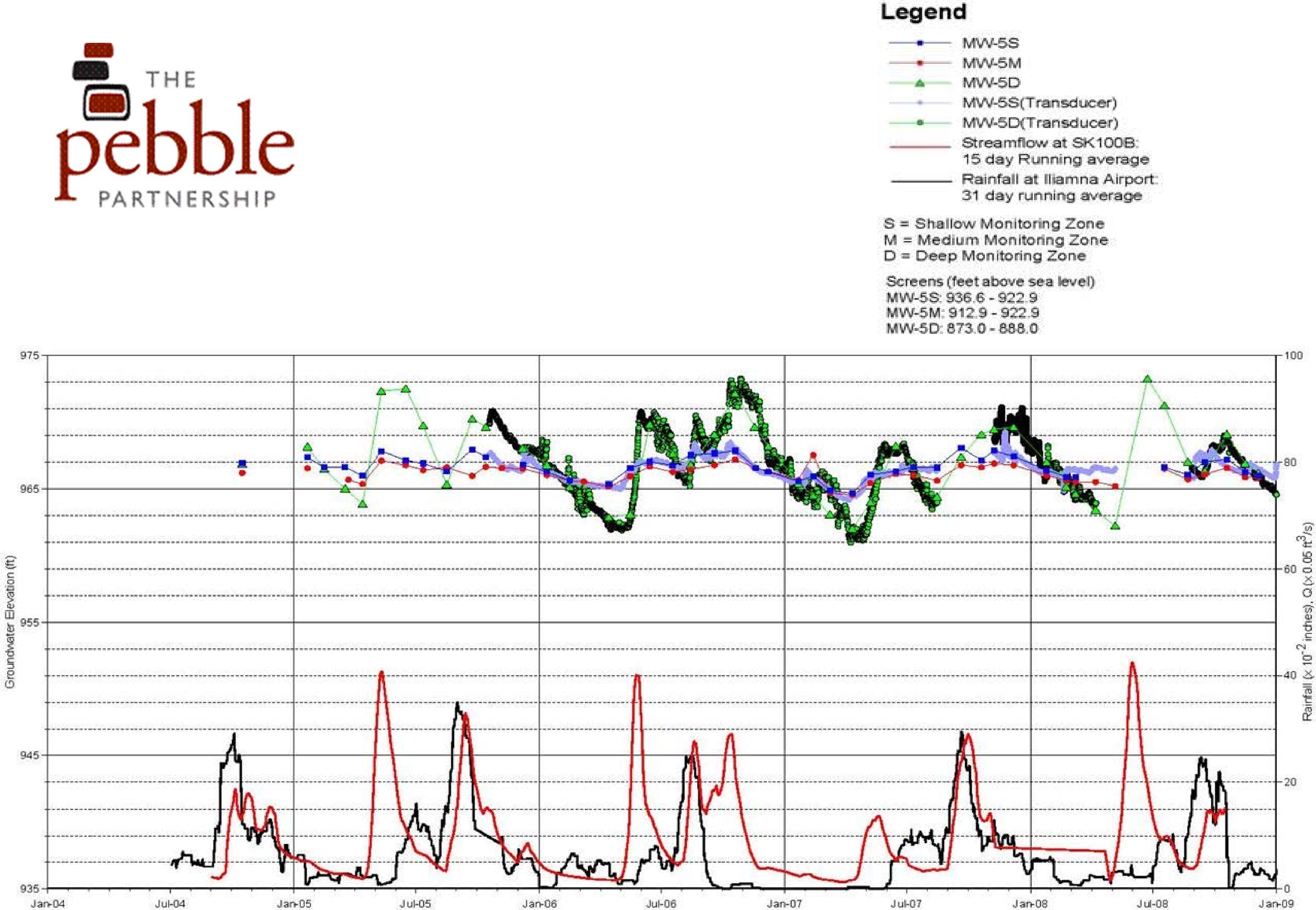
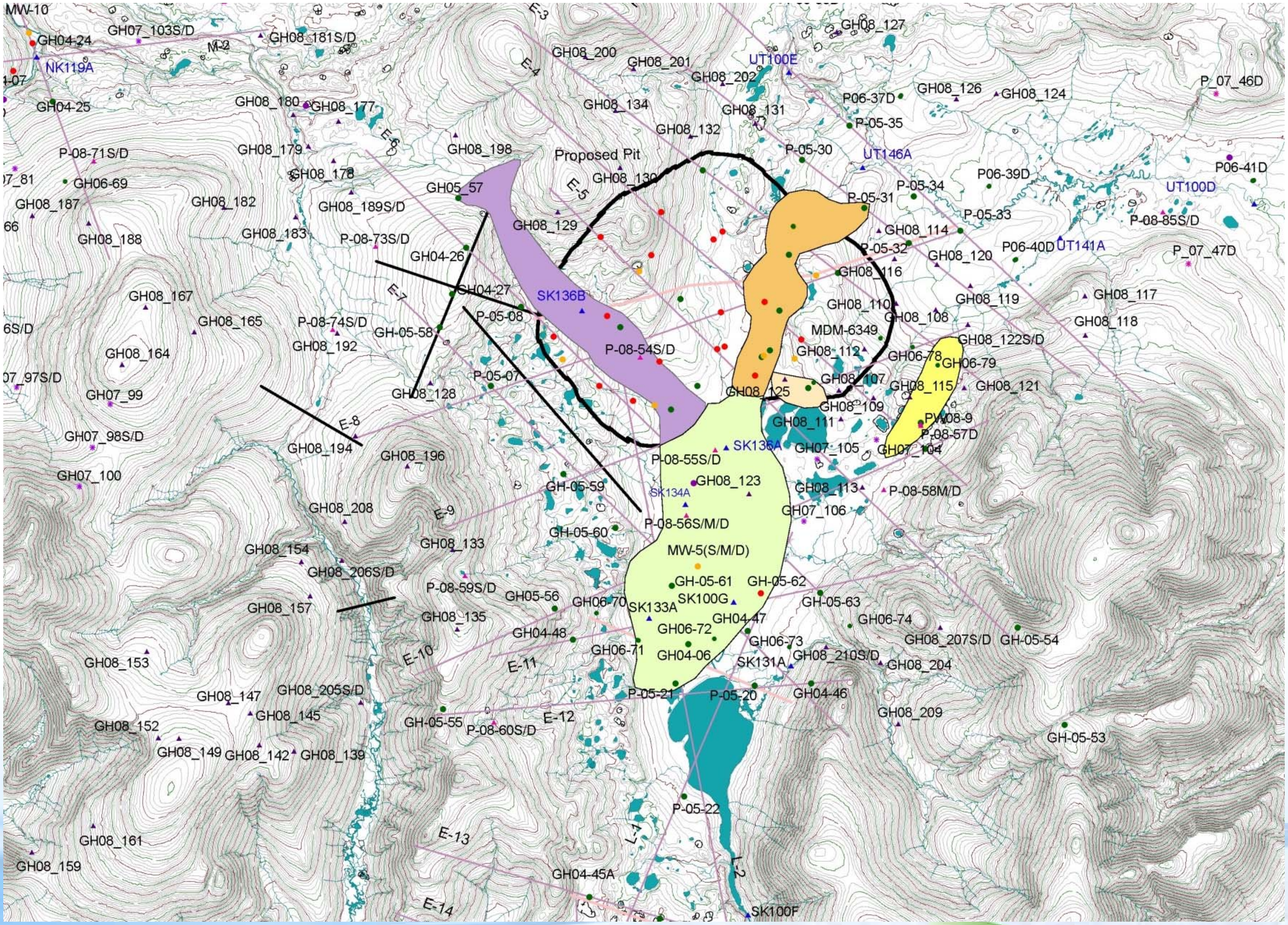


SFK Hydrogeologic Characterization u/s



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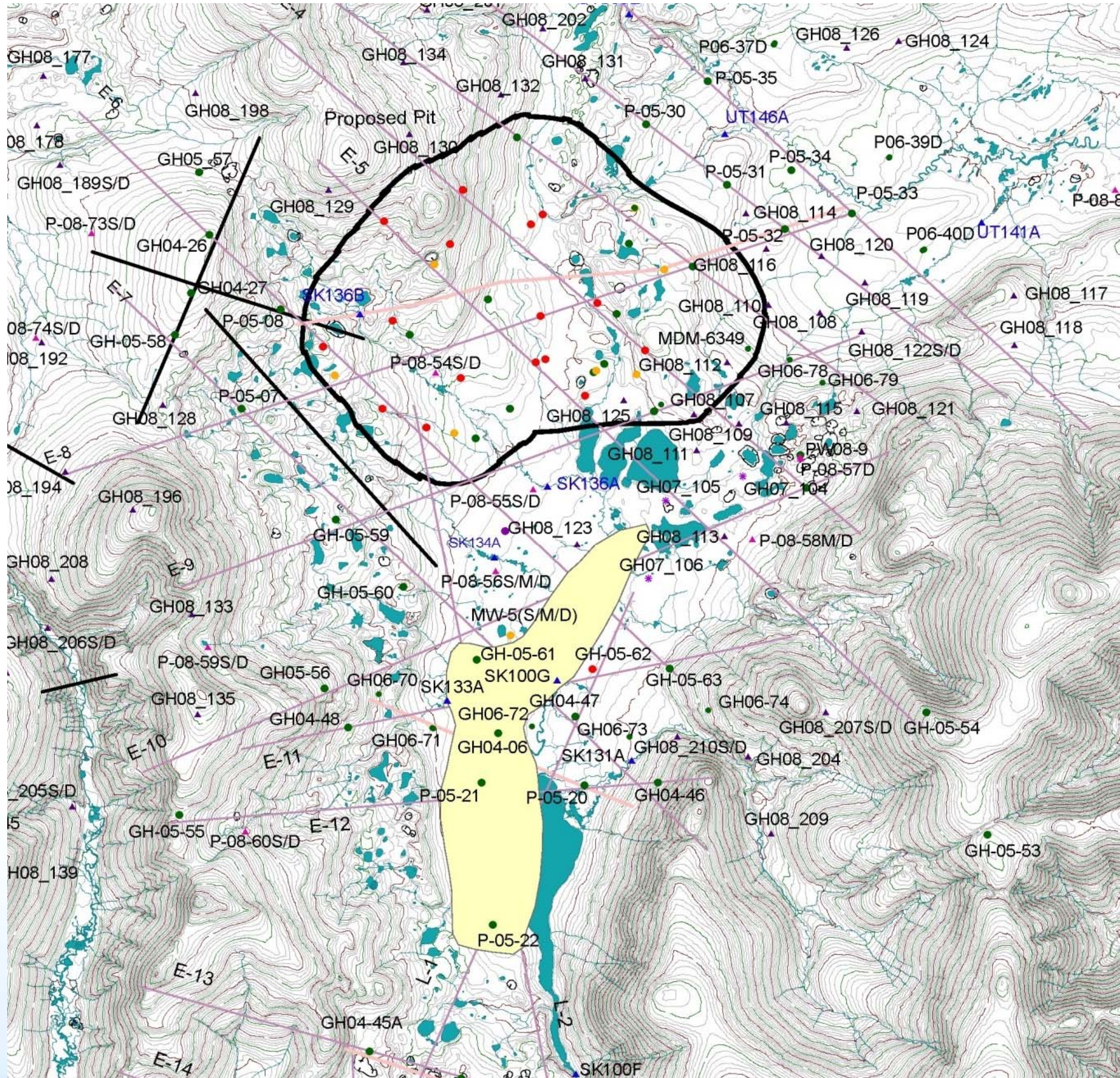
SFK Hydrogeologic Characterization u/s



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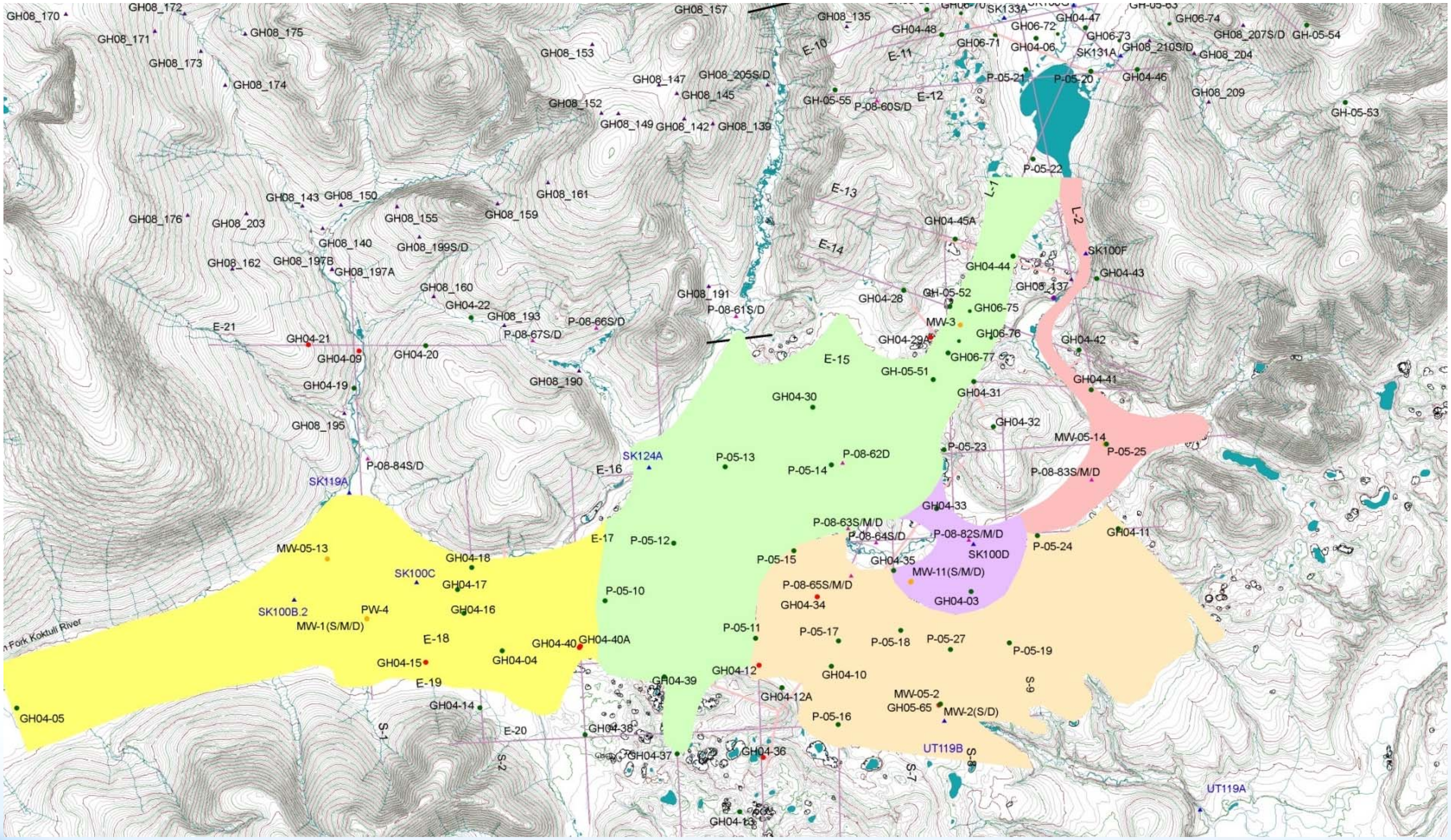
SFK Hydrogeologic Characterization d/s



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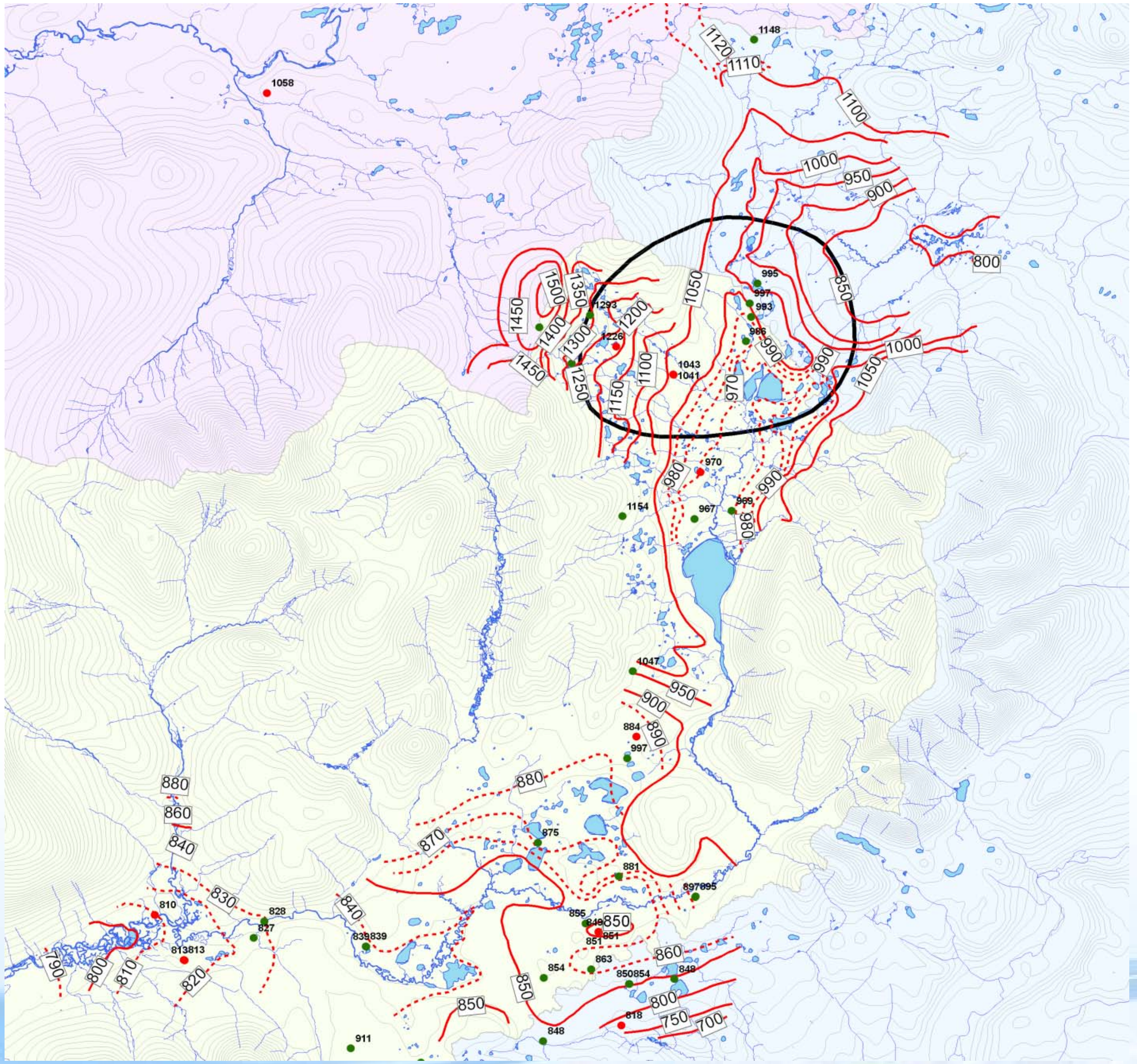
SFK Hydrogeologic Characterization

- **Potential Cross Boundary Groundwater Flows from South Fork Koktulu River Valley.**
  - **From South Fork Koktuli River Flats to Upper Talarik Tributary UT1.190. This flow is documented by stream flow measurements, and groundwater studies.**
  - **From South Fork Koktuli River Tributary 1.140 (Chiquita Lake) to Lower Talarik Creek. This potential is limited by available catchment area and lost flows have not been detected.**
  - **From South Fork Koktuli River to Kaskanak Creek. Some loss has been noted in this reach. However, the flows are recovered downstream. Loss is probably due to bank storage and or adjacent pirate tributaries.**

Equipotential
Plot
(Water Table)
October 2006
Study Area



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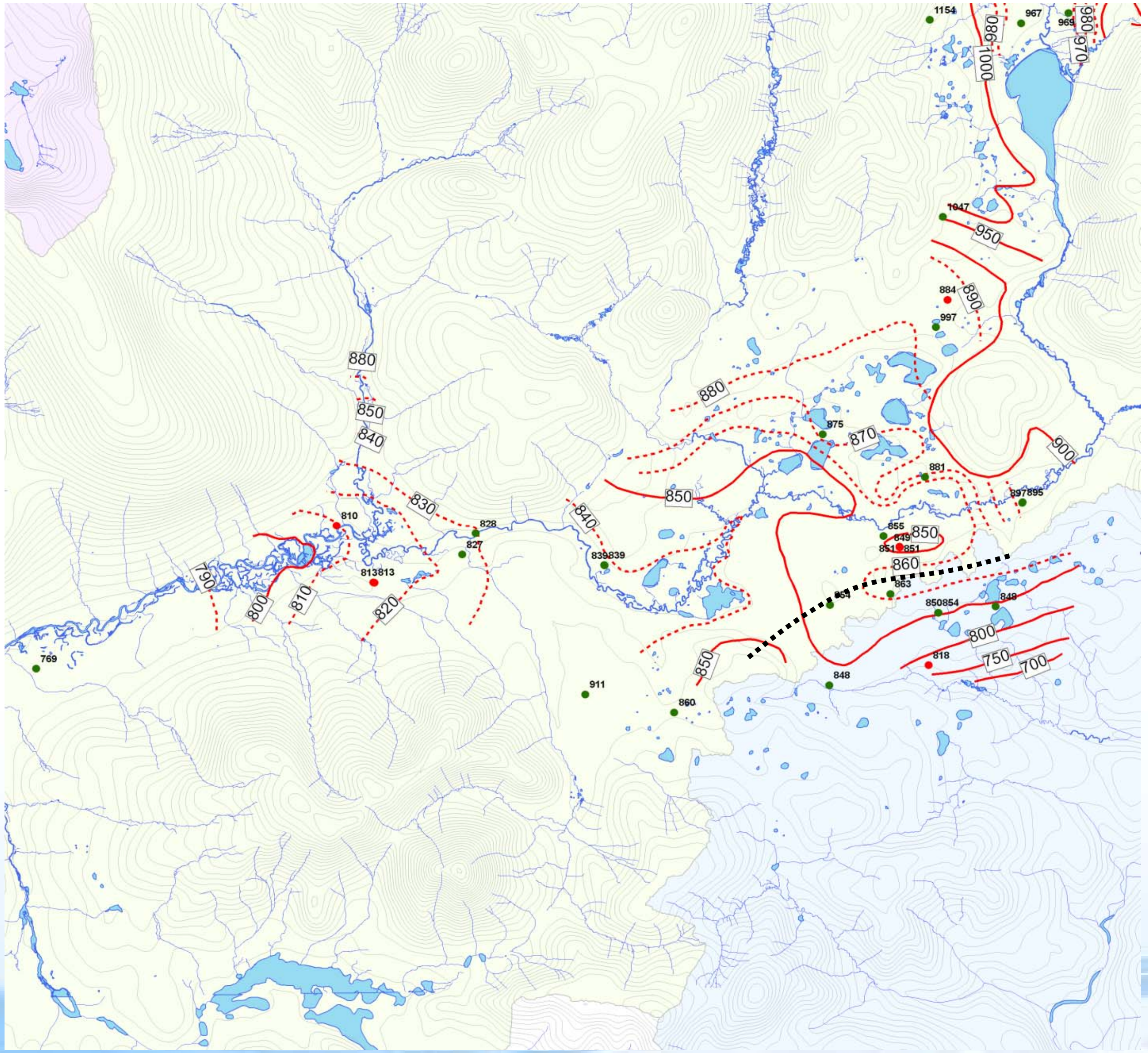
Equipotential Plot
(Water Table)

October 2006
South Fork Koktuli



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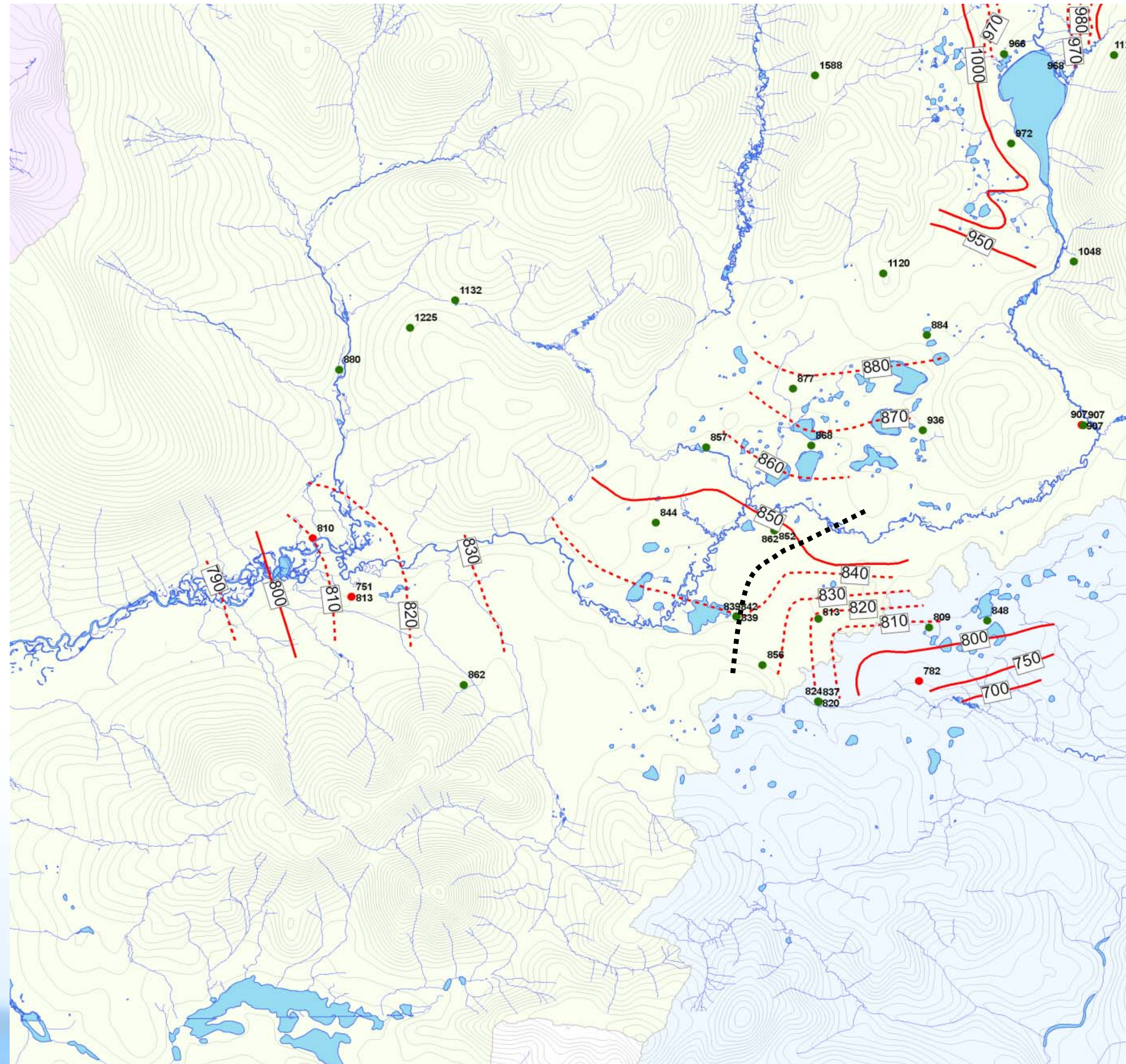
Equipotential Plot
October 2006
Deep Overburden –
Bedrock South Fork
Koktuli



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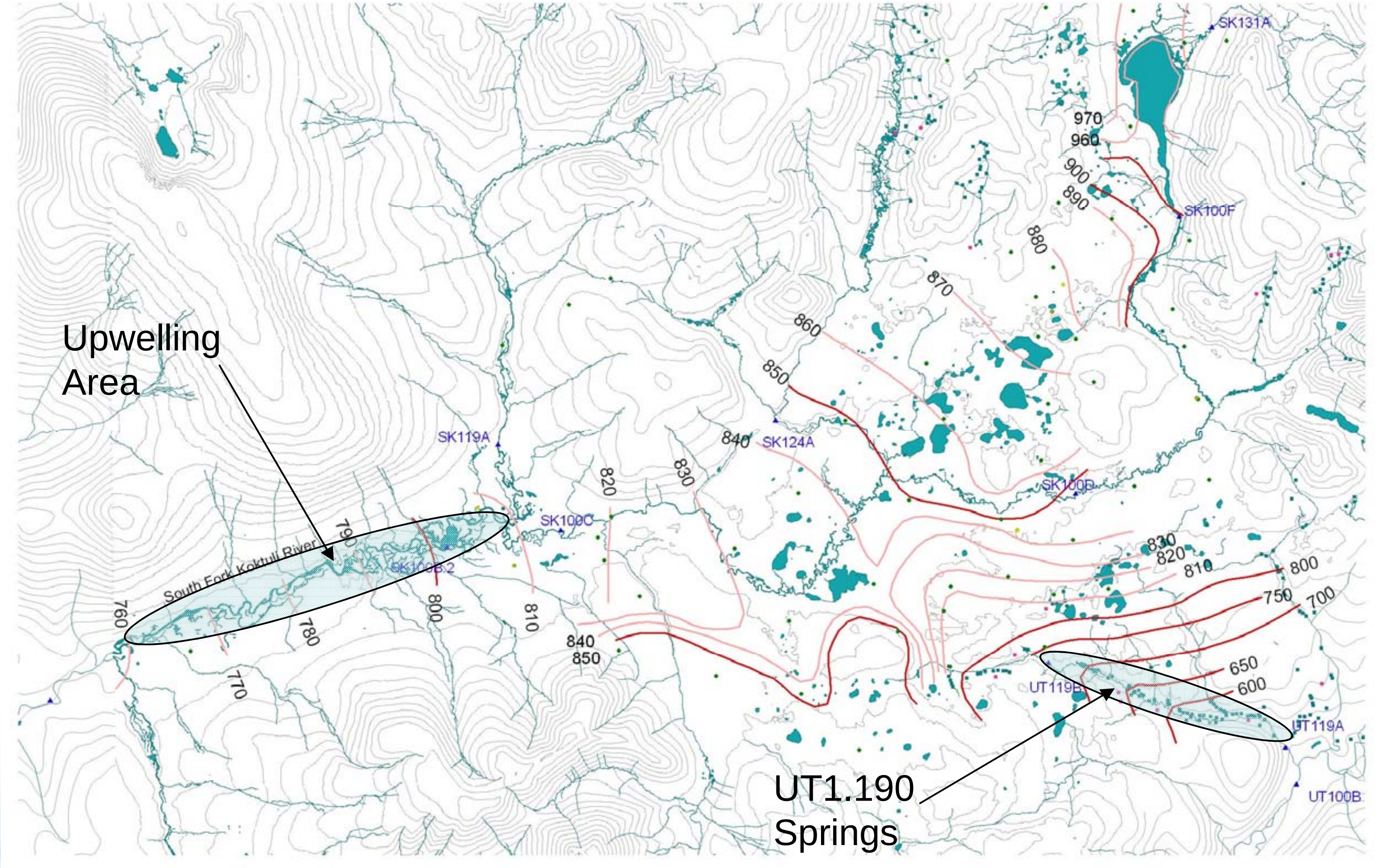

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NFK Hydrogeologic Characterization

- **Aquifers in North Fork Koktuli River Valley overburden material**
  - **Outwash and alluvial sand and gravel are present downstream of the Kvichak Stade terminal moraines.**
  - **Less extensive outwash, delta and fan delta deposits downstream of the Iliamna Stade terminal moraine within the Big Wiggly Lake Basin.**
  - **Thin sand and gravel within tributary valleys.**
- **Glacial lake deposits influence the distribution of permeable material through the Big Wiggly Lakes Basin.**

NFK Hydrogeologic Characterization

- **Potential Cross Boundary Groundwater Flows from North Fork Koktuli River Valley.**
  - **From North Fork Koktuli River headwaters to Upper Talarik Creek at the low divide. Based on available drillhole data and groundwater levels, any such cross divide flow is expected to be relatively small.**
  - **From North Koktuli River headwaters into Chulitna River drainage at the low divide. This is also expected to be a limited rate, based on the geology and the surface water distribution near the divide.**

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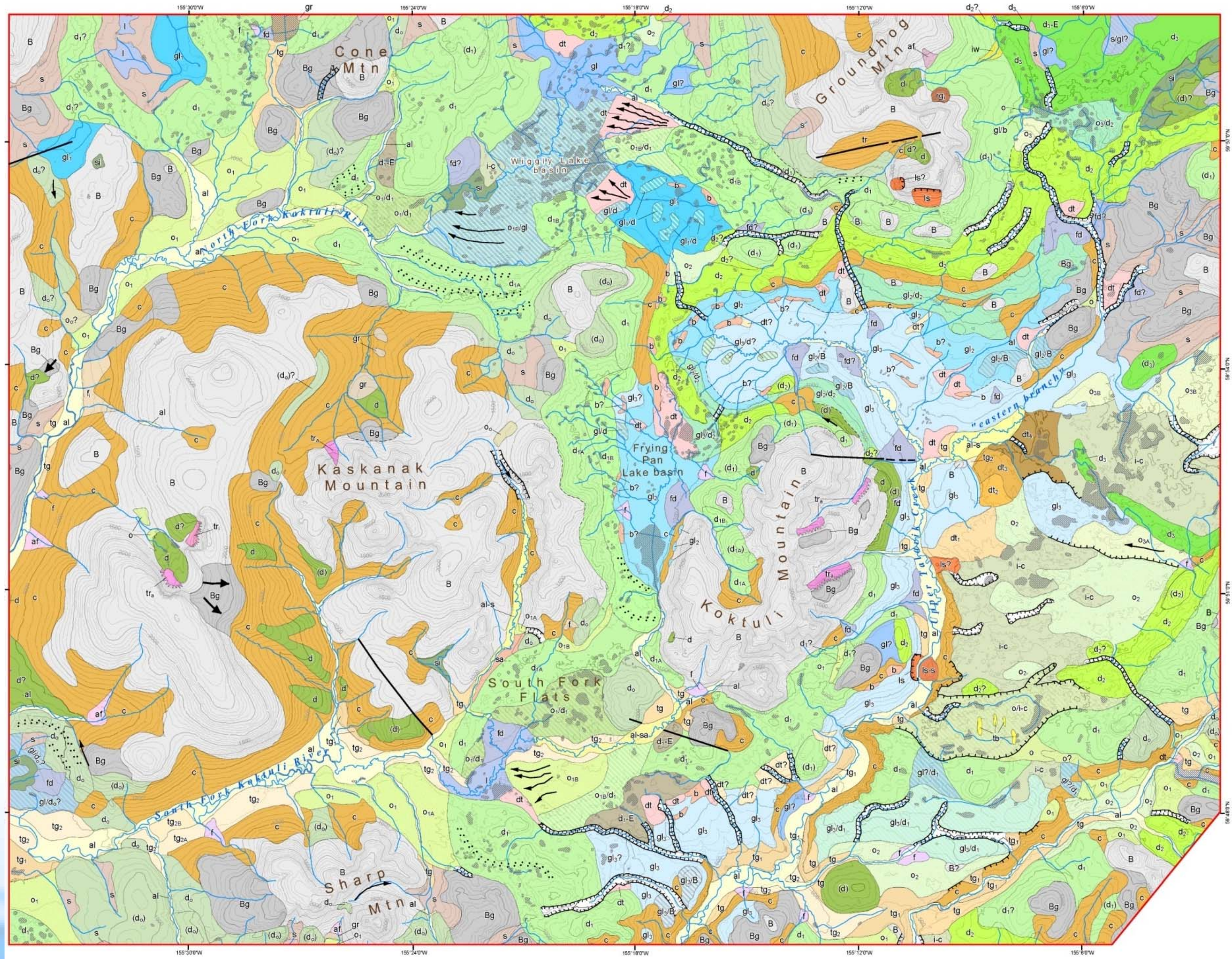
UTC Hydrogeologic Characterization

- Aquifers in Upper Talarik Creek Valley overburden material.
  - Extensive ice contact meltwater deposits, outwash deposits and deltaic deposits of the Iliamna Stade east of Upper Talarik Creek.
  - Less extensive outwash deposits associated with the Iliamna Stade near the upper reaches of Upper Talarik Creek.
  - Terrace and alluvial sand and gravel within the valley.
- Glacial lake deposits influence the distribution of permeable material over much of the Upper Talarik drainage.



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Groundwater Recharge

- A number of site specific conditions enhance recharge at the Pebble site:
  - Disturbed bedrock at surface leaves open joints where water can easily enter the ground.
  - Frost has preferentially migrated gravel and pebbles to the surface resulting in a coarse surface that water can easily infiltrate.
  - Tussocks are common, which result in depressions that store water increasing the probability of infiltration.
  - At several locations, glacial outwash has left enclosed depressions that store water for eventual infiltration.

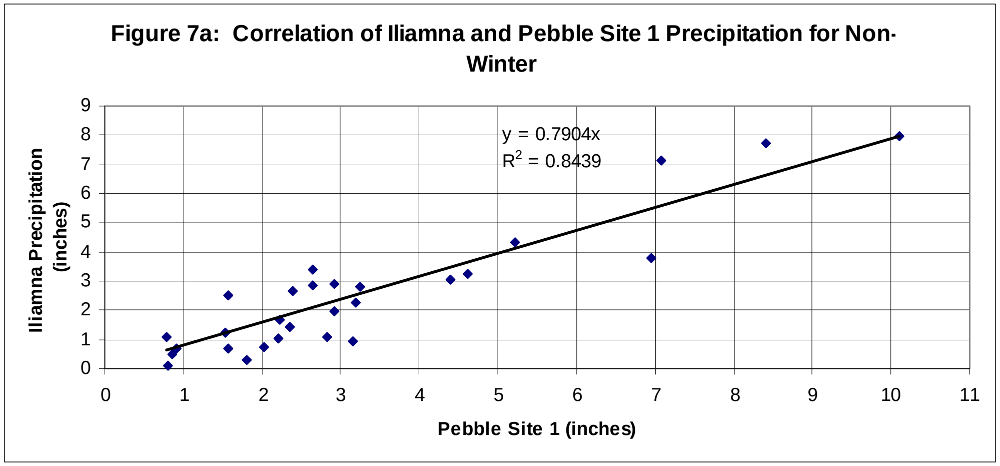
Groundwater Calculations

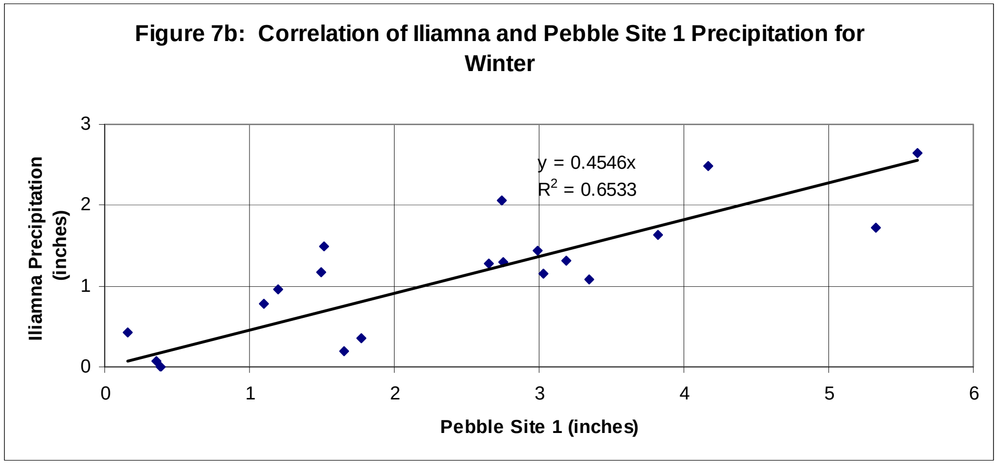
- **Two methods combined to define the complete groundwater regime.**
  - ***Site wide water balance*** **completed to constrain groundwater recharge and discharge rates, which reduces non-uniqueness of groundwater model. This procedure also useful to help define surface water groundwater interaction.**
  - ***Groundwater model*** **includes the physics of groundwater flow. Described in a separate presentation.**

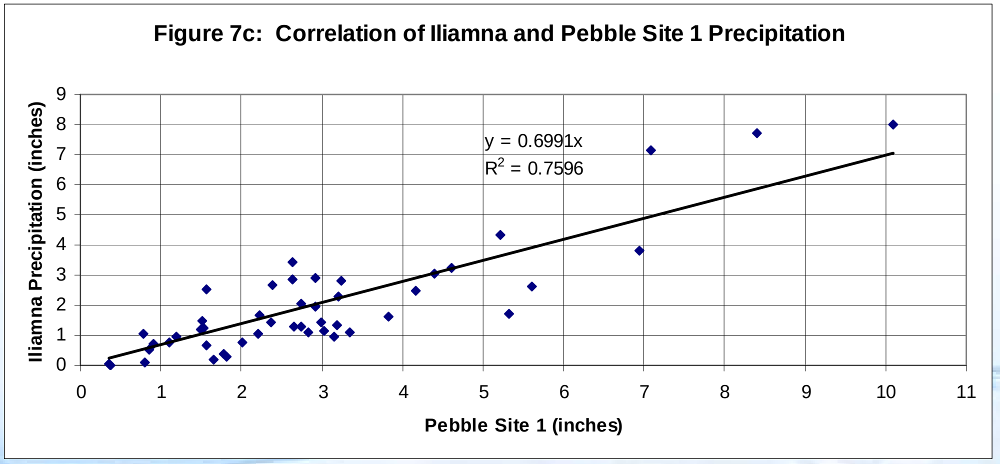
Hydrometeorology

- **Site climate records.**
- **Correlated with regional (Iliamna airport) data to develop synthetic long term (68 year) monthly precipitation and temperature record.**
- **Compared to site and regional snow course data.**
- **Compared to stream gaging, particularly low flow measurements and winter open channel mapping.**

Hydrometeorology







Hydrometeorology

Figure 9: Mass Curves for Site 1 Synthesized and Measured

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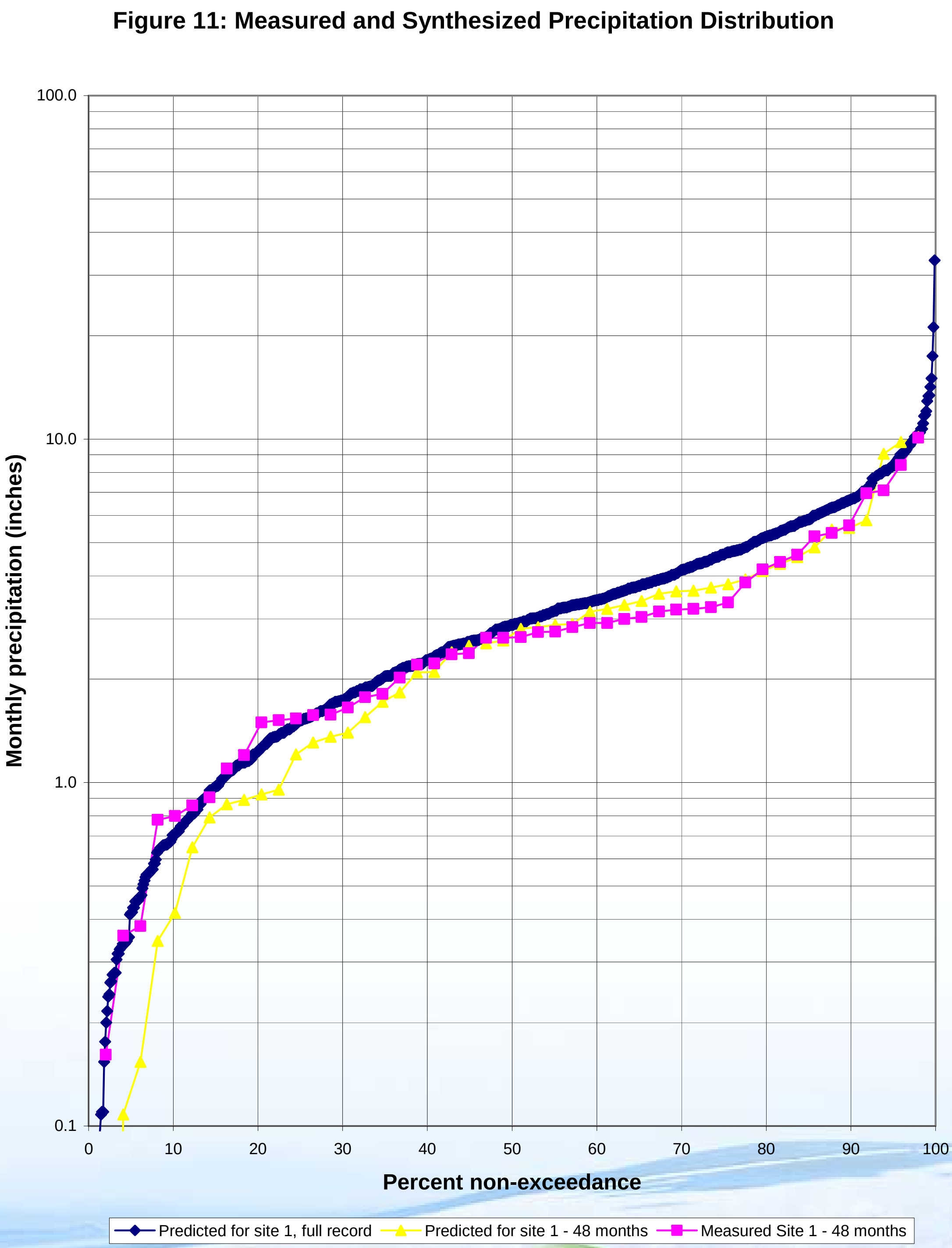
Hydrometeorology



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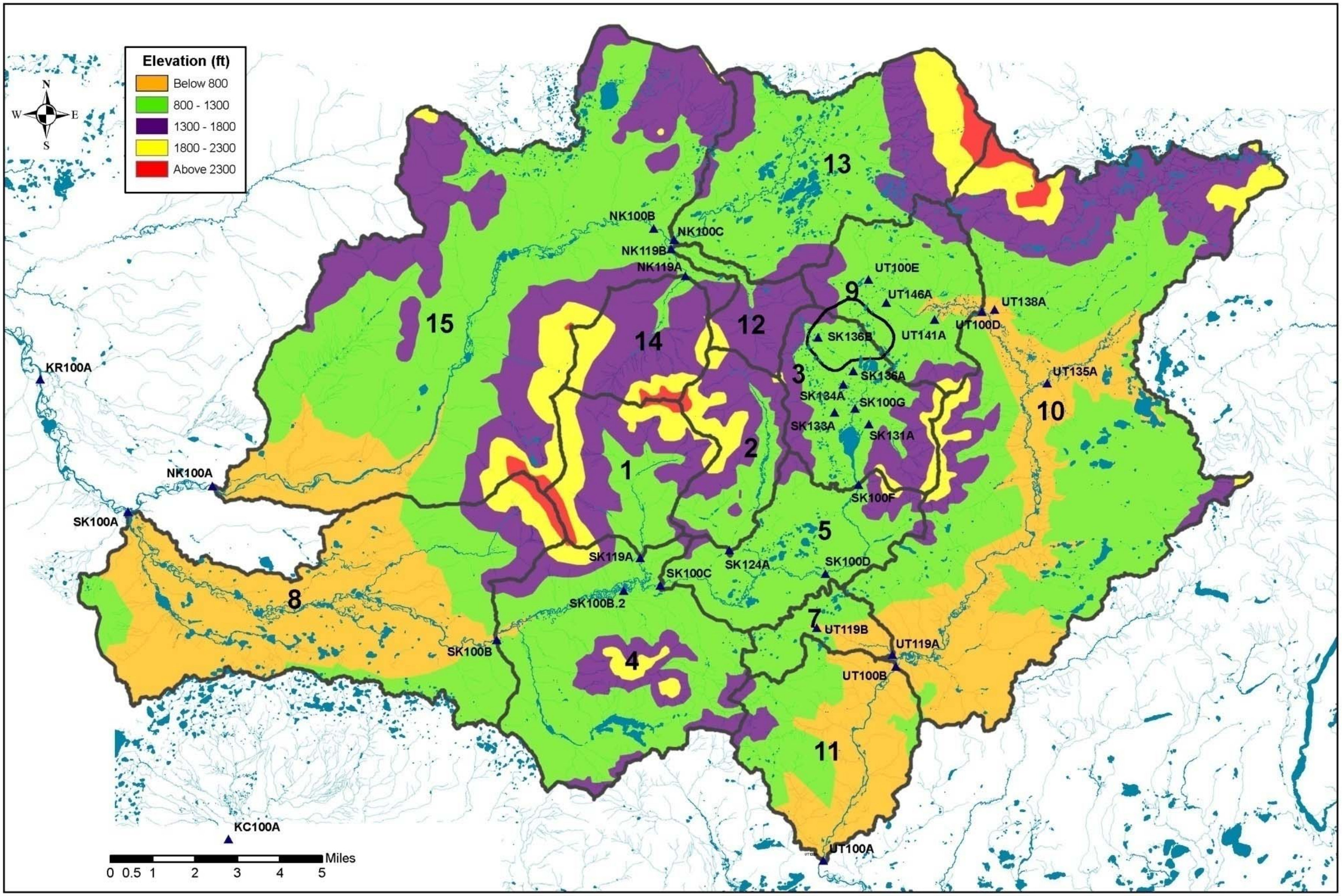
Hydrometeorology

- **Modification of Iliamna record to synthesize site record included:**
  - **Increase Iliamna winter (November through March) precipitation by a factor of 1.477 to account for gage inefficiency.**
  - **Apply a winter orographic factor of 10% per 100m (328 ft) and a non-winter orographic factor of 5.8% per 200 m (328 ft).**
- **Modification of site record to meet measured stream flows included:**
  - **Increase site winter (November through March) precipitation by a factor of 1.6 and summer precipitation by a factor of 1.25 to account for gage inefficiency.**
  - **Apply a winter orographic factor of 10% per 100m (328 ft) and a non-winter orographic factor of 5.8% per 200 m (328 ft) to migrate the precipitation record to elevation bands.**
  - **Apply a sub-catchment local factor ranging from 0.9 to 1.11 to account for conditions such as precipitation shadow and blowing snow.**

Water Balance Methodology

- The water balance was calibrated by adjusting calibration parameters to visually match calibration targets (surface water flows) while remaining within a physically reasonable range.
- The total flow was calibrated by adjusting net precipitation to visually match measured stream flows on a mass plot.
- The base flow was calibrated by adjusting recharge to match the volume and the discharge factor to adjust the slope of the recession or draindown curve.
- Mid range flows were adjusted with surface water detention and release.

Site Wide Water Balance Sub Catchment



b. Measured and Calculated Cumulative Streamflow
NK119A

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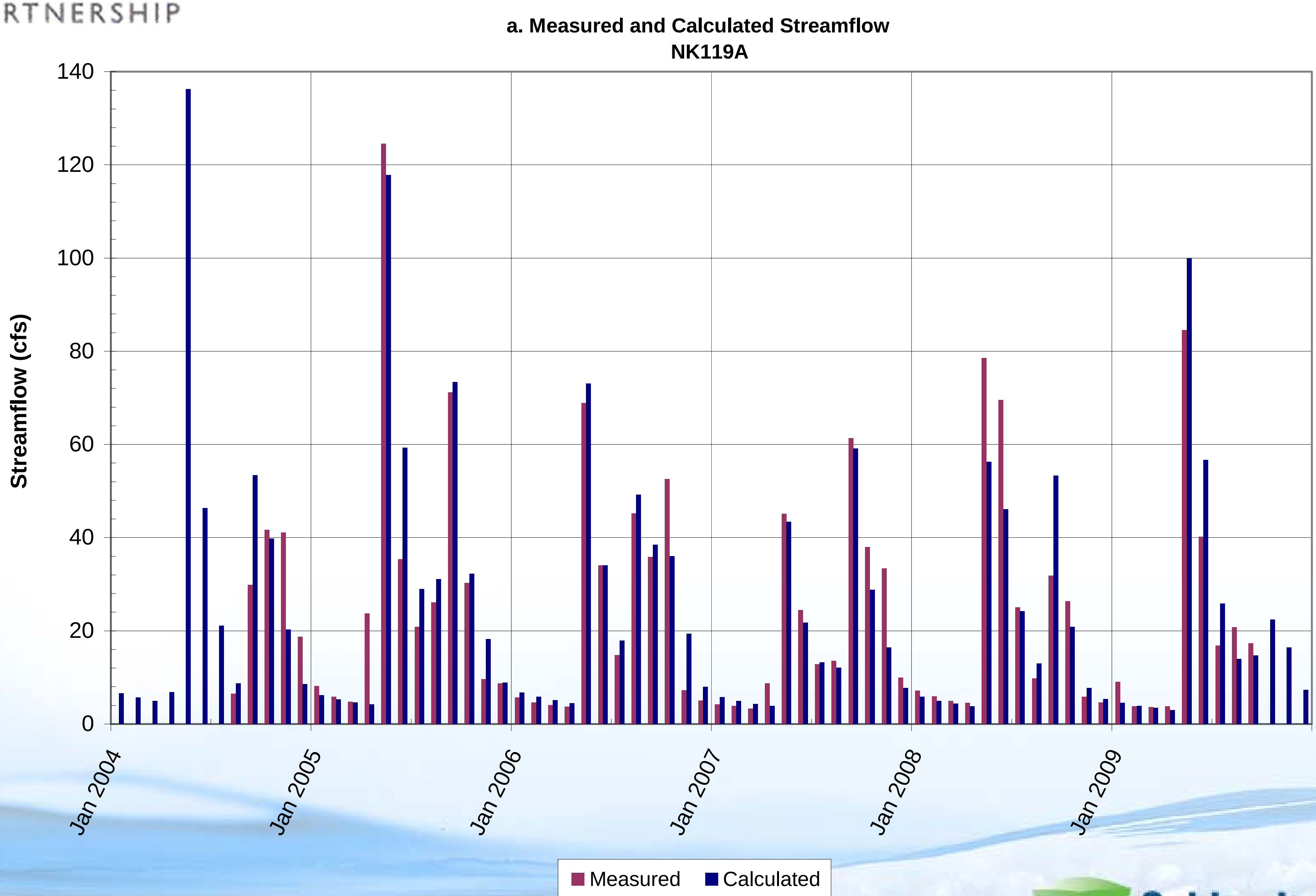

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c. NK119A Flow Distribution

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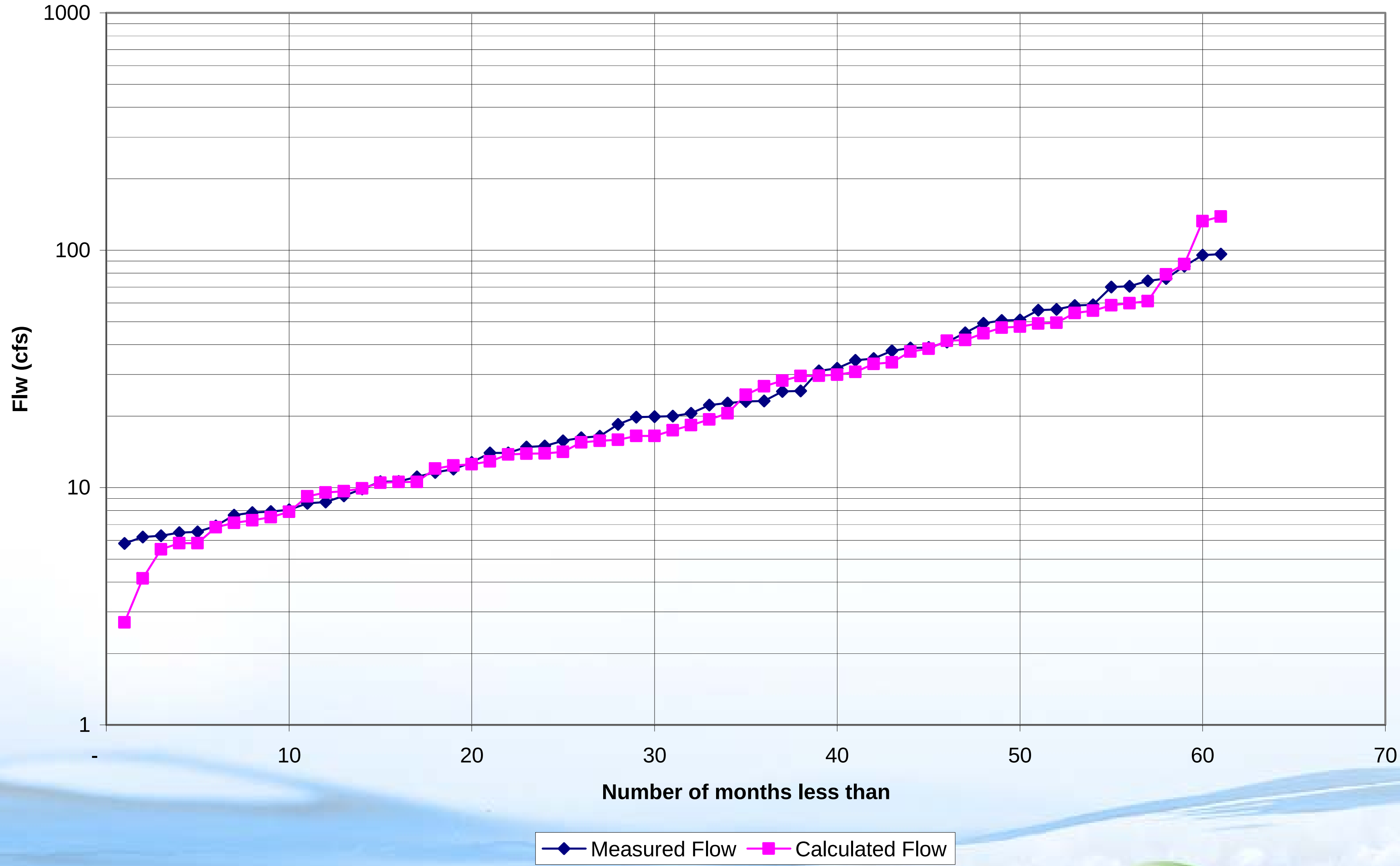
c. SK100F Flow Distribution



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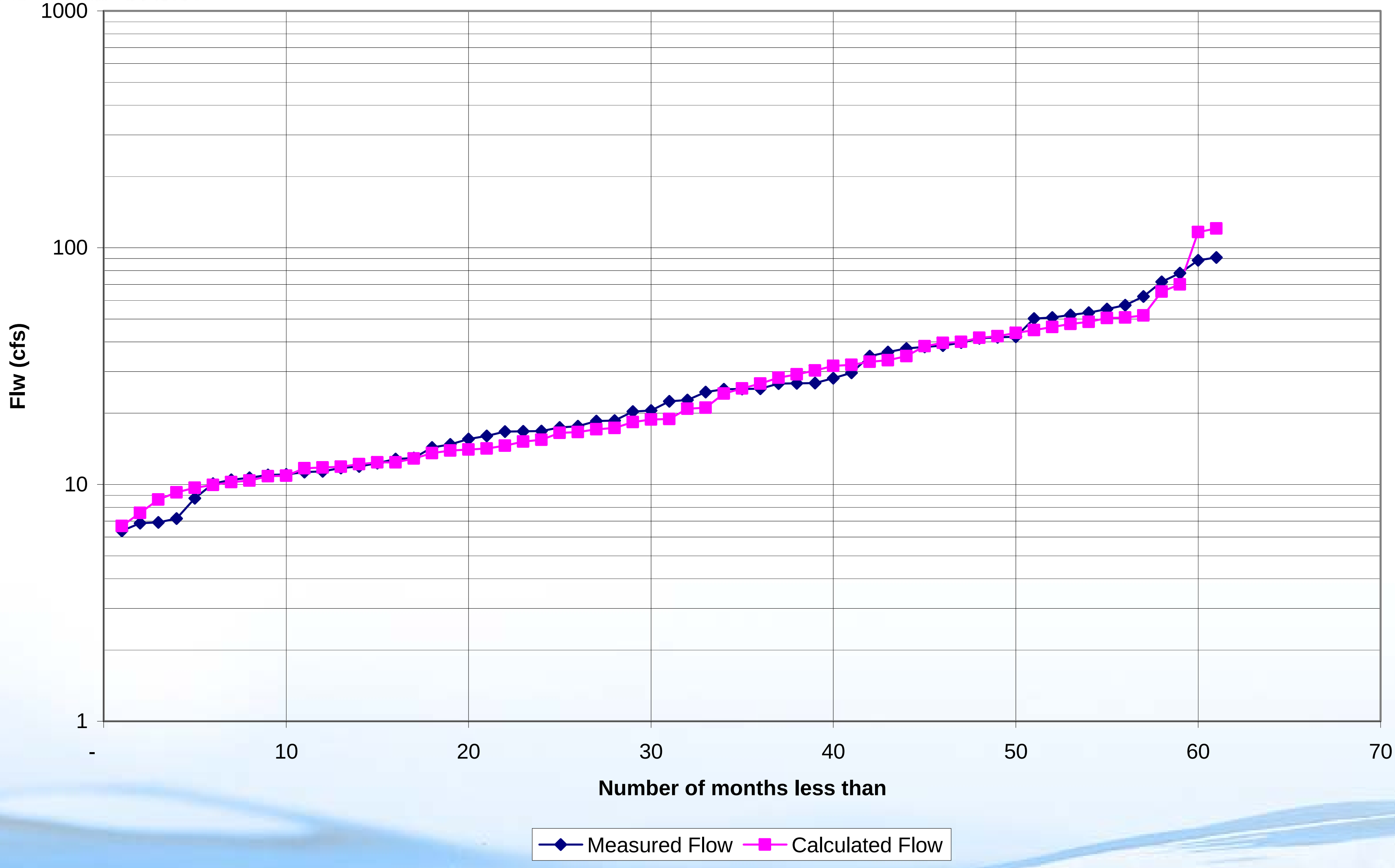
c. UT100D Flow Distribution



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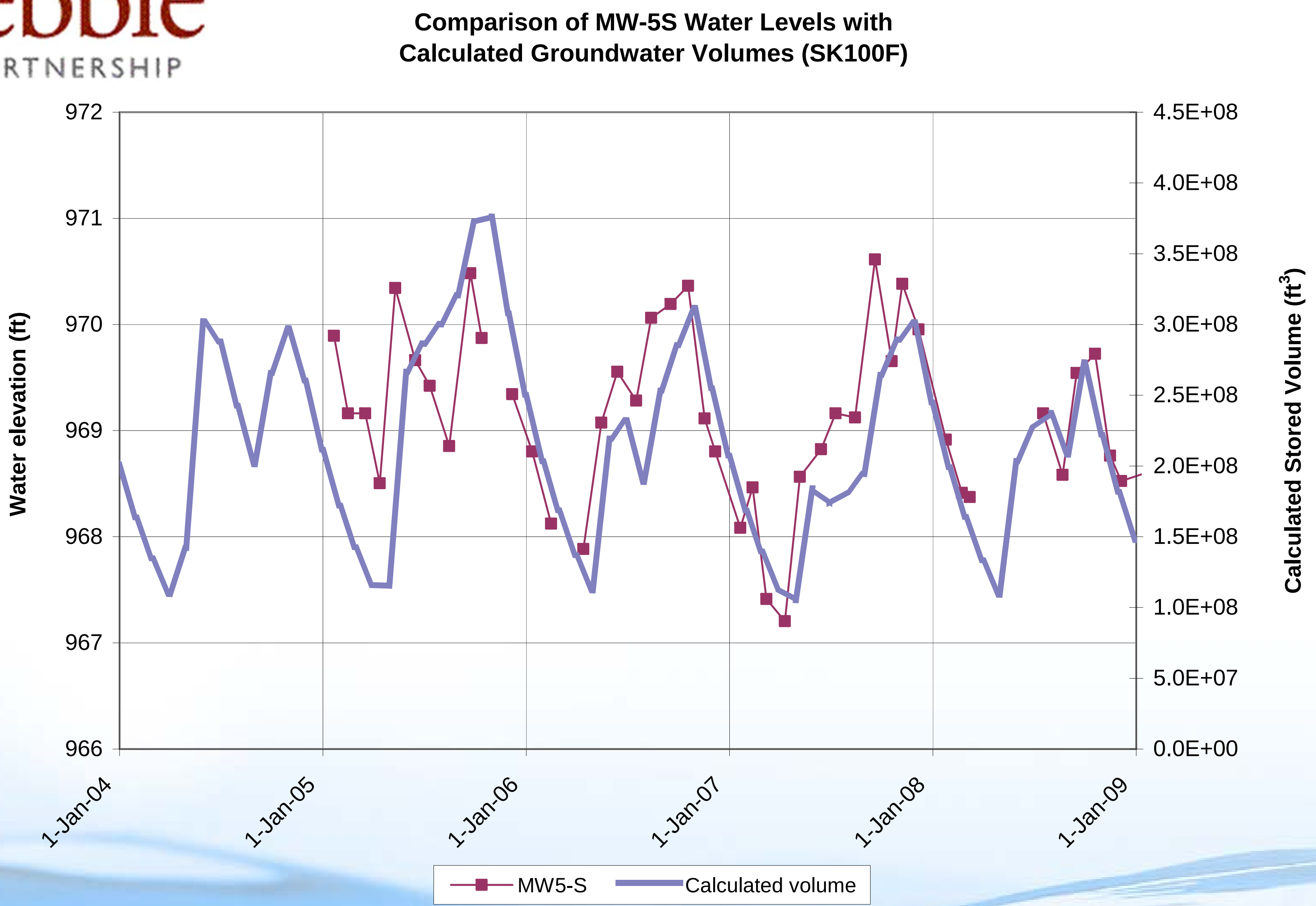

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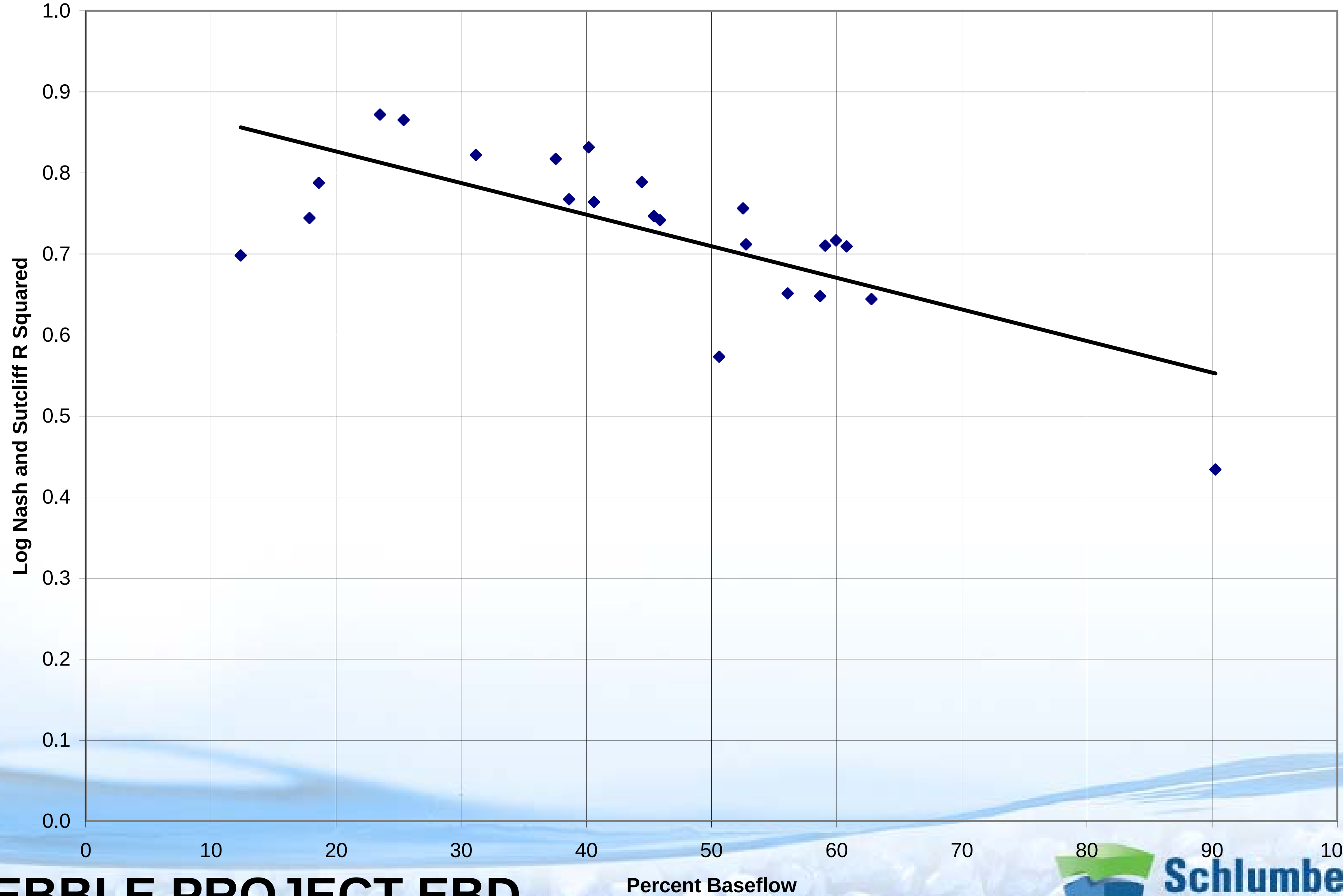
Log Nash and Sutcliffe Efficiency of Model

	Area	Average	Unit Flow	baseflow	Efficiency	Performance Rating
	sq mi	cfs	cfs/sq mi	percent		
SK119A	10.73	36.3	3.38	24	0.87	Very Good
SK124A	8.52	19.0	2.23	18	0.74	Good
SK100G	5.49	14.2	2.58	59	0.65	Satisfactory
SK100F	11.91	29.6	2.48	39	0.77	Very Good
SK100C	37.5	50.2	1.34	19	0.79	Very Good
SK100B1	54.42	132.1	2.43	31	0.82	Very Good
SK100B	69.32	187.8	2.71	40	0.83	Very Good
SK100A	106.91	269.0	2.52	53	0.76	Very Good
UT135A	20.42	42.7	2.09	56	0.65	Good
UT119A	4.05	27.9	6.88	90	0.43	Unsatisfactory
UT100E	3.72	9.8	2.63	63	0.64	Satisfactory
UT100D	11.96	28.5	2.39	46	0.74	Good
UT100C2	48.26	107.4	2.22	45	0.75	Good
UT100C1	59.74	126.3	2.11	53	0.71	Good
UT100C	70.06	167.2	2.39	59	0.71	Good
UT100B	86.22	226.8	2.63	60	0.72	Good
UT100APC1	101.43	263.6	2.60	61	0.71	Good
NK119A	7.76	24.8	3.20	25	0.87	Very Good
NK119B	3.97	4.8	1.21	12	0.70	Good
NK100C	24.35	50.5	2.08	51	0.57	Satisfactory
NK100B	37.32	90.8	2.43	41	0.76	Very Good
NK100A1	85.33	213.2	2.50	44	0.79	Very Good
NK100A	105.85	256.7	2.43	38	0.82	Very Good



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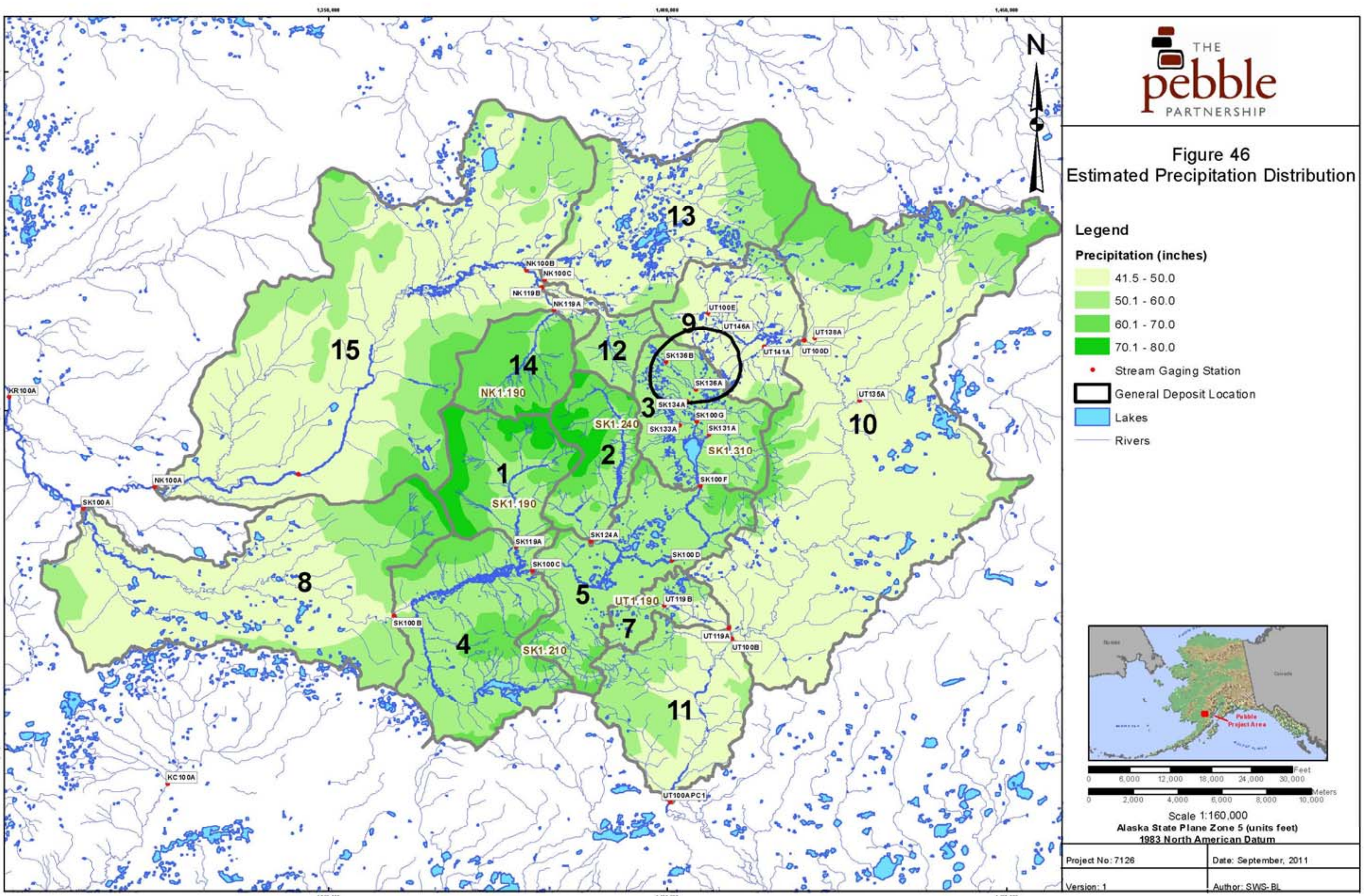

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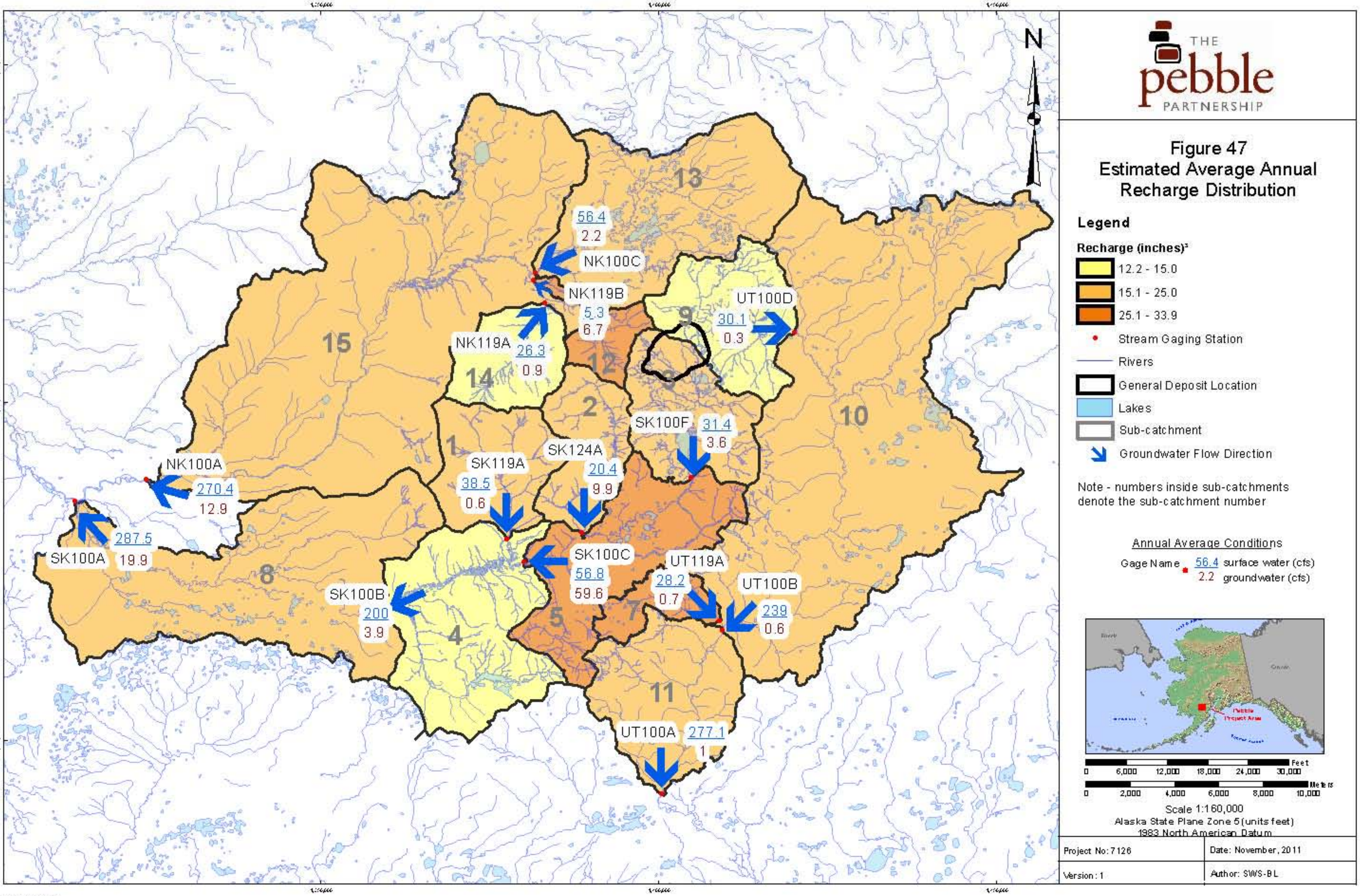

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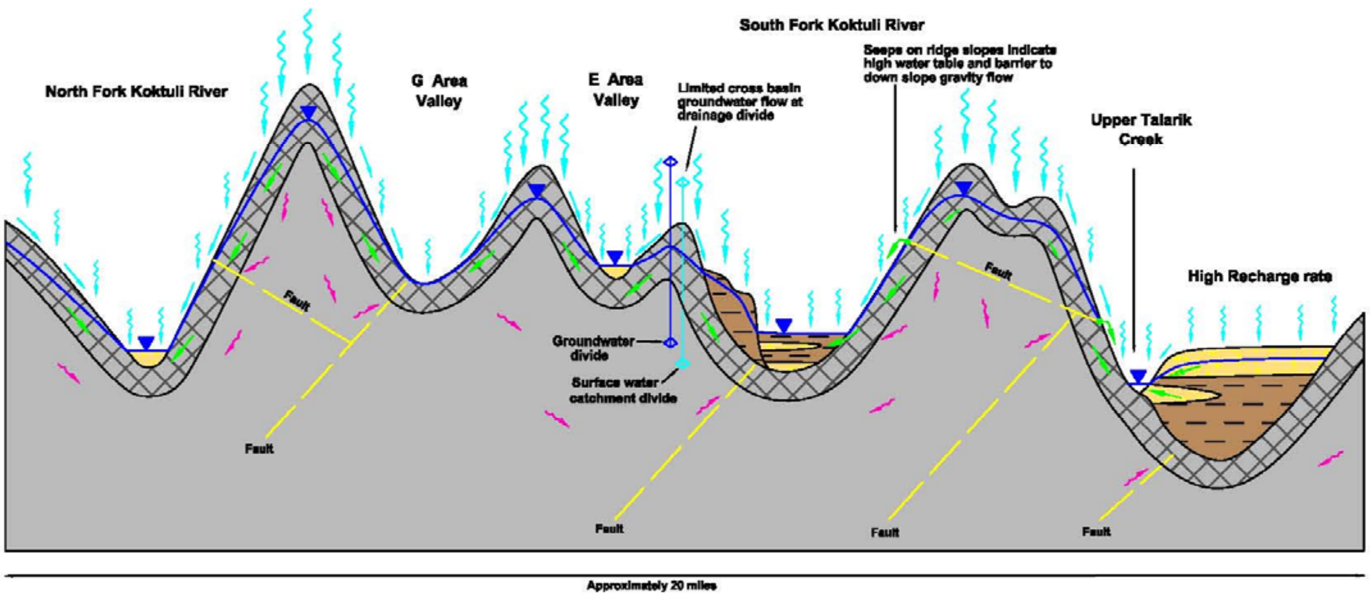

Figure 8-1
Schematic Representation of Site-Wide Groundwater System

Legend

- Sand and gravel
- Silt and clay
- Fractured bedrock
- Bedrock
- Recharge
- Seasonal surface runoff
- Spring
- Shallow bedrock groundwater flow
- Minor deep bedrock groundwater circulation
- Potentiometric surface - alluvium
- Water Table
- Groundwater divide
- Surface water catchment divide

Note:
Most groundwater flow occurs at shallow depths.
(Alluvial groundwater flow vectors are perpendicular to the section and therefore are not shown).

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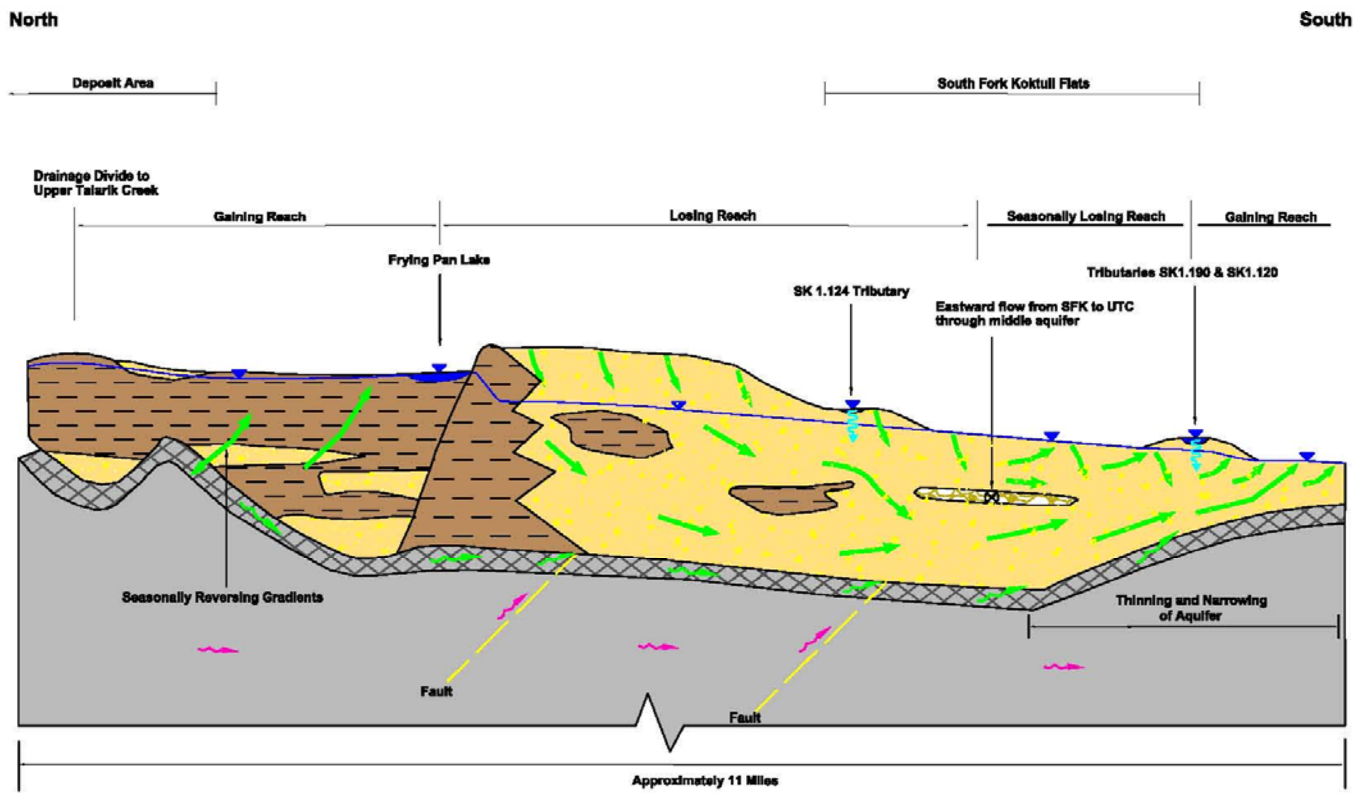

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Figure 8-2
Schematic Representation of Groundwater-Surface Water Interaction Along South Fork Koktuli River

Legend

- Sand and Gravel
- Silt and clay
- Weathered Bedrock
- Bedrock
- Groundwater Flow
- Water Table
- Direction of Groundwater Flow into Page
- Groundwater Recharge
- Minor deep bedrock groundwater circulation

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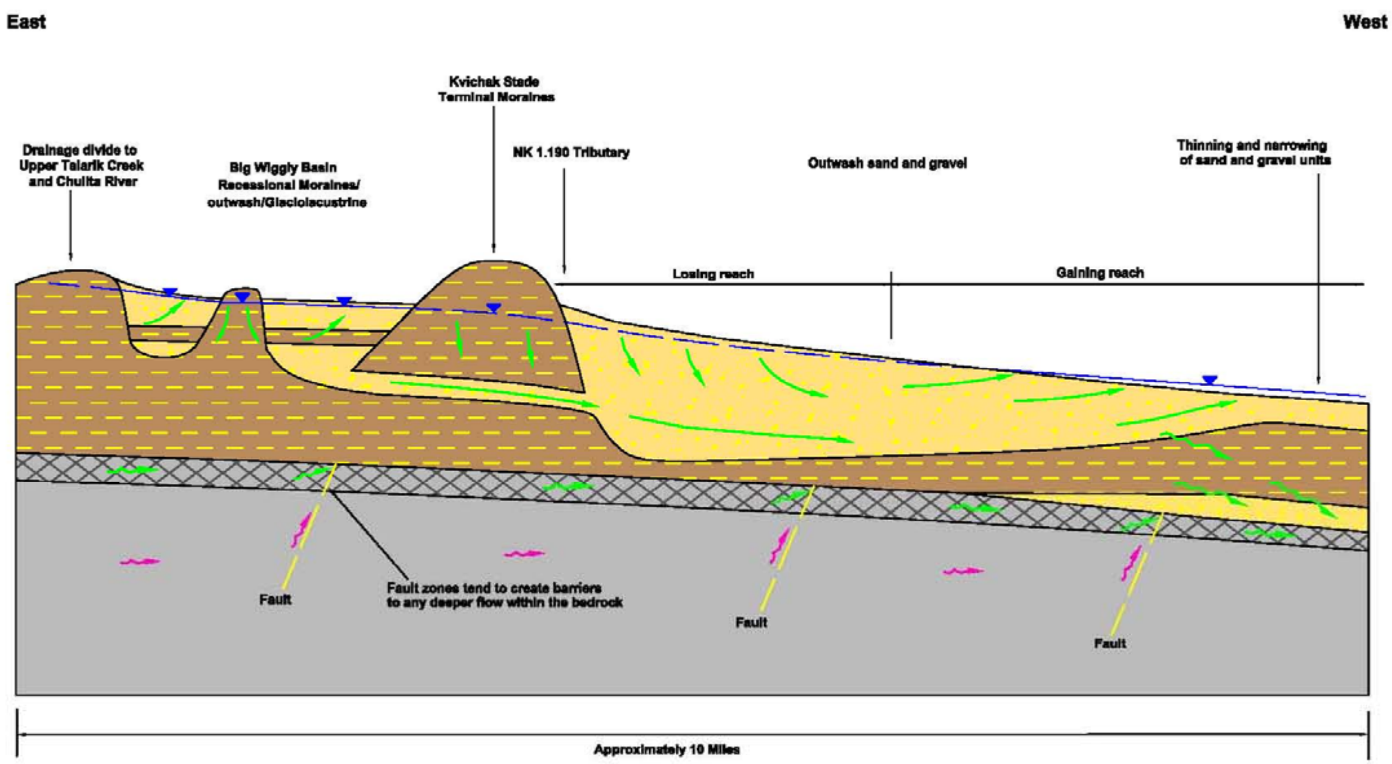
Figure 8-3
Schematic Representation of Groundwater Surface Water Interaction Along North Fork Koktuli River



Legend

- Sand and Gravel
- Silt and clay
- Weathered Bedrock
- Bedrock
- Groundwater Flow
- Potentiometric surface - bedrock
- Minor deep bedrock groundwater circulation

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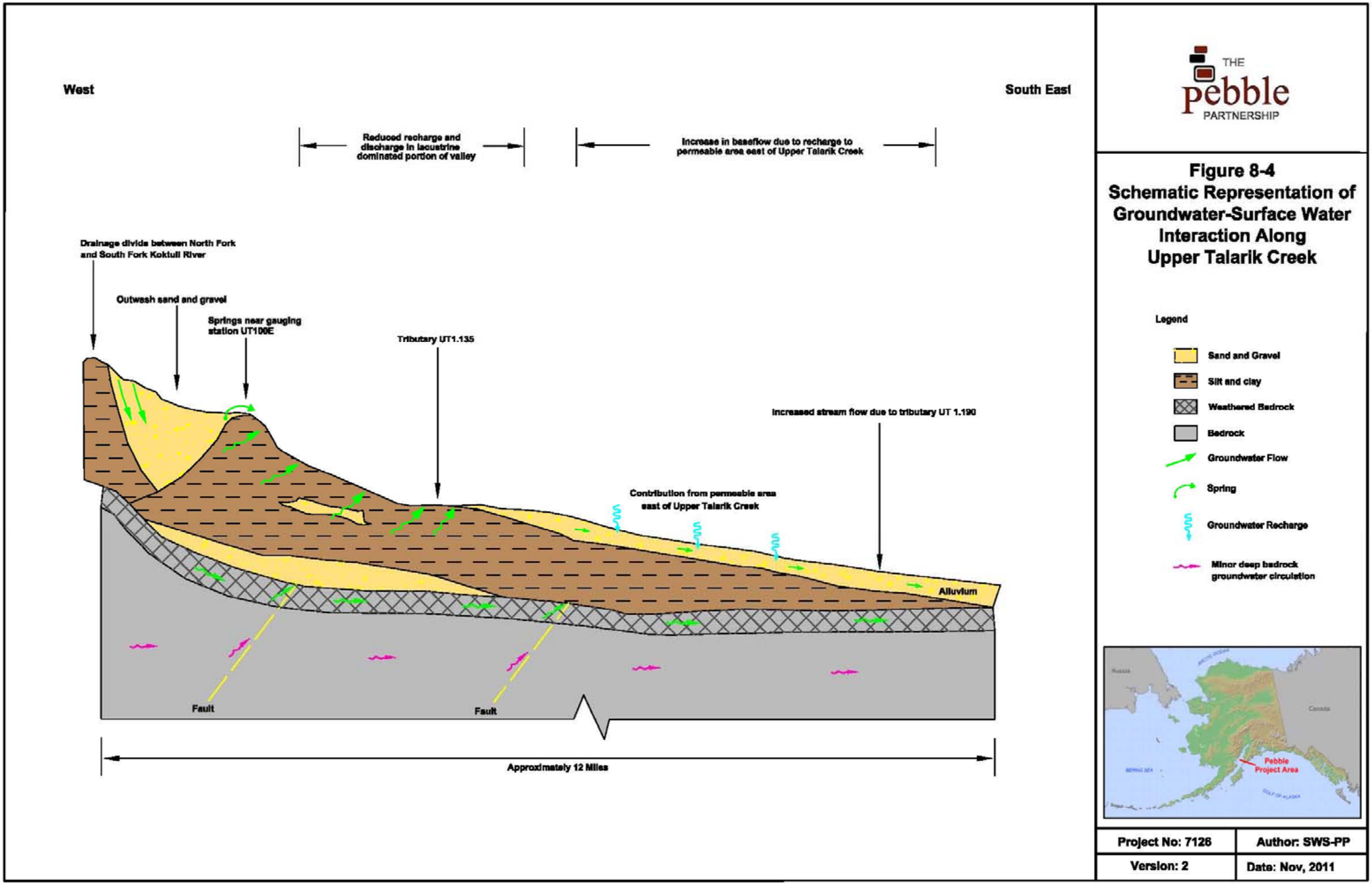

Figure 8-4
Schematic Representation of Groundwater-Surface Water Interaction Along Upper Talarik Creek

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Summary of Hydrogeologic Setting

- Glaciers deposited large surficial aquifers in the area that result in substantial groundwater/surface water interaction.
- This setting also resulted in interbasin transfer of groundwater.
- In deposit area, glacial lakes dominated so that silty units with some sandy layers are present.

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Summary of Hydrogeologic Setting

- **Regional terminal moraines are within the study area. The glaciation was depositional rather than erosional. Frost damaged rock was therefore left in place and results in the presence of an upper bedrock (10 to 50 ft) groundwater zone across the site.**
- **Hydraulic conductivity generally decreases with depth in the bedrock, primarily as a result of confining stress. Fractured zones adjacent to faults often have increased hydraulic conductivity. The presence of fault gouge causes a decreased hydraulic conductivity across faults.**

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Summary of Hydrogeologic Setting

- Intersecting faults within the area are expected to compartmentalize groundwater zones in bedrock. This phenomena is consistent with the conditions measured in the Westbay multilevel monitoring well.
- The compartmentalized groundwater regime and the presence of higher permeability near surface materials results in negligible regional groundwater flow and will also inhibit the inflow of deep groundwater into the proposed mine.