Hydrologic and Aquatic Species Implications of the Proposed Pebble Mine, Bristol Bay, Alaska

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Abstract

Bristol Bay, Alaska is one of the last ecosystems left on earth that has gone unaltered by human impacts. Bristol Bay watershed supports the largest wild sockeye salmon runs on the planet with nearly 42 million salmon migrating to the watersheds headwaters every year. The proposed Pebble Mine, containing gold, copper, and molybdenum has threatened the health of this watershed. This project asks what effects the proposed Pebble Mine will have on water quality and quantity, and more specifically, how the withdrawal of groundwater and surface water will alter the regions most pristine anadromous salmonid spawning grounds. Though comprehensive studies have been done, the groundwater of this region remains a complex topic. This research formulates unanswered questions related to groundwater that need to be answered before mining advances. Due to the unknown properties of the region's groundwater and hydrologic regime, mining poses significant risk to water quality, quantity, and aquatic species of the Bristol Bay watershed.

Introduction

Context

Bristol Bay, Alaska is one of the last ecosystems left of earth that has gone unaltered by human impacts. The Bristol Bay watershed supports the largest wild sockeye salmon runs on the planet with nearly 42 million salmon migrating through the watershed every year. The proposed Pebble Mine containing gold, copper and molybdenum has threatened the health of this watershed. Through various case studies, the EPA has ranked the mining industry as the top polluting industry; furthermore, alterations in water quantity and water quality have a reputation of dramatically altering the social and ecological health of watersheds within mining. To prevent this mine from becoming a reality, my term project proposes to synthesize the hydrologic alterations that the mine would have, looking at water quantity and water quality measurements.

"The proposed mine site straddles the headwaters of two highly productive Bristol Bay drainages, the Kvichak and Nushagak Rivers" (Hauser 2007) (Figure 1, 2, 3). The Bristol Bay watershed is 40,000 square miles and is home to the world's largest sockeye salmon fishery with strong runs of chum salmon, silver salmon and king salmon, each occurring seasonally. The environment also supports large migrations of caribou, migratory birds, and an abundance of other species ("Exploring Public Lands" n.d.). Believed to have a lifespan of 40-50 years, the proposed project will drastically alter the ecosystem and landscape features, some of which include a thirty square mile surface mine, two tailings ponds housing billions of tons of mine tailings and toxic materials. The Pebble mineral deposits are on state lands and are therefore open and vulnerable to development.

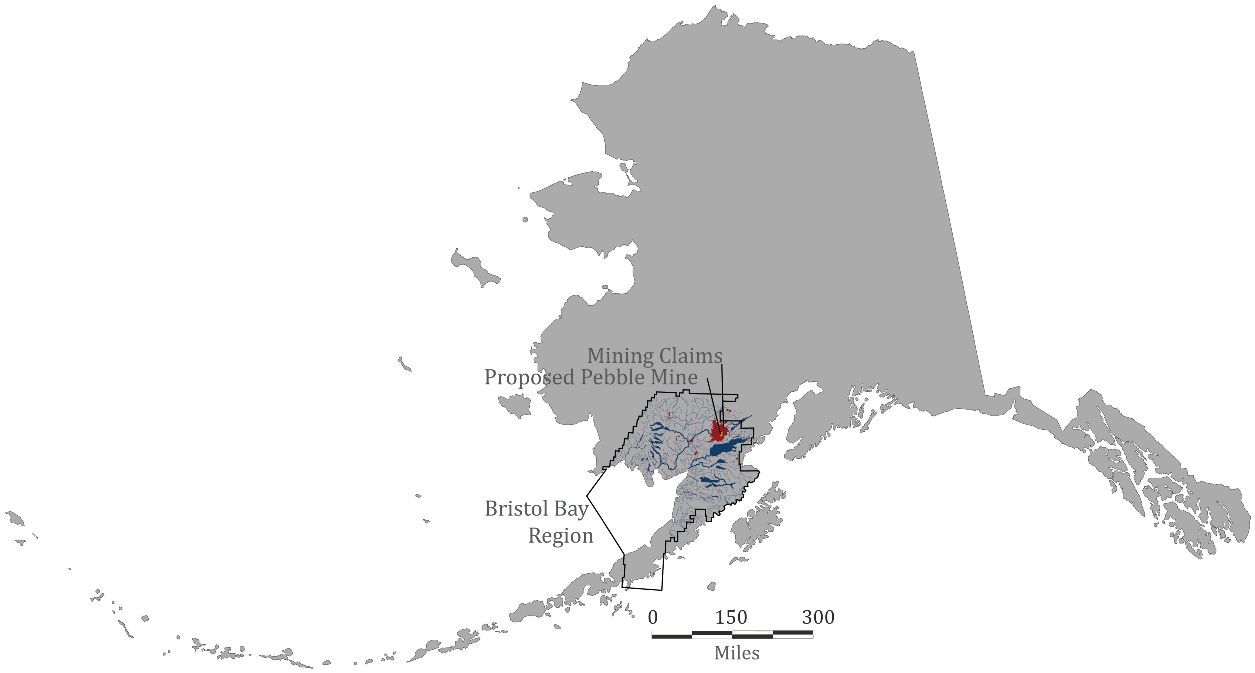


Figure 1: Alaska Context Map
(Source: Fiona Cundy)

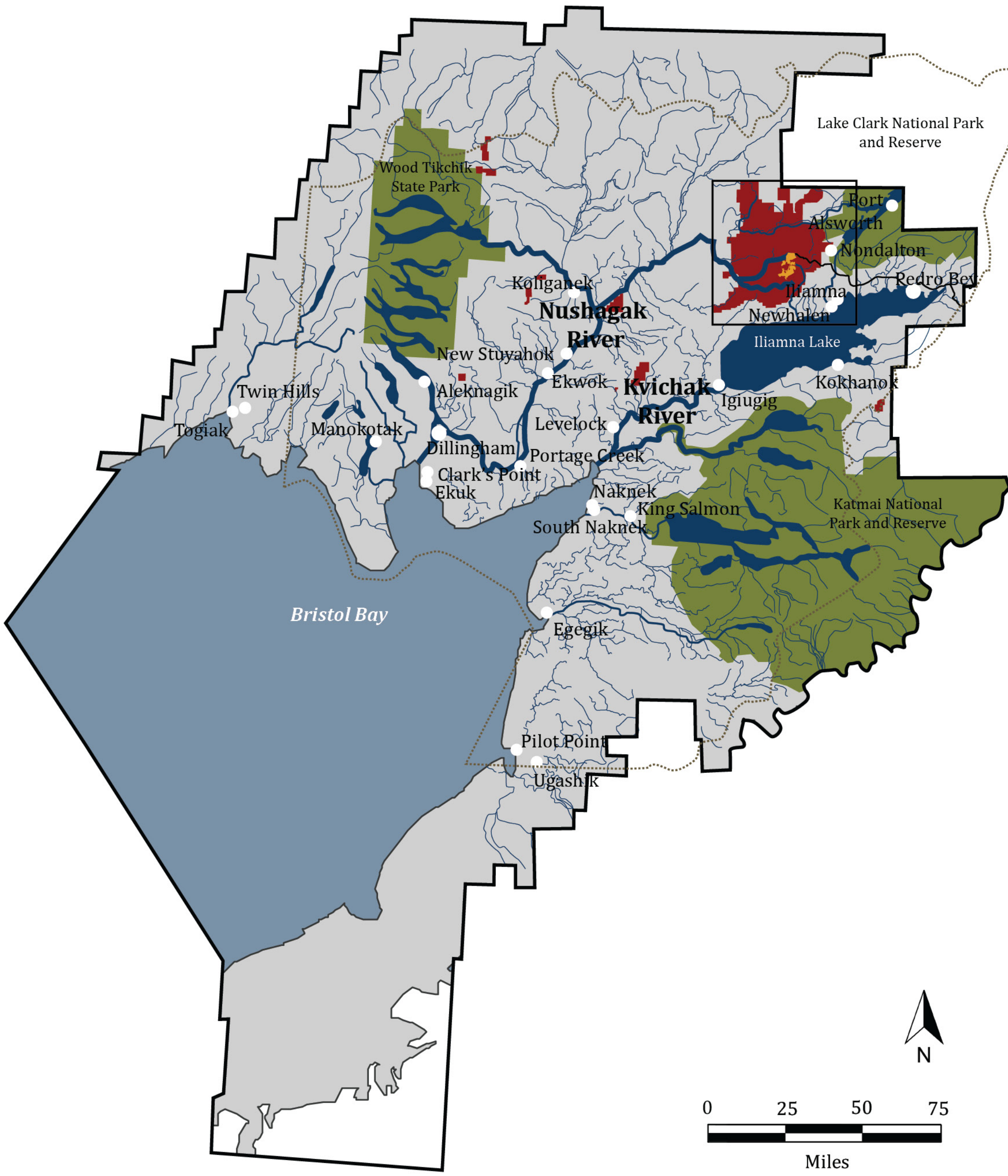


Figure 2: Bristol Bay Region Context Map
(Source: Fiona Cundy)

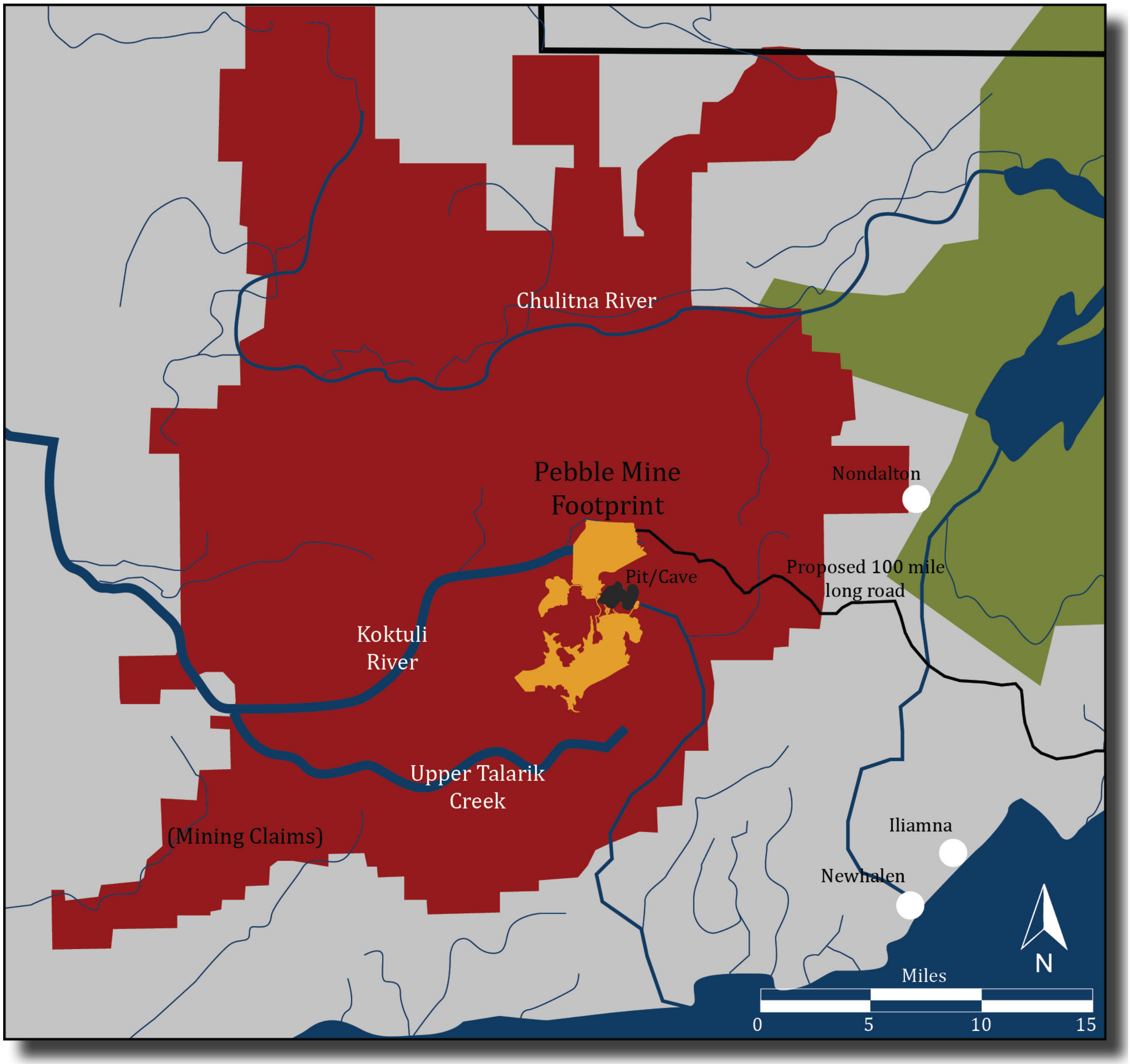


Figure 3: Pebble Mine Context Map
(Source: Fiona Cundy)

<u>Competing values</u>

The Bristol Bay region is particularly unique for its highly productive rivers, but also because subsistence villages and commercial fisheries depend on the health of this ecosystem for their resources. Exploitative resource extraction therefore threatens healthy communities, resilient ecologies, and Pacific salmon fisheries. The salmon fisheries that define this area don't have the capacity to exist with large-scale mining. There are several small communities and native villages within the watershed. The average population within the three boroughs of Bristol Bay is approximately 8,877 (Dillingham 1,258, Bristol Bay 4,922, and the Aleutians East 2,697). To give the importance of fisheries some perspective, wild salmon alone makes up approximately 52% of the overall native diet. Bristol Bay Native communities harvest 2.4 million pounds of salmon per year for subsistence ("Bristol Bay Subsistence Use" 2009), worth between $77.8 and $143.1 million dollars (Figure 4). Commercial fisheries account for nearly 75% of local jobs and account for nearly 175 million per year towards the local economy (Figure 4). Furthermore, these fisheries hold an economic value for their sport fishery. Recreation and tourism of Bristol Bay bring nearly $90 million into state tax and license revenues (Figure 4).

Subsistence $143 million/ yr

- Overall, the value of the Bristol Bay subsistence harvest by Alaskan Natives is worth between $77.8 million and $143.1 million.

Commercial $175 million/ yr

- The annual payroll for fish and wildlife-related employment totals $175 million.
- Commercial fisheries have a 2-5% tax bracket.

Sport $90 million/ yr + $1.4 billion/ yr

- Recreation and tourism in Bristol Bay brings $90 million/year to the state in the form of taxes and licenses
- In 2007, $1.4 billion spent on fishing trips, fishing equipment, and development and maintenance of land used, etc.

Figure 4: Significance of The Bristol Bay Salmon Fisheries
(Source: Fiona Cundy)

Project Information

This term project focuses on the impacts of Pebble Mine at both the regional watershed scale as well as a local scale. At the headwaters of this region, atop the mineral deposits in Bristol Bay, there are three subwatersheds. The North Fork Koktuli, South Fork Koktuli, and the Upper Talarik Creek each begin at the site of mineral claims and the proposed open pit (Figure 6). As high order streams, these waterbodies are smaller than the rivers they meet up with, yet they are of relatively significant scale. As an example, in April 2011, the USGS gauge ("Stream Gauge Data" 2011) on the Upper Talarik Creek measured nearly 700 cfs (Figure 5).

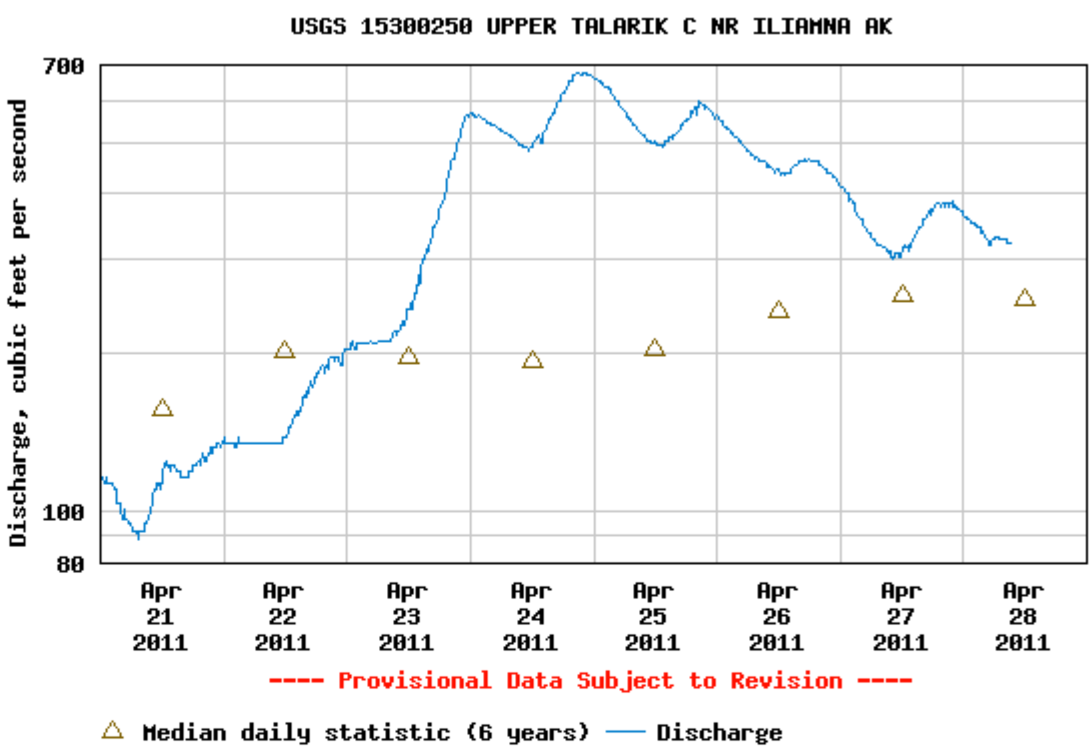


Figure 5: USGS Stream Gauge 15300250: Upper Talarik Creek
(Source: "Stream Gauge Data" 2011)

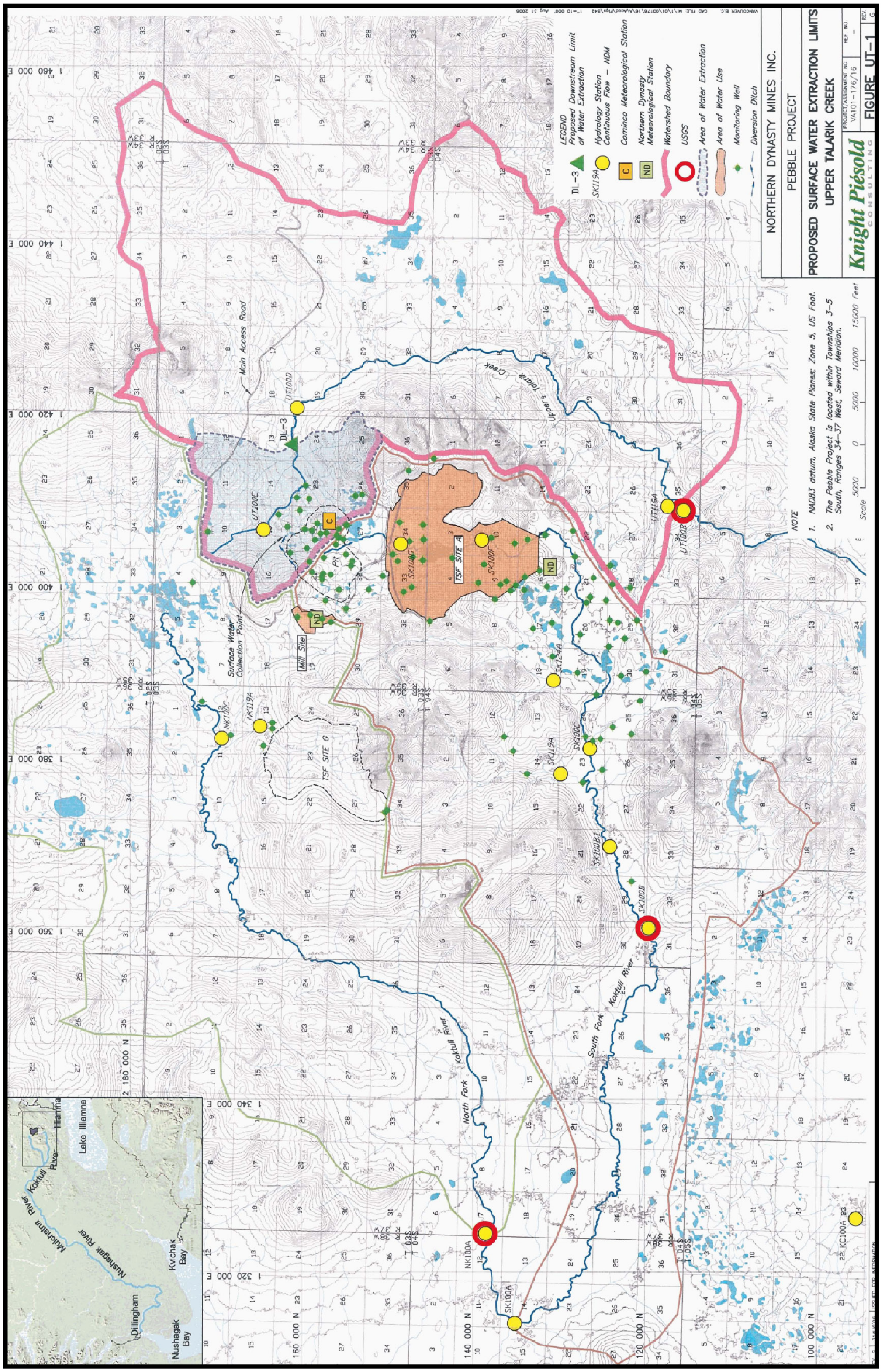


Figure 6: Subwatersheds and Proposed Surface Water Extraction Limits
(Source: Northern Dynasty Minerals, Ltd, 2006)

Because the proposed Pebble Mine would be the largest mine of its type in the world, its required infrastructure and associated impacts would be widespread over a large region. The footprint of all mining activities, including open pit, tailings and facilities would encompass approximately 18,000 acres (the equivalent of 28 square miles) (Moran 2007). The mineral deposits are situated northwest of where the Pacific plate meets the North American plate, resulting in a tectonically active region (Figure 7). Any earthquake activity poses the risk of break the tailings ponds reinforced by dam structures, leaking toxic chemicals (Figure 8).

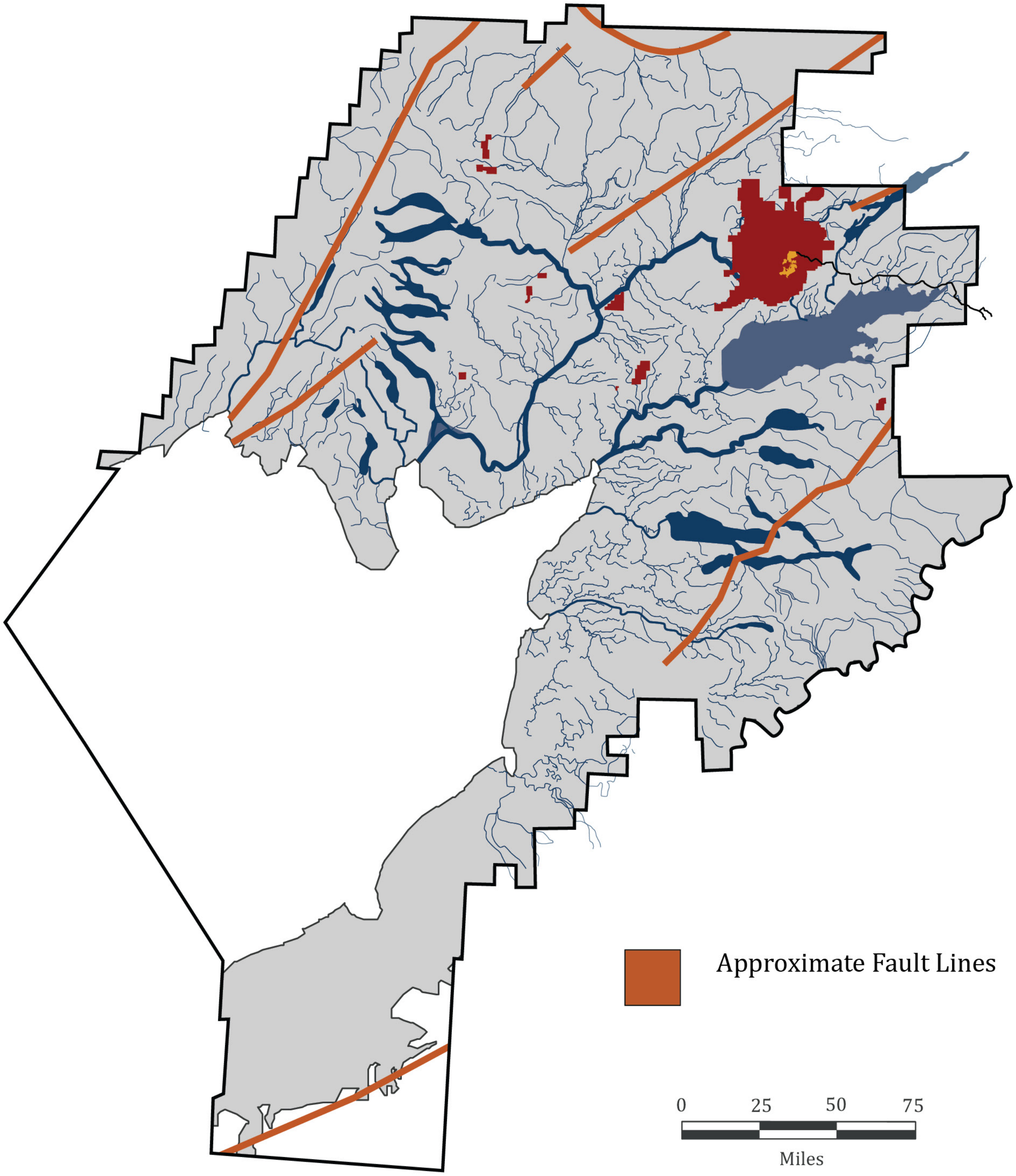


Figure 7. Fault Lines in the Bristol Bay Region
(Source: Fiona Cundy)

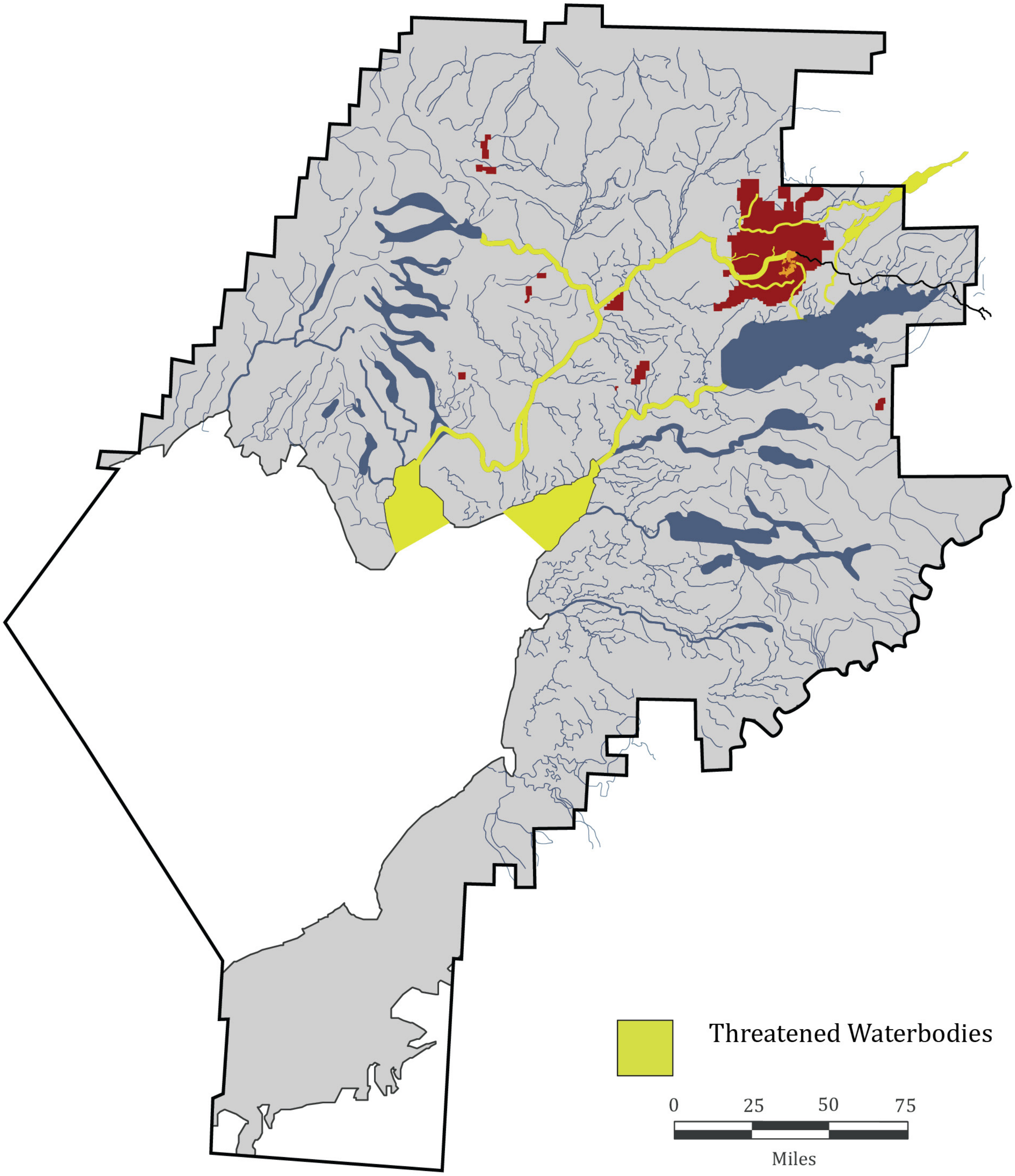


Figure 8: Waterbodies critically threatened by the proposed Pebble Mine
(Source: Fiona Cundy)

The mineral deposits sought for extraction occur at various depths. Minerals concentrated at the west end of the deposit occur at up to depths of 2000 feet, while minerals at the east side of the deposit are at much greater depths (Figure 9). Therefore the proposal by Pebble Partnership Corporation would extract minerals on the western half through open pit mining, and the eastern minerals through block-caving techniques, whereby massive volumes of minerals with relatively low grade orebodies are extracted by caving and extraction. Using such methods typically create a large-scale surface and subsurface depression, or subsidence (Caldwell n.d.).

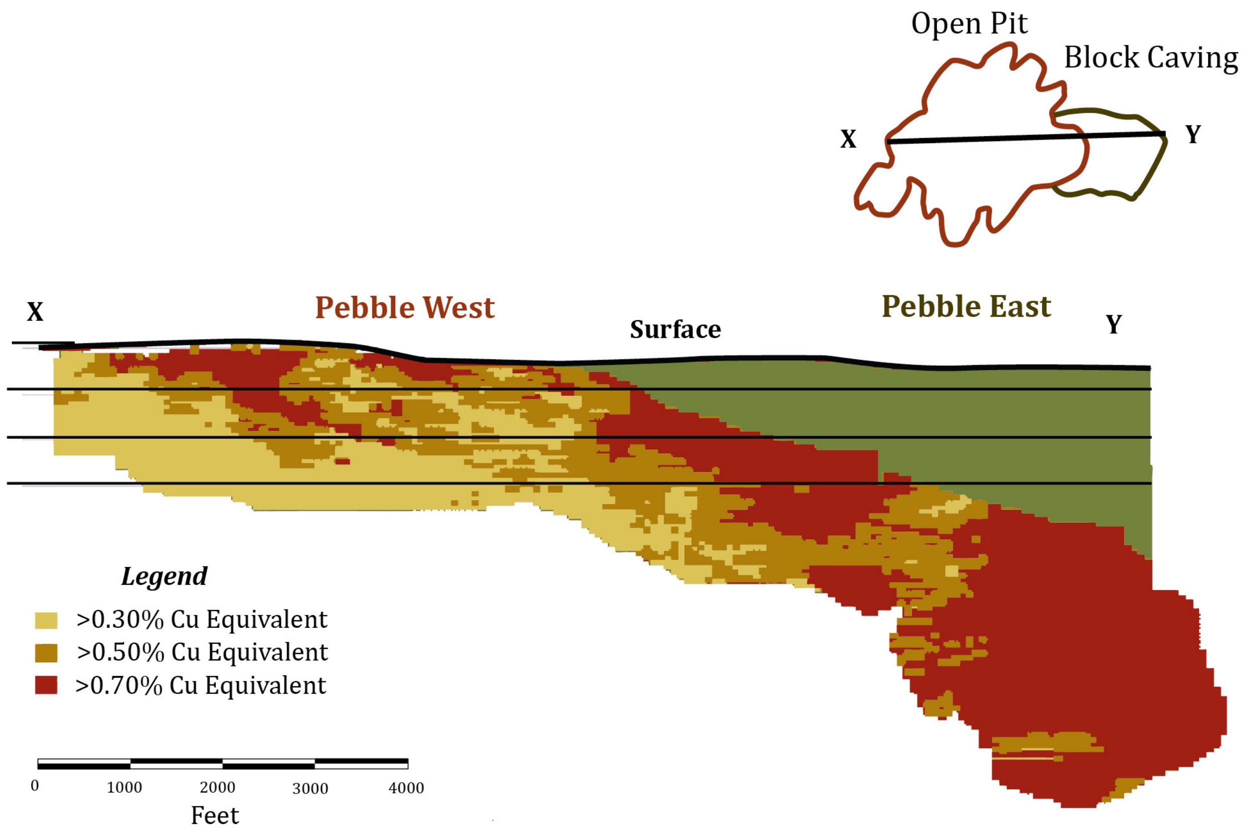


Figure 9: Pebble Mine Copper Deposit Distribution Model
(Source: Northern Dynasty Minerals Ltd. 2011)

Both open pit and block cave mining techniques have myriad consequences on the environment. Open pit mining utilizes mass production techniques as a means of moving large quantities of ore and waste. Such techniques are detrimental to the local and regional environment because they use an ammonium nitrate and diesel fuel mixture as a blasting agent (Moran 2007). The underground mining process of block caving that would be used at the East Pebble typically causes subsidence. When subsidence occurs, water at East Pebble can enter the underground mine, coming in contact with the broken rock that remains underground causing acid mine drainage (Moran 2007).

Problem Statement

While there is a long list of problems associated with their operations, this term paper focuses on problems that could potentially arise in Bristol Bay, particularly because Pebble Partnership has never operated a large mine with a high sulfide content in a subarctic environment. The hydrology of the watershed where Pebble Mine is proposed could suffer irreversible damage. Widespread changes in water regime have historically severely affected sensitive ecosystems. Mining processes to extract gold, copper and molybdenum require a great deal of water from nearby streams, which will likely further alter the water regime (Hauser 2007). "Spawning, rearing and overwintering habitats will be destroyed or damaged in the downstream, partially dewatered reaches where reduced discharge will affect stream productivity because the average velocity will be reduced" (Hauser 2007).

The general research question of this term paper asks what the water quality and quantity effects of the proposed open pit mine, Pebble Mine in Bristol Bay, Alaska will have. Specifically, I question how the withdrawal of groundwater will affect surface water of the region's most pristine anadromous salmon spawning habitat, and what impacts the change of water quality will have on aquatic organisms.

Methods

Due to the geographic proximity to Bristol Bay, Alaska, and the scope of this study, my methods comprise of a research-based approach to some of my unanswered questions concerning the hydrology of the proposed mine. The research questions addressed are as follows:

1. How much water will be used for mining processes?
2. What are characteristics of the local hydrology?
3. How will water usage at Pebble Mine alter the local hydrology?
4. How does the local geology affect groundwater?
5. How will groundwater extraction affect surface water?
6. How will water usage impact Bristol Bay ecosystem (aquatic species & habitat)?
7. How is mining harmful, and what will happen once mining operations cease?

Research

1. How much water will be used for mining processes?

Modern metal mining requires massive volumes of water, which are typically diverted from fisheries, domestic, recreational, and agricultural uses ("Pebble Mine: Water Related Impacts" n.d.). In July of 2006, Northern Dynasty Minerals, Inc. (a partner of Pebble Partnership) applied to the State of Alaska for water rights, requesting a permit for nearly 35 billion gallons of water a year, which translates to nearly 107,500 acre-feet ("Pebble Mine: Water Related Impacts" n.d.). If diverted continuously over a year, this translastes to approximately 150 cubic feet per second. Figure 10 reflects the sources and quantities of water the proposed Pebble Mine anticipate using ("Pebble Mine: Water Related Impacts" n.d.).

Figure 10. Water Rights Requested for the Proposed Pebble Mine, July 2006 (gallons per year)

Location	**Surface Water**	**Groundwater**
South Fork Koktuli River	12.03 Billion	2.8 Billion

North Fork Koktuli River	8.02 Billion	0.2 Billion
Upper Talarik Creek	6.84 Billion	1.7 Billion

(Source: "Pebble Mine: Water Related Impacts" n.d.)

2. What are characteristics of the local hydrology?

The project area of the proposed Pebble Mine encompasses 361 square miles, receiving a long-term annual precipitation mean of 34.1 inches, 30 percent of which is snow (Moran 2007). Due to its subarctic location, the region has a sporadic distribution of permafrost (as exemplified in Figure 11). Permafrost can be defined as a thickness of soil, surficial deposit, or even of bedrock, at a variable depth beneath the surface of the earth in which a temperature below freezing has existed continuously for anywhere from two to tens of thousands of years (Hopkins 1955).

Figure 11: Meanders near the headwaters of the South Fork Koktuli River
(Source: Erin McKittrick, *AK Trekking*)

Regional permafrost tends to obscure groundwater properties. Due to patches of both recent and ancient permafrost, groundwater circulates through horizontally and vertically thawed zones of frozen ground (Hopkins 1955). Additionally, local differences in topography, lithology and drainage result in sharp differences in the character and distribution of permafrost that tend to obscure the regional zonation (Hopkins 1955). The presence of significant dissolved oxygen concentrations in most of the Northern Dynasty Minerals wells are further evidence that shallow ground water flow rates are relatively high in this area (Moran 2007). As a result of the obscured groundwater patterns and groundwater tables being very shallow, the landscape at the grounds of these minerals consists of seeps, springs, and disconnected waterbodies that continually recharge the tundra (Hopkins 1955).

The characteristics of this landscape are dynamic and unstudied. Mining in a subarctic region with permafrost not only adds to the complexity of this project, but mining in this region would also contribute to the loss of tundra, which is a rare landscape that cannot be restored (Figure 12).

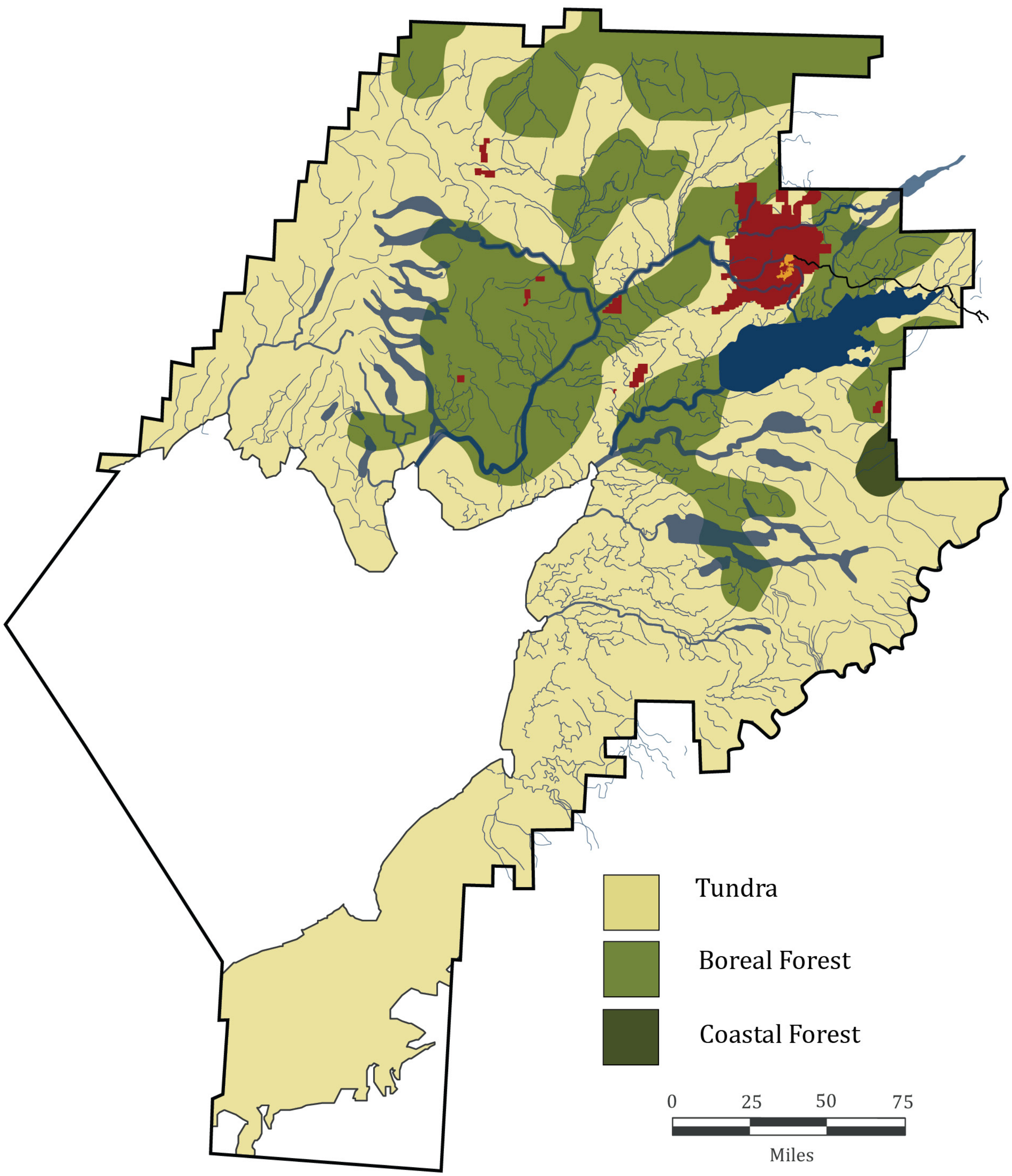


Figure 12: Ecosystem Types of the Bristol Bay Region
(Source: Fiona Cundy)

3. How will water usage at Pebble Mine alter the local hydrology?

Because the environment surrounding the mineral deposits of Bristol Bay is one with shallow groundwater, the development of a large-scale open pit mine would naturally penetrate the regional water table. Extraction processes require a dry environment, and thus the local area must be dewatered. Dewatering processes typically use a combination of well points, deep boreholes, dewatering galleries, drains and sump draining encircling a large area around the pit (Morton 1993) (refer to Figure 21). These methods artificially drawdown the local water table, pumping water out of the area, and causing a cone of depression in the water table. For a proposed pit measuring 2.6 miles wide and 2,000 feet deep, dewatering technologies would encircle an area 4.6 miles in width, and 3,000 feet in depth (Parker et al. 2008) (refer to Figure 22). Lastly, dewatering a mine area is directly related to loss of salmon habitat, displacing water used from aquatic species for mining processes.

4. How does the local geology affect groundwater?

The geology of the area within and around the proposed Pebble Project is a result of glaciation in the last Ice Age (Figure 13). Receding glaciers left a landscape of features including moraine, meltwater channels, and broad outwash aprons with abundant kettle depressions, atop a combination of well-drained gravelly soils and marshy fine-grained soils with boulder covered areas (The Pebble Partnership n.d.).

FIGURE 5.—Index map of Alaska showing permafrost zones.

Figure 13: Permafrost Map
(Source: Hopkins et al. 1955)

The geology underneath this landscape is comprised of permeable alluvium and shallow bedrock (Figure 14, 15). The geological composition and the features of the landscape above create a typical "mountain ground water system" which is highly permeable, transmitting groundwater throughout the region to local streams (Moran 2007). Preliminary studies by Northern Dynasty Minerals reflect fractures in the bedrock, a hydrogeologic feature, which also add to the high conductivity rates of water in the region (Moran 2007). Additionally, geology adds to the complexity of the hydrology, in creating groundwater, which flows under natural pressure to the land surface, or what can be known as artesian flows (Moran 2007).

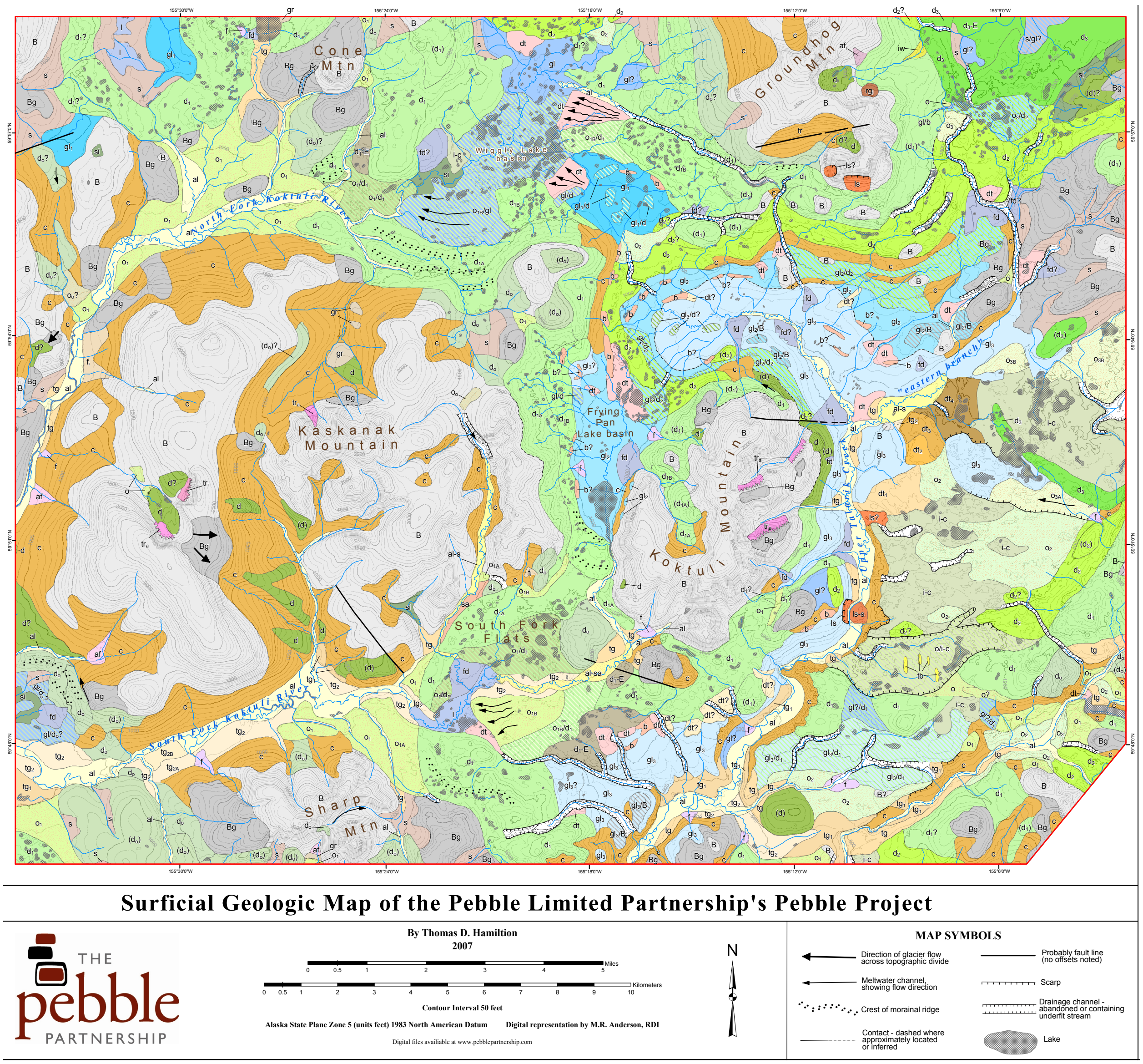
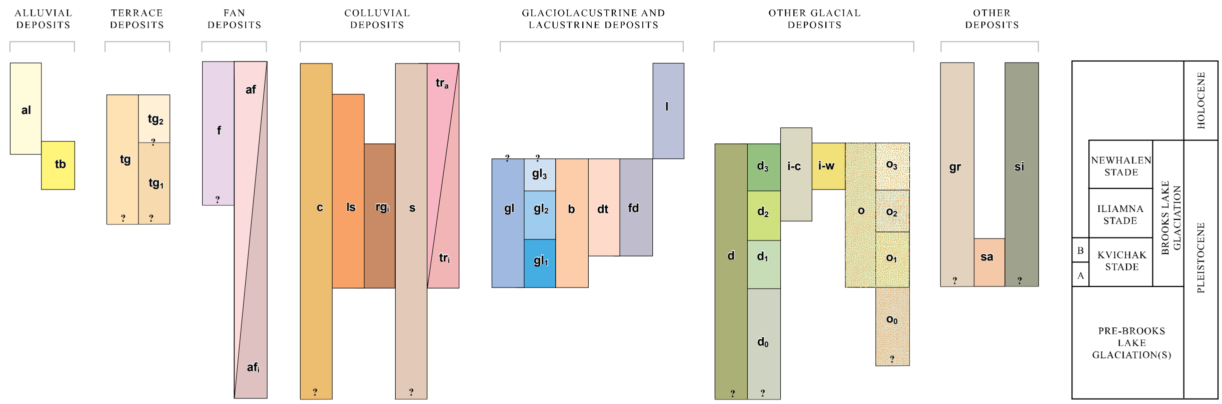


Figure 14: Surficial Geology Map
(Source: "Report C - Surficial Geology Map" 2009)

CORRELATION OF SURFICIAL MAP UNITS



DESCRIPTION OF MAP UNITS

[Map units shown with slashes, such as **gl/d**, indicate deposits of the first unit over known or inferred deposits of the second unit. Map units shown in parentheses, such as (**id**), indicate thin and generally discontinuous deposits. These overlie bedrock unless an underlying surficial deposit is specified. Units of either type are described below only where additional explanation is necessary. Units are queried where uncertain.]

BEDROCK SURFACE FORMS

B — **Bedrock, undifferentiated**—May bear thin and discontinuous cover of rock rubble.

Bg — **Bedrock, glaciated**—Bedrock smoothed and abraded by overriding glacier ice. Generally well exposed rock surfaces; commonly streamlined in direction of ice flow and channeled by glacial meltwater. Dispersed glacial erratic boulders and cobbles typically present.

ALLUVIUM

al — **Alluvium, undivided**—Varies from moderately sorted, stratified, coarse gravel in upper valleys to muddy fine gravel or gravelly sand in depositional basins. Along smaller streams, unit includes fan, floodplain, and low terrace deposits that are too small to be designated separately.

Subunit **al-sa** designates alluvium in which sand dominates. Mapped only within South Fork Flats.

Subunit **al-s** designates alluvium in which silt dominates. Mapped only on east fork of Upper Talarik Creek and on stream that flows south into South Fork Flats.

tb — **Transverse bars**—Alluvial gravel forming elongate deposits oriented normal to inferred former flow direction. Flanks facing downcurrent are steeper (20^{o}-24^{o}) than flanks facing upcurrent (14^{o}-16^{o}). Mapped only in broad west-trending outwash channel (map unit **o/i-c**) in southeast sector of map area.

TERRACE DEPOSITS

tg — **Terrace gravel**—Alluvial gravel and sandy gravel, capped locally by floodplain deposits of silt, sand, or peat. Older terrace deposits commonly have thicker mantles of eolian silt or thaw-lake deposits.

Differentiated into $\mathbf{tg_1}$ (highest and oldest terrace) and $\mathbf{tg_2}$ (lower and younger terrace) where multiple terrace units present.

FAN DEPOSITS

f — **Fan deposits**—Range from poorly sorted, weakly stratified, silty, sandy coarse gravel at mouths of mountain valleys to gravelly sand and silt within lowlands.

Subunit $\mathbf{f_i}$ designates inactive fan deposits, as described above. These generally stand above modern stream levels, and commonly are graded to river terraces that rise above modern floodplains.

af — **Deposits of steep alpine fans**—Coarse, very poorly sorted, angular to subrounded silty sandy gravel at mouths of avalanche chutes and steep canyons. Upper segments generally channeled, with levees of angular to subangular coarse debris. Lower segments commonly littered with similar coarse debris. Subject to snow avalanches during winter, slushflows during spring snowmelt, and debris flows during heavy summer rainstorms. Surface gradients intermediate between talus cones and alluvial fans. Mapped only on west flank of Kaskanak Mountain block.

Subunit $\mathbf{af_i}$ designates steep alpine fan, as described above, that appears no longer active. Mapped only on east flank of Groundhog Mountain.

COLLUVIAL DEPOSITS

c — **Colluvium, undivided**—Widespread slope deposits consisting of rock rubble on upper slopes grading downslope into rock debris mixed with finer sediment. Frost creep may dominate on upper slope segments; solifluction on lower slopes.

ls — **Landslide deposits**—Very poorly sorted, nonstratified, coarse to fine angular rubble, commonly with matrix of finer debris. Forms lobes below detachment scars and slide tracks on steep rock walls. Commonly formed by rapid downslope movement followed by period of relative stability, but may alternatively form by slow and progressive creep. Recognized only on southeast corner of Groundhog Mountain block and along east side of Upper Talarik Creek.

Subunit **ls-s** designates slump deposits (nearly intact blocks of rock or debris formed by sudden or progressive downslope movements, commonly with rotational component. Mapped only along west side of Upper Talarik Creek in southeast part of map area.

rg_i — **Inactive rock-glacier deposit**—Very poorly sorted, nonstratified, coarse angular rock debris, with matrix of silt and fine rubble; formerly contained abundant interstitial ice. Frontal slope stable, gradually rounding back to upper surface. Mapped only near southeast corner of Groundhog Mountain block, where it forms lobate deposit at base of steep north-facing valley wall.

s — **Solifluction deposits**—Slope deposits consisting of very poorly sorted, nonstratified to weakly stratified, stony silt and organic silt. Form smoothly graded, gently to moderately sloping sheets and aprons.

tr — **Talus rubble, undivided**—Angular, unsorted rock debris, forming cones and aprons at bases of cirque headwalls and other steep bedrock slopes. Areas of active talus (unvegetated, unweathered to slightly weathered, with lichen cover sparse to absent) commonly are interspersed with vegetated talus that may have become stabilized following late Pleistocene (Brooks Lake) glaciation. Also forms thin and generally discontinuous sheets over many uplands mapped as "Bedrock".

Locally differentiated into $\mathbf{tr_a}$ (active talus) and $\mathbf{tr_i}$ (inactive talus), as described above, where these form sufficiently large mappable units.

GLACIOLACUSTRINE AND LACUSTRINE DEPOSITS

gl — **Glacial-lake deposits, undifferentiated**—Stratified to weakly stratified silt, organic silt, and silty fine sand, commonly with dispersed dropstones. Grades into gravelly sand to sandy fine gravel near former stream mouths. Marked by smooth and poorly drained surface morphology, with sharp upper limit that coincides with beach and delta deposits (as described below). Mapped as compound unit (for example, **gl/d**) where drapes or overlies bedrock or other glacial deposits.

gl_3 — **Glacial-lake deposits, youngest**—Glacial-lake deposits, as described above, rising to altitudes of 800-850 ft above sea level (asl) along Upper Talarik Creek, and to about 900 ft asl along the Talarik's east and west forks. Postdate Iliamna-stade glaciation; persisted into Newhalen stade.

gl_2 — **Glacial-lake deposits, intermediate age**—as described above. Rise to altitudes of about 900 ft asl along Upper Talarik Creek near south margin of map and 1050 ft asl farther north along Upper Talarik Creek, in proposed Pit Area, and in basin north of Frying Pan Lake. Accompanied Iliamna-stade glaciation, and persisted during deglaciation.

gl_1 — **Glacial-lake deposits, oldest**—Glacial-lake deposits, as described above, rising to altitudes of about 1150 ft asl in Wiggly Lake area. A smaller remnant may also occur on northwest flank of basin that extends north from Frying Pan Lake. Accompanied Kvichak-stade glaciation, and persisted during deglaciation.

b — **Beach deposits**—Moderately well sorted gravelly sand or sandy fine gravel. Forms ridges parallel to topographic contours along upper margins of glacial-lake deposits; their steepest flanks face lake basin. Wave-abraded platform with dispersed relict glacial boulders commonly lies beyond beach face, with platform and beach face meeting at sharp angle.

dt — **Deltaic deposits**—Well sorted to very well sorted sand to sand with fine gravel. Form lobes with axes normal to topographic contours that extend across margins of former glacial-lake deposits. Where preserved, surface channels have digitate pattern. Generally border modern streams or abandoned meltwater channels. Queried where interpreted from aerial photographs but not field checked.

Subunits $\mathbf{dt_1}$, $\mathbf{dt_2}$, $\mathbf{dt_3}$, and $\mathbf{dt_4}$ are successively lower deltaic deposits built into moraine-dammed lake near junction of east and west forks of Upper Talarik Creek as lake level progressively lowered from 880 to 770 ft asl.

fd — **Fan-delta deposits**—Alluvial-fan deposits (as described in unit **f**) that grade downslope into deltaic and lacustrine facies (as described in units **dt** and **gl**). Generally have fan-shaped surface form, but distal (lower) segment is broader, more poorly drained, and more gently sloping than normal alluvial fan.

l — **Lake deposits**—Silt and silty fine sand, stratified to weakly stratified. Probably of postglacial (Holocene) age. Mapped only on floor of South Fork Flats and near northwest corner of map area.

OTHER GLACIAL DEPOSITS

d — **Drift, undifferentiated**—Unsorted to poorly sorted, generally nonstratified, compact till ranging in composition from muddy gravel to sandy coarse gravel. Contains local stratified ice-contact meltwater deposits consisting of moderately sorted sand and sandy gravel. Pebbles and small cobbles generally dominant, but faceted and striated stones up to boulder size are generally dispersed throughout deposit. Surface morphology commonly includes morainal ridges, dry and water-filled kettle depressions, conical to subdued mounds, and meltwater channels.

d_3 — **Drift of Brooks Lake glaciation, Newhalden stade**—Glacial deposits, as described above. Moraines sharp crested, with irregular topography little modified by weathering or erosion. Forms arcuate end moraines in northeast corner of map area and near its east-central margin.

d_2 — **Drift of Brooks Lake glaciation, Iliamna stade**—Glacial deposits, as described above. Moraine crests irregular, but generally less sharp than those of Newhalen Stade. Forms large crescentic end moraine north of Frying Pan Lake basin that encloses proposed Pit Area and is traceable farther east along south and southeast flanks of Groundhog Mountain block. Other end moraines occur north of Wiggly Lake basin at north-central margin of map area and at southeast corner of map area.

d_1 — **Drift of Brooks Lake glaciation, Kvichak stade**—Glacial deposits, as described above. Moraine crests more subdued than those of younger Brooks Lake stades, and drift is more eroded on mountainsides. Form extensive end moraines that (1) cross North Fork Koktuli River near its head, (2) enclose South Fork Flats, and (3) extend west-southwest to Upper Talarik Creek in southeast sector of map area. A small portion of the massive Kvichak moraine around Iliamna Lake extends into extreme southwest corner of map area.

Subunits $\mathbf{d_{1A}}$ (older) and $\mathbf{d_{1B}}$ (younger) differentiated west and south of Frying Pan Lake and in Wiggly Lake area. The younger subunit, a recessional moraine, dams Frying Pan Lake.

Subunit $\mathbf{d_1}$**-E** designates areas of Kvichak-Stade drift that have been eroded by an uncertain agent (either flowing meltwater or wave action along margin of glacial lake).

d_0 — **Drift of pre-Brooks Lake age**—Highly modified glacial deposits, generally remaining only as thin and discontinuous patches of drift on uplands beyond limits of younger glacial advances. A conspicuous moraine segment north of South Fork Koktuli River near southwest corner of map area was deposited by a glacier that expanded northward from Iliamna Lake area and dammed the South Fork. Drift and (or) outwash may also have dammed North Fork of Koktuli River at this time.

i-c — **Ice-contact meltwater deposits**—Meltwater-washed sand and gravel deposited in contact with stagnating glaciers. Commonly forms conical to subdued mounds with well drained surfaces interspersed with dry and water-filled kettle depressions and abandoned meltwater channels.

iw — **Inwash deposit**—Alluvial sand and gravel, commonly with interstratified silt, deposited where stream partly dammed against moraine flank. Mapped only on east flank of Groundhog Mountain at western edge of Newhalen stade drift (unit $\mathbf{d_3}$).

o — **Outwash, undifferentiated**—Moderately well sorted and stratified sandy gravel forming broad aprons and elongate valley trains in front of moraines, and also terrace remnants farther downvalley. Largest stones decrease in size downvalley from large cobbles and very small boulders near moraine fronts to pebble-small cobble gravel in more distal locations.

o_3 — **Outwash associated with drift of Newhalen stade**—Gravel aprons and valley trains, as described above. Associated with moraines of Newhalen stade in northeast and east-central sectors of map area.

Subunits $\mathbf{o_{3A}}$ and $\mathbf{o_{3B}}$ differentiate outwash generated during maximum Newhalen advance (o_{3A}) from recessional outwash that formed during glacier retreat (o_{3B}).

o_2 — **Outwash associated with drift of Iliamna stade**—Valley train, as described above. Mapped only in southeast sector of map area, where broad terrace remnants extend west-southwest toward Upper Talarik Creek from end moraines near southeast corner of map.

o_1 — **Outwash associated with drift of Kvichak stade**—Extensive outwash aprons and valley trains, as described above. Mapped within and west of South Fork Flats and west of Wiggly Lake at head of North Fork drainage. Also associated with Kvichak moraine in extreme southwest corner of map area.

Subunits $\mathbf{o_{1A}}$ (older) and $\mathbf{o_{1B}}$ (younger) are differentiated only southwest of Frying Pan Lake and in South Fork Flats, where they are related to older and younger end moraines of Kvichak stade.

OTHER DEPOSITS

gr — **Gravel, undifferentiated**—Isolated, gravelly erosion remnants of uncertain composition and origin. Mapped primarily in north-trending valley that bisects Koktuli Mountain block.

sa — **Sand deposits, undifferentiated**—Well sorted fine to medium sand of uncertain origin near north margin of South Fork Flats.

si — **Silt, ice-rich**—Poorly drained areas on lowlands that contain abundant small ponds interpreted as thaw lakes. Common on floors of lake basins in proposed Pit Area and north of Wiggly Lake, where they generally are not differentiated from glaciolacustrine deposits.

Figure 15: Surficial Geology Map- Key
(Source: "Report C - Surficial Geology Map" 2009)

The many pathways for water circulation between groundwater and surface water aid salmon productivity in the local and regional aquatic environments. The highly permeable nature of both the landscape and the geology continually recharge groundwater, providing naturally pure and high water flows in the nearby water bodies. While salmon currently benefit from this permeable water exchange network, this network would work against them with toxic contaminants and metals flowing through the permeable layers of this landscape ("Pebble Mine: Water Related Impacts" n.d.). Toxic mining contaminants would, contaminate surface water and groundwater, and would have potential to move between river basins ("Pebble Mine: Water Related Impacts" n.d.). Potential sources of toxic contaminants in mining operations include, but are not limited to, explosives, fuel, oil, grease, antifreeze, water treatment chemicals, herbicides, pesticides, and road de-icing compounds, all of which threaten aquatic species such as salmon ("Pebble Mine: Water Related Impacts" n.d.). Furthermore, 99% of the toxic water used to separate ore will be stored at the proposed project site in tailings ponds. Storing such enormous quantities of toxic water and waste in a permeable environment with high circulation presents substantial risks. Photographs taken by the Alaska Department of Natural Resources in 2007 reflect that poor practices regarding isolation of toxic wastes in a permeable environment have already failed, even at a small scale. Figure 16 reflects a photo from earlier exploration activities with an unlined sump for effluent rapidly infiltrating the tundra (Woody 2008). This raises the question of future practices by the Pebble Partnership regarding their ability to isolate toxic contaminants from the local hydrology.

Figure 16: Poor environmental practices documented by the DNR.
(An unlined sump for effluent and infiltration of effluent into tundra)
(Source: Woody, Carol Ann, Ph.D. 2008)

5. How will groundwater extraction affect surface water?

There is relatively minimal baseline data regarding the surface water hydrology of Bristol Bay, and particularly the North and South Fork Koktuli and Upper Talarik Creek. With large annual precipitation rates and frequent regional flooding, there is an inadequate body of data regarding flow to determine the possible future flood events of the local project site (Moran 2007). The collection of long term data would also provide the information necessary to more clearly characterize areas of surface water and groundwater interactions. Additional data to help develop baseline calculations for both sediment and chemical constituent loads throughout the side would advance our understanding of the system (Moran 2007). Furthermore, data collection with greater detail would help answer questions related to groundwater. For example, Moran indicates that former data collected by the partnership points to portions of the bedrock that "are fractured, and transmit varying amounts of water although permeability seems to generally decrease with depth. There are also indications that some ground water is artesian and flows under natural pressure to the land surface. The presence of significant dissolved oxygen concentrations in most of the partnership's wells is further evidence that shallow ground water flow rates are relatively high in many zones" (Moran 2007).

While the intricacies of groundwater and surface waters are unknown, there are general characteristics that may be applied to their relationship. For example, preliminary baseline studies reflect an obvious relationship between groundwater inflows and surface water flows, using groundwater as a recharge for local streams such as the forks of the Koktuli and Upper Talarik Creek.

The relationship between groundwater and surface waters can be characterized as either gaining or losing, based on the transfer of water quantities between the two sources relative to the stream. While the local streams currently exist as gaining streams, a drawdown of the local and regional groundwater table would result in a loss of surface water flows, making them "losing streams" (Figure 17). Losing streams occur when the adjacent groundwater table drops below level the stream. If no upstream source of water exists to maintain a stream flow, the stream risks complete desiccation (American Groundwater Trust 2003).

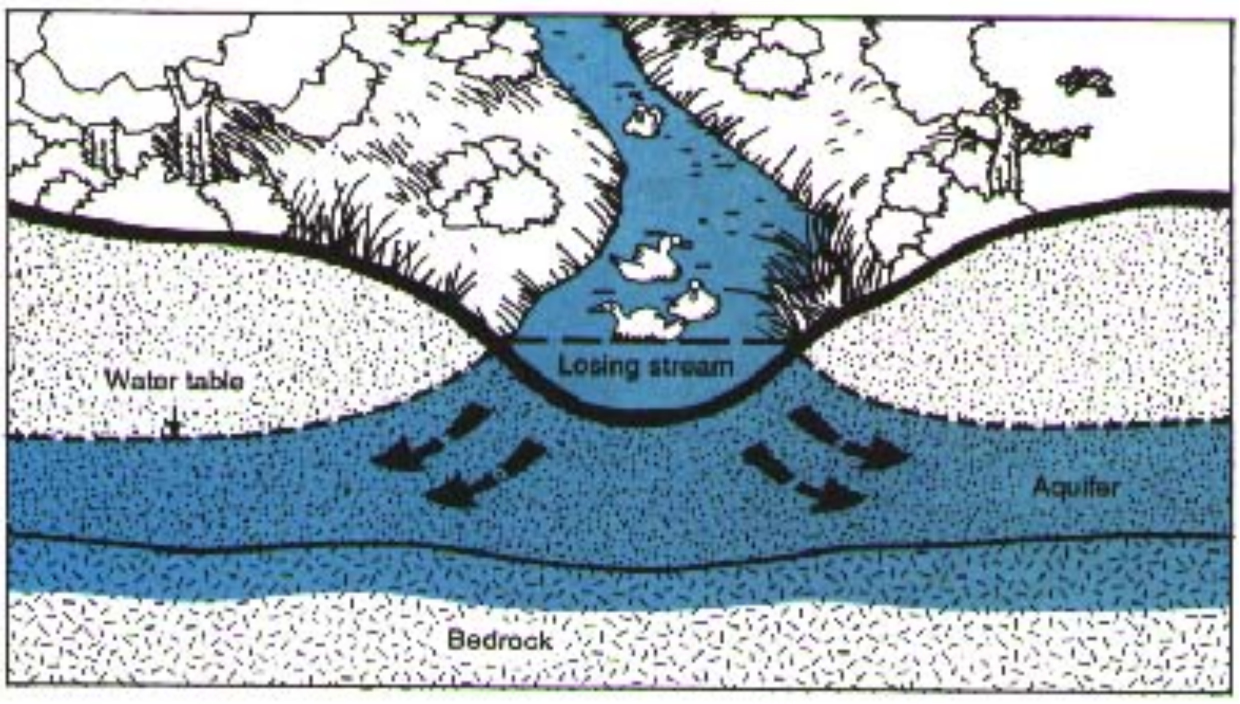


Figure 17: Diagram of a Losing Stream
(Source: "Groundwater: Myths or Facts?" 2011)

6. How will water usage impact Bristol Bay ecosystem (aquatic species & habitat)?

In total, there are five types of Pacific salmon that migrate in US waters, including Chinook (*Oncorhynchus tschawytscha*), chum (*Oncorhynchus keta)*, coho (*Oncorhynchus kisutch*), pink, (*Oncorhynchus gorbusha),* and sockeye *(Oncorhynchus nerka)* (Figure 18). Two other types of Pacific salmon, masu salmon (*Oncorhynchus masou*), and amago salmon (*Oncorhynchus rhodurus*) occur only in Asia. In southwest Alaska, including Bristol Bay, all 5 North American types are present, meaning that these regions are the United States richest area of wild salmon varieties. Other fish species include rainbow trout, arctic char, Dolly Varden, whitefish, pike, grayling, lake trout, blackfish, burbot, smelt, and longnose sucker.

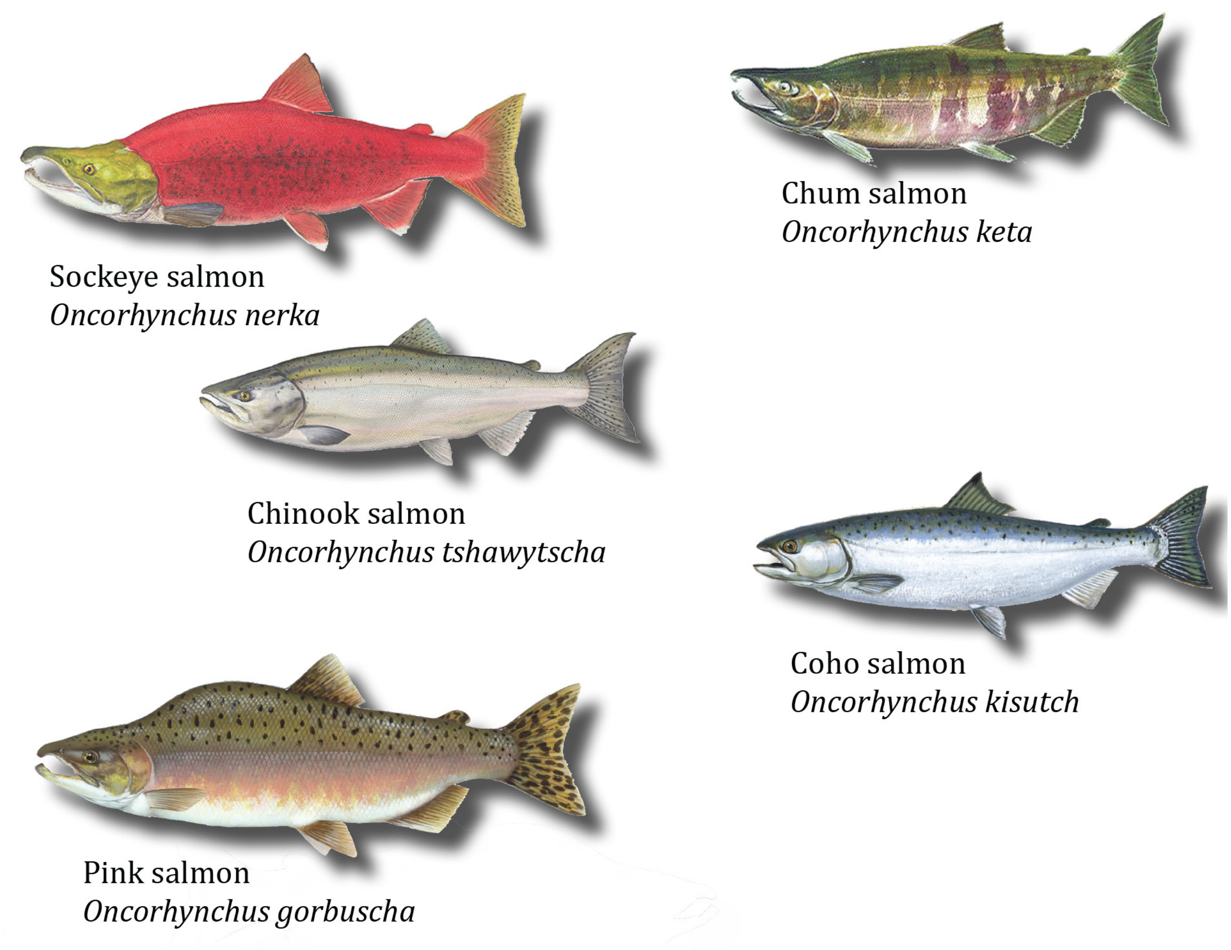
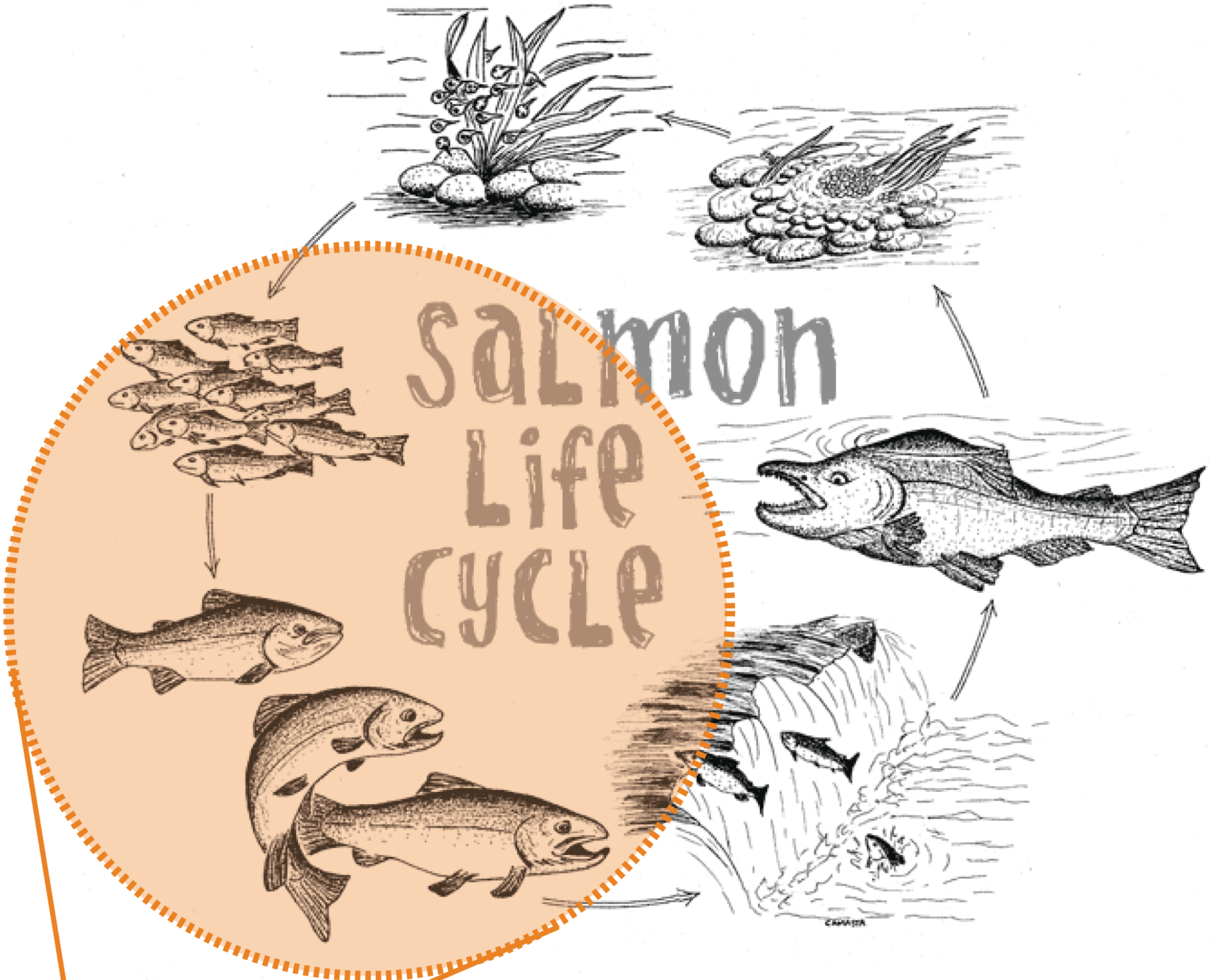


Figure 18: Types of Alaska Salmon Fisheries
(Source: Lackey 2001)

In 2010, 42 million salmon returned to the headwaters of Bristol Bay to spawn. The use of cyanide and other equally toxic chemical agents employed to facilitate metal and ore separation could change the water quality and damage the aquatic habitat within Bristol Bay. Toxins of these types in even minute quantities are lethal to juvenile salmon (Figure 19). Parker et al. reflect that copper, a mineral of the pebble deposit, has "lethal and sub-lethal effects on the aquatic food chain" (Parker et al. 2008). Copper causes impairment of brain function in salmon; changes in enzyme activity, blood chemistry, and metabolism; leads to difficulties in respiration; and impairs of their olfactory sense (Parker et al. 2008). Impairment of the olfactory sense has devastating effects on the sensitive species, enabling their ability to cope with copper concentrations in the water (Parker et al. 2008). The presence of dissolved metals and other toxic contaminants pose a significant risk to the health of Pacific salmon and other aquatic populations. Additionally, groundwater withdrawals will have such a large effect on surface waters, large reaches of aquatic habitat within headwater streams risk being lost.



Impacts of Cyanide & Copper on Fisheries

Both cyanide and copper have devastating impacts on juvenille salmon, both lethal and sub-lethal. Researched effects include impairment of brain function, changes in enzyme activity, blood chemistry, and metabolism, difficulties in breathing, and impairment of their olfactory, augmenting their ability to return to their spawning grounds. With an inability to find their spawning grounds, the genetic strain of wild salmon and their populations may be lost.

Figure 19: Salmon Life Cycle
(Source: "Exploring Salmon")

7. How is mining harmful, and what will happen once mining operations cease?

The proposed Pebble Mine presents elevated potential for acid mine drainage, due to the high sulfide content in the local rock. By mining large amounts of ore with a high metallic sulfide content to obtain copper, gold, and molybdenum deposits, sulfide ore is exposed to air and water, causing sulfuric acid. Sulfuric acid has the ability to dissolve metals present in the host rock, which are toxic to aquatic species (Parker et al. 2008). Other natural rock elements that could be exposed in the development of this mine include aluminum, antimony, arsenic, barium, cadmium, chromium, cobalt, iron, lead, manganese, mercury, molybdenum, nickel, selenium, silver, thallium, zinc, sulfides, and natural radioactive constituents (uranium, thorium, potassium-40) ("Pebble Mine: Water Related Impacts" n.d.).

Once mining operations cease and the mine is abandoned (estimated after approximately 50 years of mining), the dewatering system will stop operating and the cone of depression created from pumping large amounts of groundwater away from the mine will return to some resemblance of its former state (Figure 23). This change will cause groundwater to permeate the project area, and the open-pit mine will fill up with groundwater to form what is known as a pit lake. The geochemistry of the exposed mining benches will then be exposed to the groundwater, allowing toxic substances to permeate groundwater and surface water, migrating toward local rivers, and contributing to the regional decline of water quality (Moran 2007).

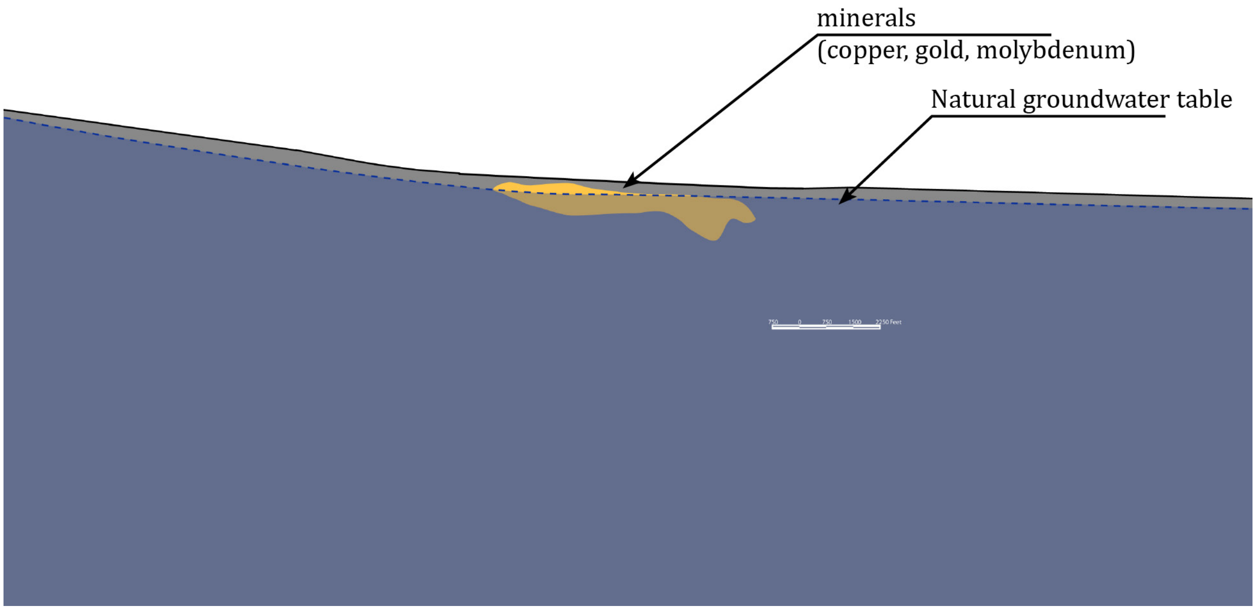


Figure 20: Pre-mining section
(Source: Fiona Cundy 2011)

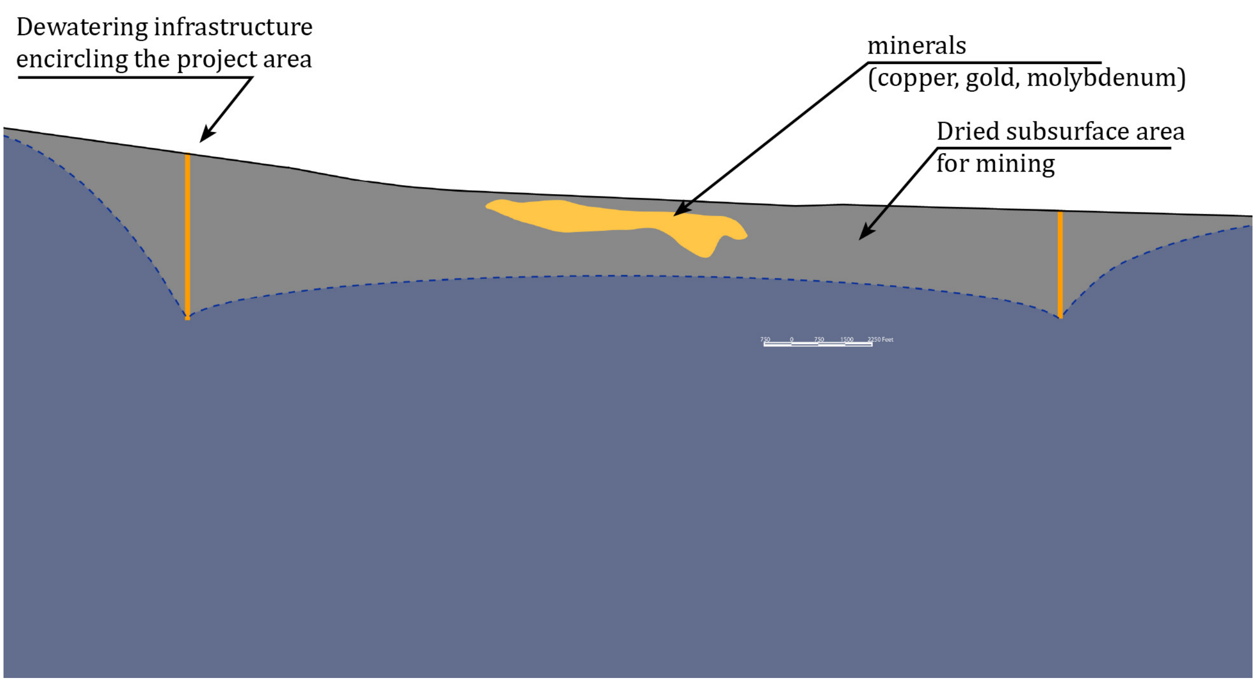


Figure 21: Dewatering Section
(Source: Fiona Cundy 2011)

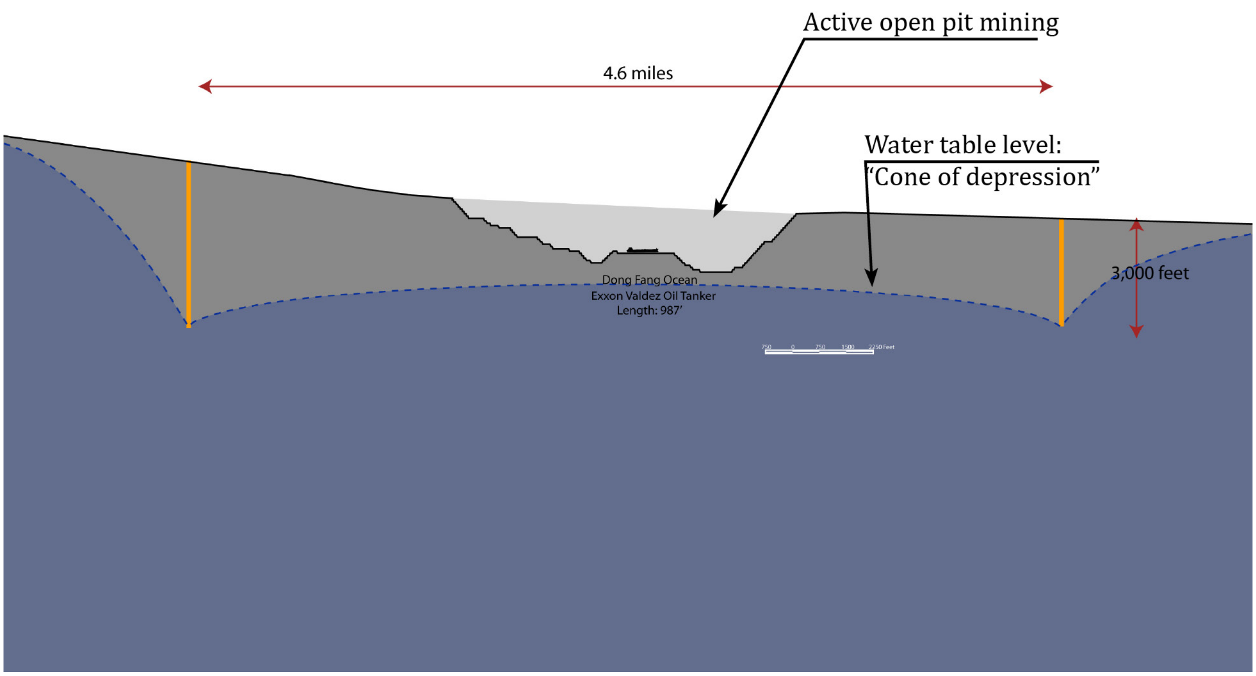


Figure 22: During mining section
(Source: Fiona Cundy 2011)

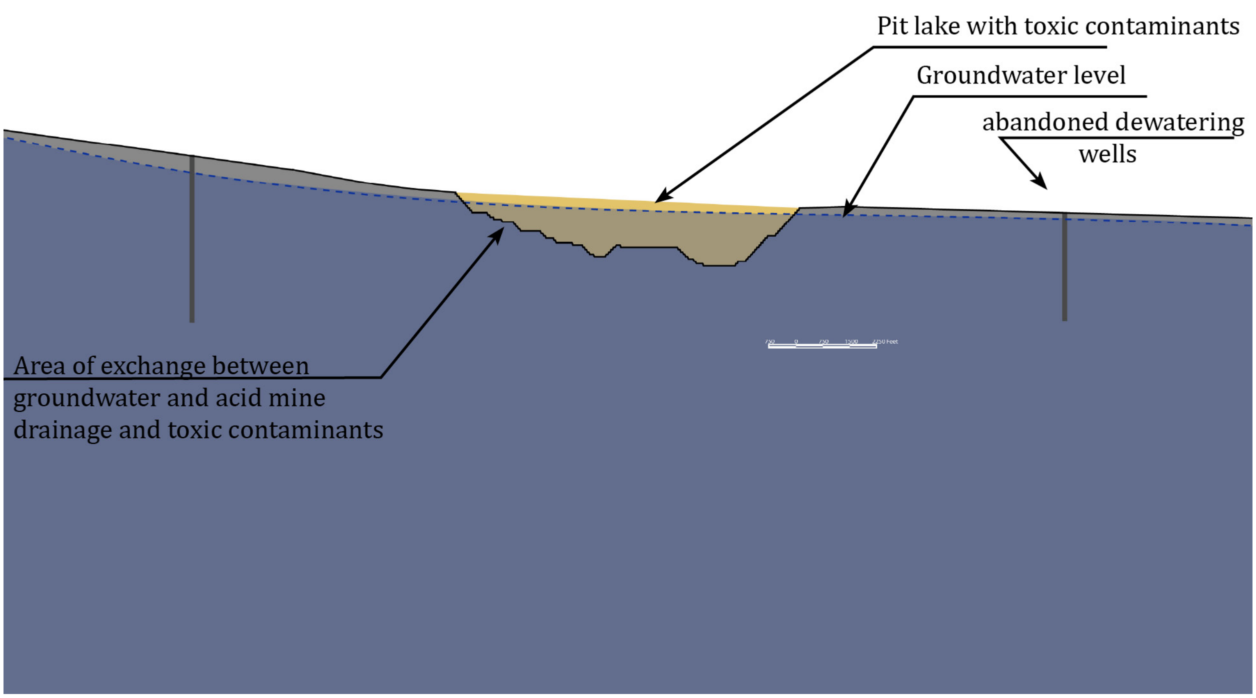


Figure 23: Post-mining pit lake section
(Source: Fiona Cundy 2011)

Results and Discussion

Salmonid Habitat

There is a clear and obvious relationship between the health of a watershed and the health of salmonid populations. Fortunately, surveying and documenting all existing conditions of the local waterbodies has become a priority among a handful of scientists in recent years. The scientific research and literature of Carol Ann Woody, William Hauser (2007), and Geoffrey Parker (2008) has been particularly beneficial in understanding the effects of mining on the environment and local species, and in advancing federal protections. Their documentation of pre-mining small scale streams and waterbodies in the headwaters of this watershed will help provide a justification of the importance of water quality and water quantity in determining the permitting and regulations of this mine, should it be allowed to advance by the State of Alaska. Additionally, their work has helped protect fourth and fifth order streams that would otherwise have little to no legal protection.

In April 2011, fisheries research scientist Carol Ann Woody compiled stream data from 2008-2010, which indicated salmon presence in three of every four headwater streams of less than 10 percent gradient, draining to an anadromous river. Her surveys included many streams on top of the Pebble prospect. Her data also documented rearing salmon above dry stream reaches and in waters disconnected from rivers, suggesting salmon access through either annual floods or through subsurface groundwater channels (Bauman 2011). Woody's data will be used by adding these waterbodies to Alaska's *Catalog of Waters Important for the Spawning, Rearing, or Migration of Anadromous Fishes.* When these waterways are included in the states catalog, nobody may use, divert, obstruct, pollute or change the natural flow of that waterbody without a permit from the Alaska Department of Fish and Game. The inclusion of these streams in the catalog will help to defend salmon and areas of documented salmon habitat in the decision of Pebble Mine's permitting process.

Water Quality and Quantity

It is obvious that the hydrologic impacts of Pebble Mine would be many. Hard rock mining is incredibly taxing on the local landscape and regional environment, and would require such significant amounts of water from the local watersheds, that headwater streams face dry out. The research of this hydrologic regime also reflects the permeable nature of the local landscape and geology. Groundwater and surface water and inherently related and face large consequences with the scale and demands of the Pebble Mine.

Conclusion

While this term project attempts to answer some of the larger questions related to the impacts of the proposed Pebble Mine on the hydrologic regime and aquatic species, there are still many more questions that have yet to be answered. Unanswered questions are due largely to the lack of data at this time. While the Pebble Partnership is required to collect baseline studies of the local regime, a more thorough and unbiased set of data collected over a much larger period of time, would provide a more comprehensive body of scientific data.

This research most accurately identifies the lack of importance placed on small headwater streams in the decision-making process. Currently, the importance placed on small streams is relatively little to none. However, the work of scientists reflect that such small waterbodies have a significant role as salmon producing habitats, particularly in Alaska. Small waterbodies provide the grounds for the production of millions of salmon. A lack of information on the use of ephemeral aquatic habitats and groundwater as potential avenues of aquatic passage leave the role of the ecosystem above the mineral deposits of Bristol Bay undervalued (Bauman 2011).

To conclude this research, there is an obvious need for more research and data, particularly before mine permitting advances. The current risk for widespread habitat degradation and loss is huge, as is the risk toxic contamination and water withdrawals could have on the ecosystem. A greater understanding of the permafrost distribution, groundwater gradients and movements, and hyporheic zone connections is needed (Hancock 2002). Meanwhile, a greater consideration for the mining activities and toxic contaminant storage is needed to fully understand the implications Pebble Mine would have on the regional watershed and the larger migratory resource of Pacific salmon as well.

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