8. GROUNDWATER HYDROLOGY

8.1 Introduction

The baseline groundwater hydrology study for Pebble Project was undertaken between 2004 and 2008. The study area was focused on an area within a two to six miles radius of the deposit. The current study area for groundwater hydrology is within the mine study area depicted on Figure 1-4 (in Chapter 1) and does not extend into the transportation-corridor study area. Data for parameters that are subject to seasonal variations, such as water levels and streamflows, were collected all year around. Data for other parameters that are independent of the seasons, such as aquifer properties, were collected between May and October of each year.

The objectives of the groundwater hydrology study were as follows:

- To characterize the existing groundwater flow regime and define how the local regime of the deposit area interacts with the regional groundwater system.
- To evaluate the interaction between groundwater and surface water and the potential for cross-basin transfer of groundwater.
- To develop baseline water-flow and water-chemistry models.
- To support aquatic, fish-resource, and wetlands habitat assessments.

The study program included the following elements:

- Collection of surface and subsurface geologic data.
- Examination of drilling logs.
- Installation of monitoring wells and piezometers, including multilevel well completions.
- Installation and testing of pumping wells.
- Measurement of hydrogeologic parameters such as piezometric water level and hydraulic conductivity using various testing methods, including pumping tests.
- Characterization of seeps and springs within the study area.
- Delineation of groundwater recharge and discharge zones.
- Evaluation of sub-basin drainage areas, channel lengths, annual precipitation, topographic relief, typical flow regimes, and stream characteristics.
- Characterization of groundwater quality in the bedrock and alluvial groundwater systems.

Data collection, analysis, and interpretation used procedures set forth in the Unified Soil Classification System and the American Society for Testing and Materials (ASTM) Method D 2488-00, Standard Practice for Description and Identification of Soils (Visual Manual

Procedure); ASTM Method D4044-96(2002), Standard Test Method (Field Procedure) for Instantaneous Change in Head (Slug) Tests for Determining Hydraulic Properties of Aquifers; ASTM Method D1586-99, Standard Test Method for Penetration Test and Split-Barrel Sampling of Soils; and ASTM Method D5092, Standard Practice for Design and Installation of Monitoring Wells. All data collected were subjected to a rigorous quality assurance/quality control procedure.

8.2 Results and Discussion

8.2.1 Geologic Controls

Bedrock in the study area consists mostly of Jurassic and Cretaceous sedimentary and volcanic rocks intruded by Cretaceous granodiorite to monzonite and overlain by Tertiary sedimentary and volcanic rocks.

The upper slopes and ridges in the study area include exposures of highly fractured bedrock, talus, rubble, and solifluction deposits. This near-surface weathered zone allows enhanced local-scale groundwater recharge. The zone of weathering is variable but may be typically up to about 50 feet thick.

In general, below the near-surface weathered zone, the hydraulic conductivity of most bedrock units decreases with depth. However, zones of elevated permeability, associated with geologic structures, can occur at deeper levels (Figure 8-1). Structures are interpreted to exhibit enhanced hydraulic conductivity along their direction of strike and reduced conductivity across strike. Therefore, fault zones oriented perpendicular to the local groundwater-flow direction may potentially act as hydraulic barriers, while some of the structures oriented parallel to the groundwater-flow direction may act as local-scale conduits. Faults with elevated permeabilities terminate within the study area where they are cross-cut by other faults, there is a change in the rock properties, or the fault pinches out.

The overall pattern of cross-cutting geologic structures in the study area has resulted in the formation of groundwater compartments, particularly within the deeper groundwater system, where the effects of weathering are less. This condition is typical of bedrock groundwater systems developed in crystalline, volcanic, and metamorphic rock settings. The local and intermediate flow systems dominate the overall groundwater regime. Most groundwater flow occurs at shallow levels within the overburden and shallow bedrock.

The lower slopes and valley bottoms are in-filled with glacial deposits, with some surficial alluvial deposits. These glacial landforms include end, lateral, and recessional moraines; ground moraines; outwash sands and gravels; and glaciolacustrine deposits. Of the alluvial deposits, outwash sands and gravels are typically observed to have the highest hydraulic conductivity. Highly fractured bedrock up to 50 feet thick is present below the overburden deposits.

Within the overall alluvial sequence, three distinct permeable and extensive glacial sand and gravel deposits are of particular note, as follows:

- Along the South Fork Koktuli River south of Frying Pan Lake (”The Flats,” see Figure1-3a in Chapter 1). These deposits include a sand and gravel moraine, and sand and gravel outwash deposits (Figure 8-2).
- In the North Fork Koktuli River valley downstream of the terminal moraines of the Kvichak Stade (Figure 8-3).
- East of Upper Talarik Creek where there are extensive outwash and glacial-contact sand and gravels (Figure 8-4).

There are also a number of distinct areas where low-permeability surficial deposits occur. Extensive low-permeability lacustrine deposits underlie the glacial Frying Pan Lake basin and create widespread marsh areas. Similar low-permeability lacustrine deposits are present in the North Fork Koktuli River and Upper Talarik Creek drainages. Buried lacustrine deposits serve to limit the flow of groundwater from the South Fork Koktuli “Flats” area to Upper Talarik Creek.

8.2.2 Groundwater Flow

Analysis of the baseline data set indicates that bedrock groundwater flow within the study area is generally localized. There is no evidence of regional-scale groundwater flow within any of the bedrock units. Bedrock groundwater recharge typically occurs over areas of higher ground, and groundwater flow follows the local topography towards the adjacent valley floors, where much of the bedrock groundwater percolates into the overlying alluvial deposits. This interpretation is supported by the presence of high groundwater levels beneath the bedrock ridges and the numerous high-flow seeps that are observed along the side slopes of the adjacent valleys (Figure 8-1). Upward hydraulic gradients typically occur in the lower parts of the valleys, further indicating the presence of local bedrock groundwater discharge into the alluvial deposits (Figure 8-3). Furthermore, the chemistry of the groundwater in the deep bedrock groundwater system has higher concentrations of total dissolved solids (TDS) than that measured in the shallow groundwater. Elevated concentrations of TDS can be attributed to the groundwater having a long contact time with the surrounding rock and can be used to infer that such groundwaters have longer residence times than waters with low TDS, that is, shallow groundwaters.

Alluvial groundwater in the three main valleys in the study area (North Fork Koktuli, South Fork Koktuli, and Upper Talarik) generally flows downslope as underflow below the axis of the valley. Contiguous permeable overburden units fill each of the three drainages. The majority of groundwater flow occurs within the overburden deposits. Groundwater underflow down the valleys is much lower where the alluvium is dominated by lower permeability deposits (silts and clays). In these areas, the groundwater system discharges to surface water, leading to gaining streamflow reaches. Conversely, where the alluvial deposits become more permeable downstream or where the profile of the valley widens, the surface water system can leak into groundwater, leading to losing stream reaches.

The upper reaches of tributaries have limited groundwater storage capacity, and therefore, streamflows in the upper reaches are typically flashy, with low late-winter baseflows. Further downstream, the sustained winter baseflows for the main water courses indicate that considerable groundwater is contained in storage within the main parts of the valleys. Baseflows are higher where a substantial thickness of permeable alluvium is present upstream. The overall nature of the baseflow patterns indicates that most of the groundwater storage on site occurs within the alluvium and that most bedrock units demonstrate limited groundwater storage potential.

The average annual groundwater recharge rates for the North Fork Koktuli, Upper Talarik, and South Fork Koktuli watersheds are 11, 16, and 23 inches per year, respectively. Variation in recharge rates within the watersheds reflects differences in the surficial geology. Within each of the drainages, the surficial geology varies from low-permeability glaciolacustrine deposits to high-permeability glacial outwash and ice-contact deposits. The large differences in the permeability, coupled with variations in the topographic gradient, result in estimated localized recharge rates within each drainage that vary from 5 to 47 inches per year (including leakage from streams).

The largest cross-catchment flow in the study area occurs from Area 5 in South Fork Koktuli to Area 7 in Upper Talarik Creek (Figure 8-5) and is estimated to be about 6 inches per year or about one-third of the total underflow within Area 5. Except for this cross-catchment flow, over 95 percent of the water that recharges the groundwater system within each of the three main drainages discharges within that drainage.

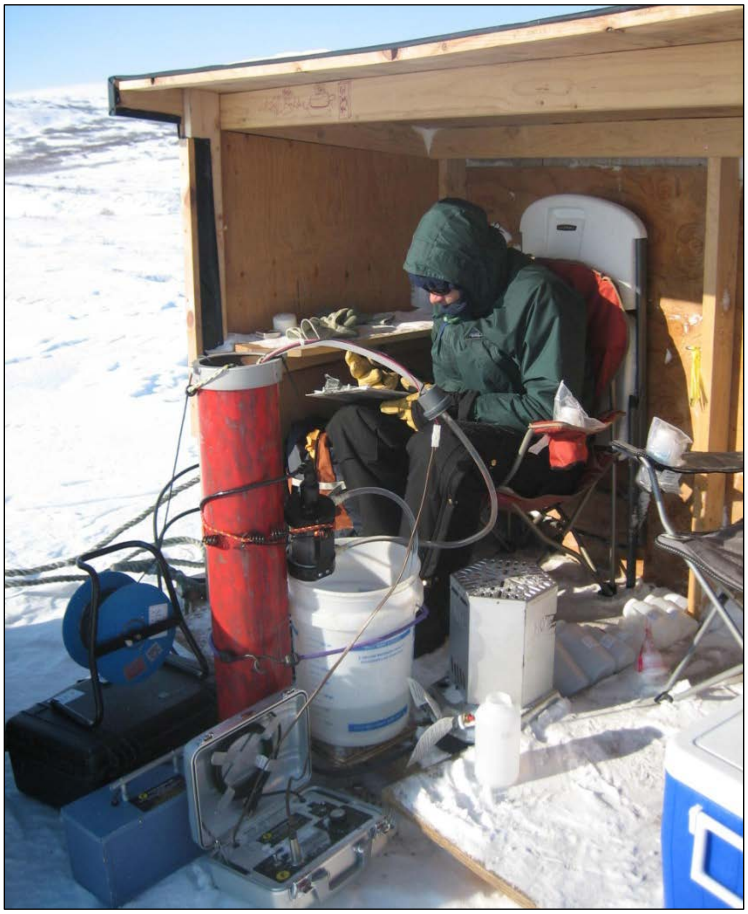
The largest seasonal changes in piezometric levels are between 10 and 20 feet. These mostly occur beneath the bedrock ridges and areas of higher ground. In these areas, the seasonal changes in groundwater storage are large because of the high recharge rates. The drainable porosity and storage potential of the bedrock are low. The similar amplitude of the piezometric variations from year to year indicates that the groundwater system is in a state of dynamic equilibrium and that the net change in groundwater storage from one year to the next is small, varying only in response to year-to-year changes in precipitation patterns.

In summary, the overall groundwater flow system in the study area is characterized as follows:

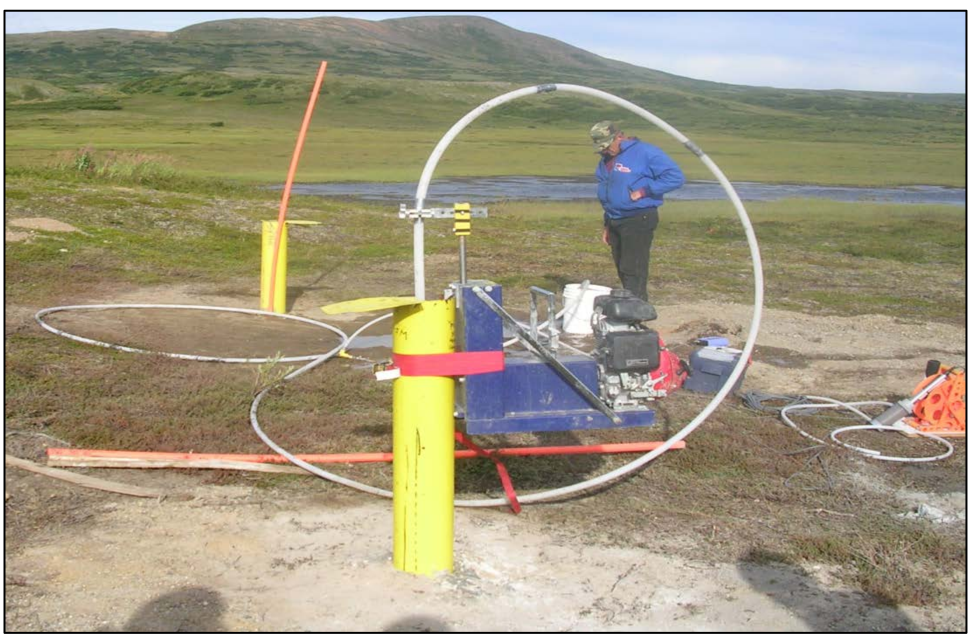
- The overall bedrock groundwater flow pattern is localized and is dominated by the upper 50 feet of the bedrock. Flow occurs from the margins of the valley downslope towards the valley floor.
- Groundwater within the valley floors moves as underflow in a downslope direction beneath the axis of the valleys, predominantly within overburden deposits.
- Analysis of the baseline data indicates that, except for some cross-catchment flow between the South Fork Koktuli River and Upper Talarik Creek, over 95 percent of the water that recharges the groundwater system within each of the three main drainages discharges within that drainage.

A South Fork Koktuli River groundwater discharge area.

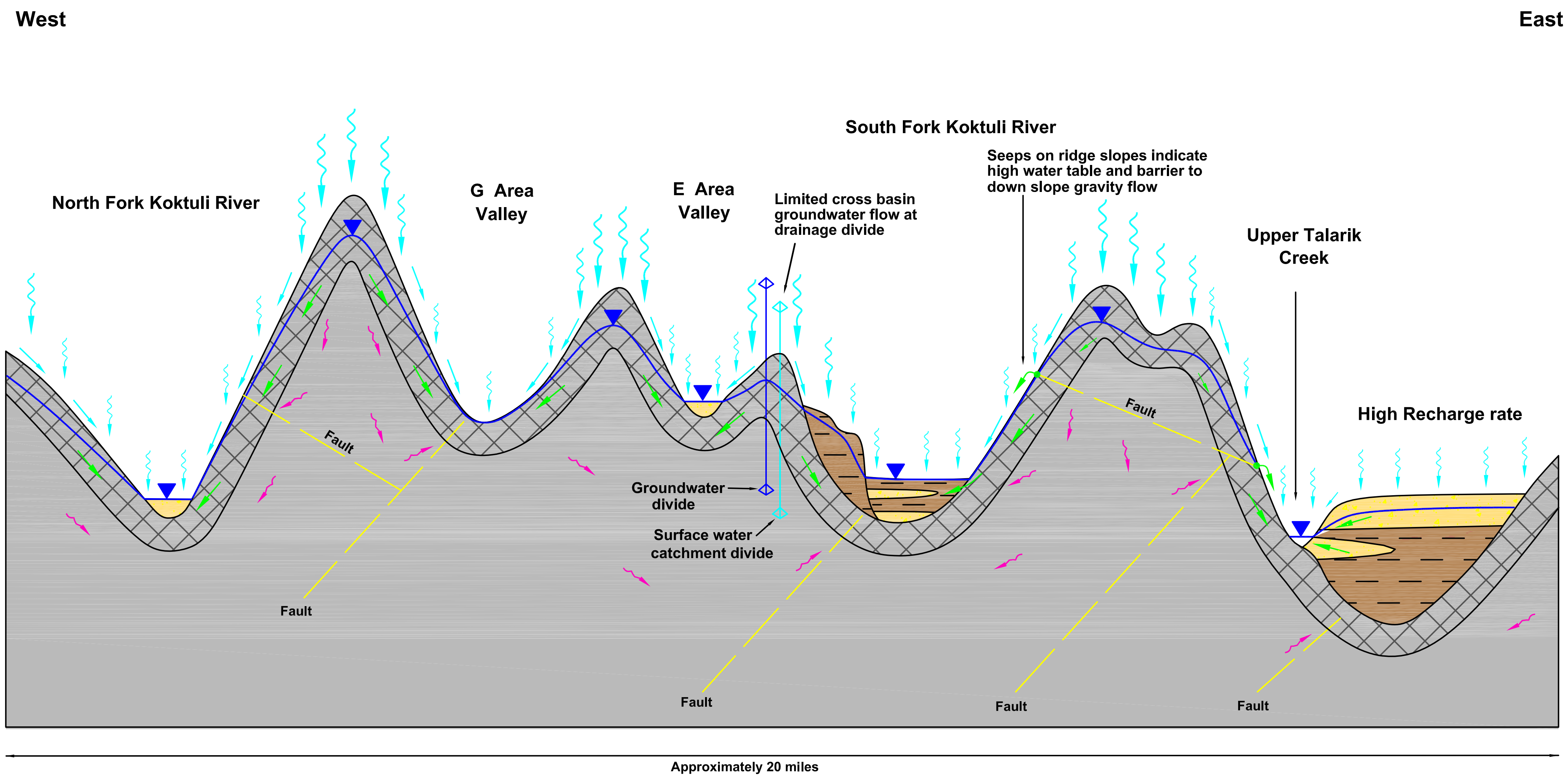
Spring within a closed depression between the South Fork Koktuli River and Upper Talarik Creek.



Winter groundwater sampling.



Well development prior to a response test at a monitoring well.



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

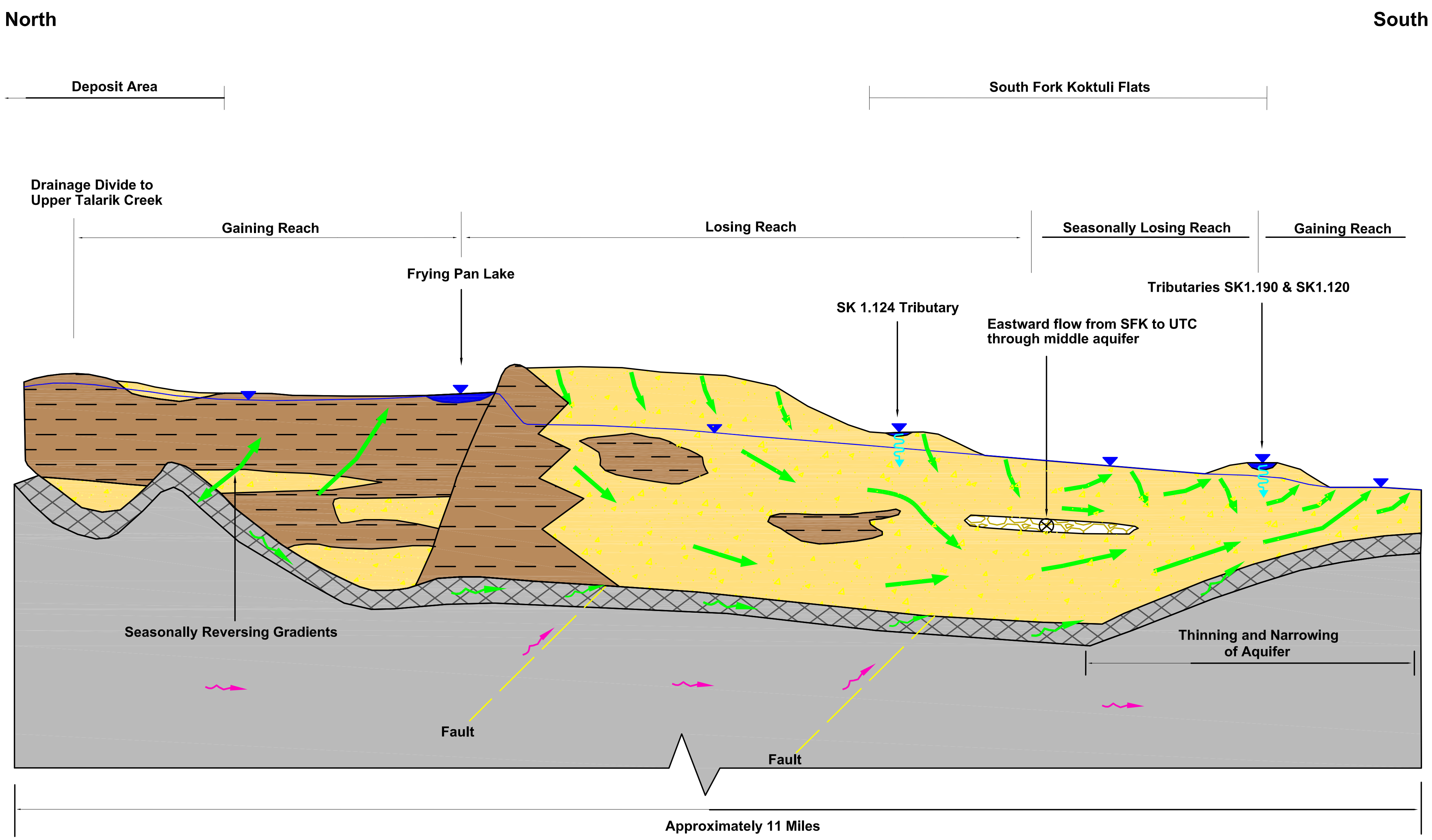
THE pebble PARTNERSHIP

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

Project No: 7126	Author: SWS-PP
Version 2	Date: Nov, 2011



THE pebble PARTNERSHIP

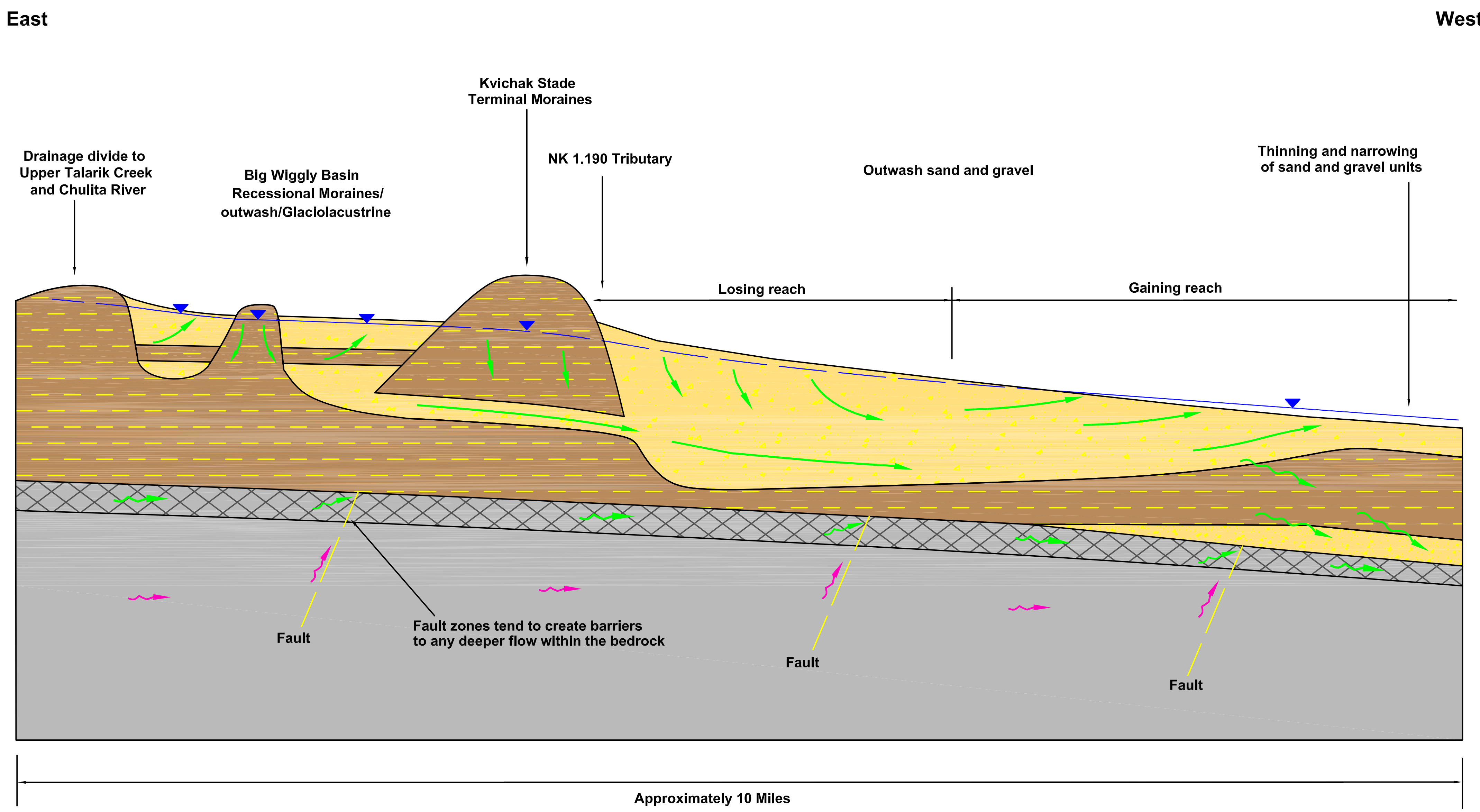
Figure 8-2
Schematic Representation of Groundwater-Surface Water Interaction Along South Fork Koktuli River

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

Project No: 7126	Author: SWS-PP
Version: 2	Date: Nov, 2011

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



Legend

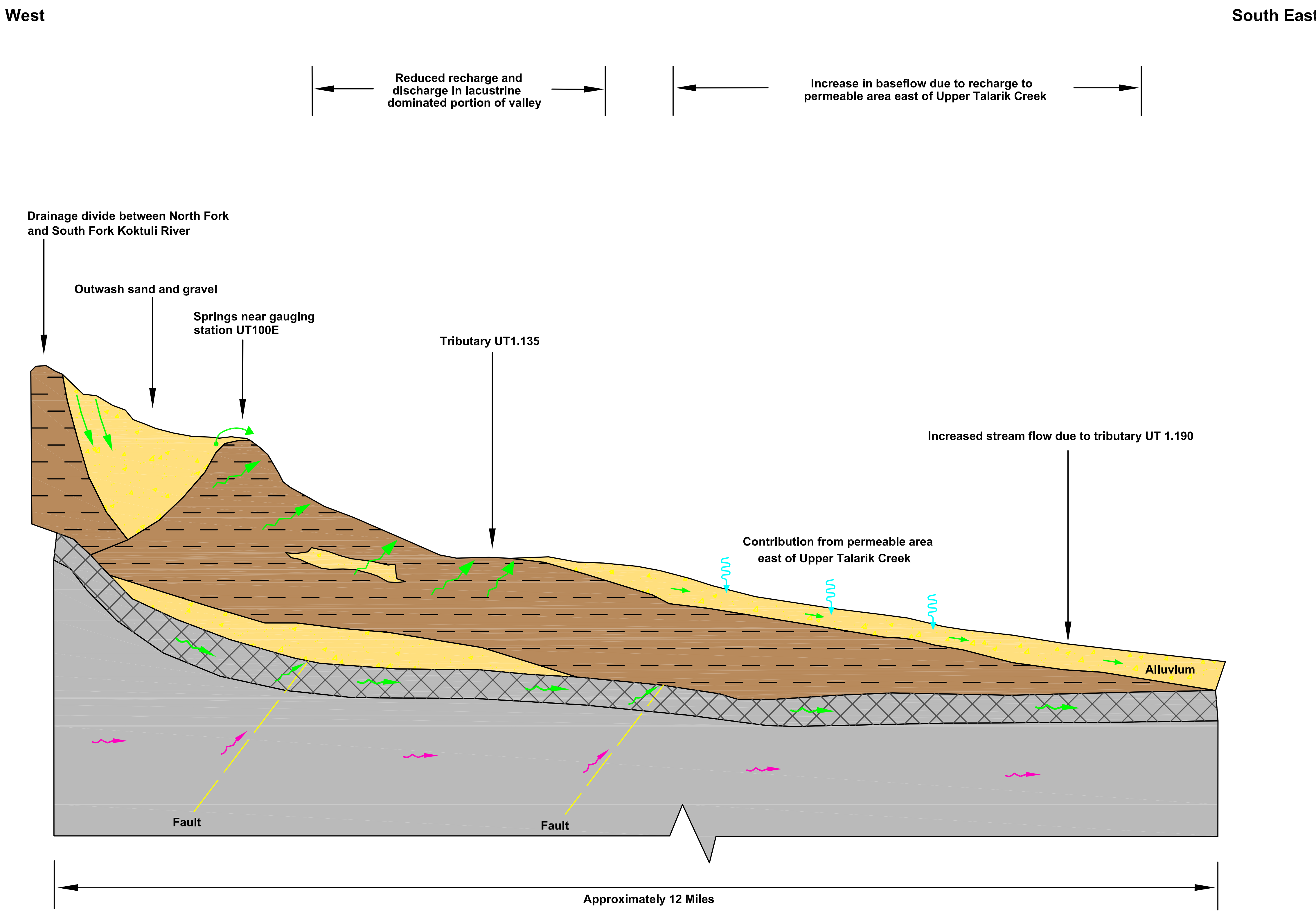
- Sand and Gravel
- Silt and clay
- Weathered Bedrock
- Bedrock
- Groundwater Flow
- Potentiometric surface - bedrock
- Minor deep bedrock groundwater circulation

THE pebble PARTNERSHIP

Project No: 7126	Author: SWS-PP
Version: 2	Date: Nov, 2011

THE pebble PARTNERSHIP

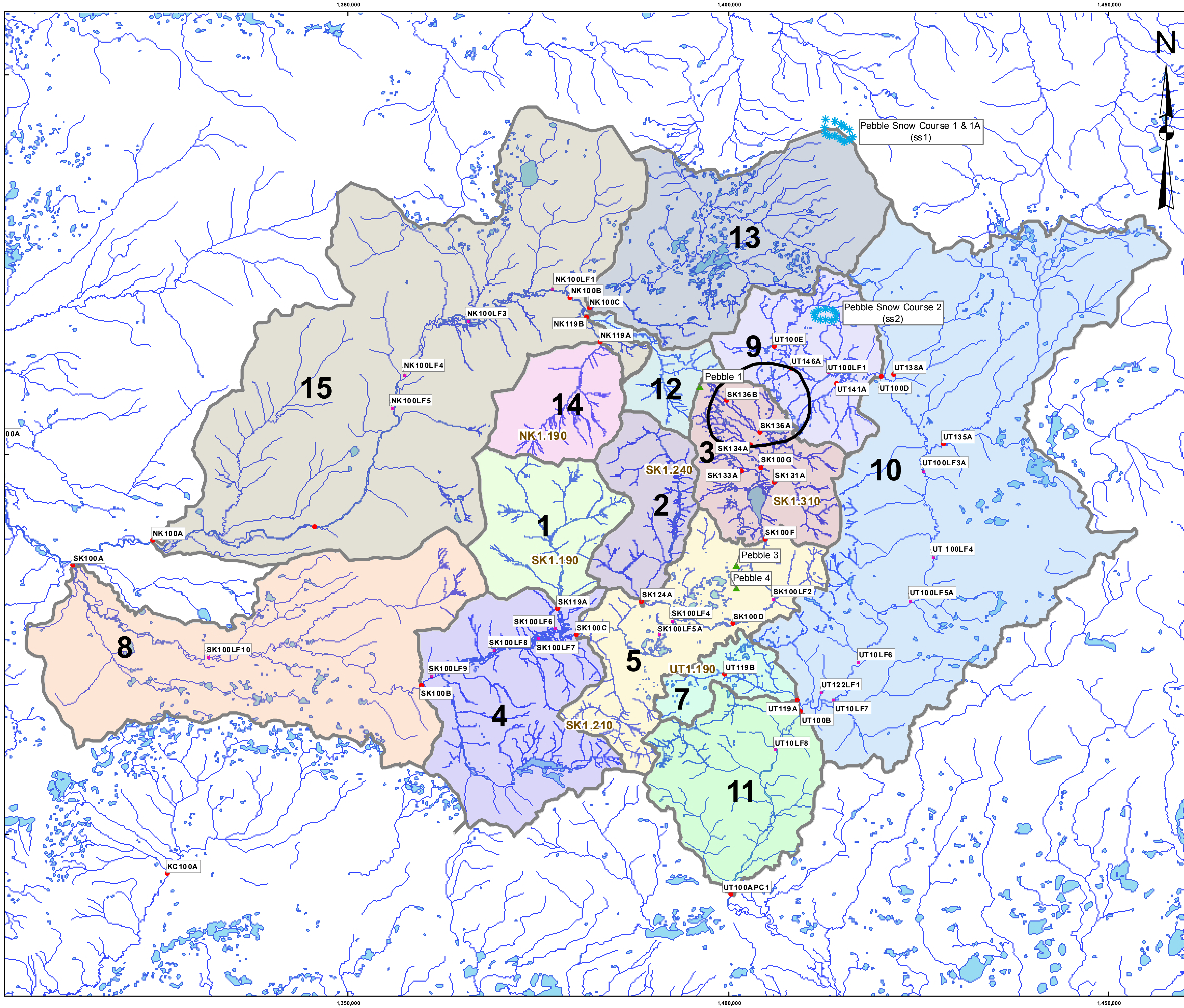
Figure 8-4
Schematic Representation of Groundwater-Surface Water Interaction Along Upper Talarik Creek



Legend

- Sand and Gravel
- Silt and clay
- Weathered Bedrock
- Bedrock
- Groundwater Flow
- Spring
- Groundwater Recharge
- Minor deep bedrock groundwater circulation

Project No: 7126	Author: SWS-PP
Version: 2	Date: Nov, 2011

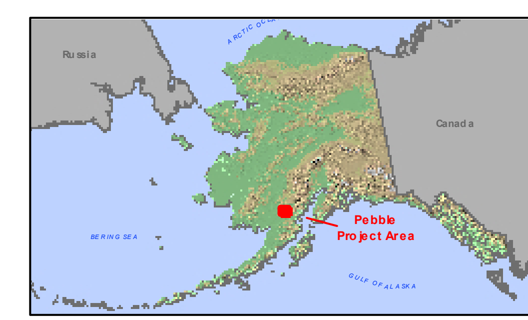


THE pebble PARTNERSHIP

Figure 8-5
Stream Gaging Stations and Watershed Boundaries

Legend

- Snow Course Station
- Meteorological Station
- Stream Gaging Station
- Low Flow Stream Gaging Station
- General Deposit Location
- Lakes
- Rivers



Feet: 0, 6,100, 12,200, 18,300, 24,400, 30,500

Meters: 0, 2,000, 4,000, 6,000, 8,000, 10,000

Scale 1:155,600

Alaska State Plane Zone 5 (units feet)

1983 North American Datum

Project No: 7126	Date: November, 2011
Version: 1	Author: SWS-BL