Groundwater as Essential Salmon Habitat In Nushagak and Kvichak River Headwaters:

Issues Relative to Mining

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Abstract

Groundwater-fed streams and rivers are among the most important fish habitats in Alaska because groundwater determines extent and volume of ice-free winter habitat. Sockeye, Chinook, and chum salmon preferentially spawn in upwelling groundwater, whereas coho prefer downwelling groundwater regions. Groundwater protects fish embryos from freezing during winter incubation and, after hatching, ice-free groundwater allows salmon to move both down and laterally into the hyporheic zone to absorb yolk sacs. Groundwater provides overwintering juvenile fish, such as rearing coho and Chinook salmon, refuge from ice and predators. Groundwater represents a valuable resource that influences salmon spawning behavior, incubation success, extent of overwintering habitat, and biodiversity, all of which can influence salmon sustainability.

Recently, over 2,000 km^2 of mine claims were staked in headwaters of the Nushagak and Kvichak river watersheds, which produce about 40% of all Bristol Bay sockeye salmon (1956-2010). The Pebble prospect, a 10.8 billion ton, low grade, potentially acid generating, copper deposit is located on the watershed divide of these rivers and represents mine claims closest to permitting. To assess groundwater prevalence and its relationship to salmon resources on mine claims, rivers within claims were surveyed for open ice-free water, 11 March 2011; open water was assumed indicative of groundwater upwelling. Upwelling was georeferenced, photodocumented, and mapped in GIS. Georeferenced salmon data from the Alaska Department of Fish and Game was mapped and the relationship between salmon spawning and groundwater examined. Over 282 linear km of open or partially open water was documented on state mine leases during the March 2011 survey. Geo-referenced salmon spawning habitats were generally coincident with or downstream from upwelling reaches with some notable exceptions. One 15 km stretch of open water in the North Fork Koktuli indicates groundwater upwelling and potential high quality spawning habitat, however, spawning salmon presence data are lacking. It is unclear if this is due to limited survey data or low habitat quality and studies are ongoing.

Upwelling groundwater was ubiquitous throughout mine claims and coarse alluvium from past glaciations facilitates groundwater transfer both within and among watersheds. Previous research indicates mines with high potential for acid mine drainage and located near ground and surface waters—-such as Pebble prospect— pose a high risk of water contamination. Combined with the low buffering capacity of area waters and the fact Pebble is a copper mine, it is likely that development of the Pebble prospect will both reduce water quantity and contaminate waters feeding salmon habitat.

Rationale

The Bristol Bay ecosystem (Figure 1) supports 5 species of Pacific salmon, which sustain major commercial, subsistence and sport fisheries. The world's largest sockeye salmon runs, comprising about 51% of world commercial harvest, originate here (Pinsky et al. 2009, Ruggerone et al. 2010). Commercial harvests during 1990-2010 averaged 25.8 million sockeye, 64,000 Chinook, 1.3 million chum, 88,000 coho and 182,000 (even year) pink salmon (Salomone et al. 2011). During the same period, Bristol Bay subsistence fishers harvested an average of about 140,000 salmon, preserving most for winter following thousands of years of tradition (Salomone et al. 2011). Sport fishers to Southcentral Alaska, which includes Bristol Bay, annually spend over $989 million and support over 11,500 thousand jobs (ADFG 2009).

Since 1956, the Nushagak and Kvichak river watersheds (Figure 1) have produced about 40% of all Bristol Bay sockeye salmon (ADFG 2011a). Proposed industrial hard rock mining on over 2000 km^2 in headwaters of these watersheds poses significant risks to groundwater (Teaf et al. 2006) and species, such as salmon, that rely on groundwater-fed habitats for survival. Obtaining a precise and accurate understanding of pre-mining ground and surface water interactions, quantity and quality is critical to obtain because mining typically impacts these parameters, and can therefore pose a risk to salmon and their food chains (Smith et al. 1987, Notenboom et al. 1994, Fetter 2001).

This report :

- Provides a brief overview of groundwater ecology in glacially influenced watersheds such as those documented in headwaters of the Nushagak and Kvichak river watersheds.
- Documents salmon-groundwater links in Nushagak and Kvichak river headwaters.
- Summarizes potential risks to groundwater quantity and quality posed by industrialized hard rock mining in Nushagak and Kvichak headwaters.

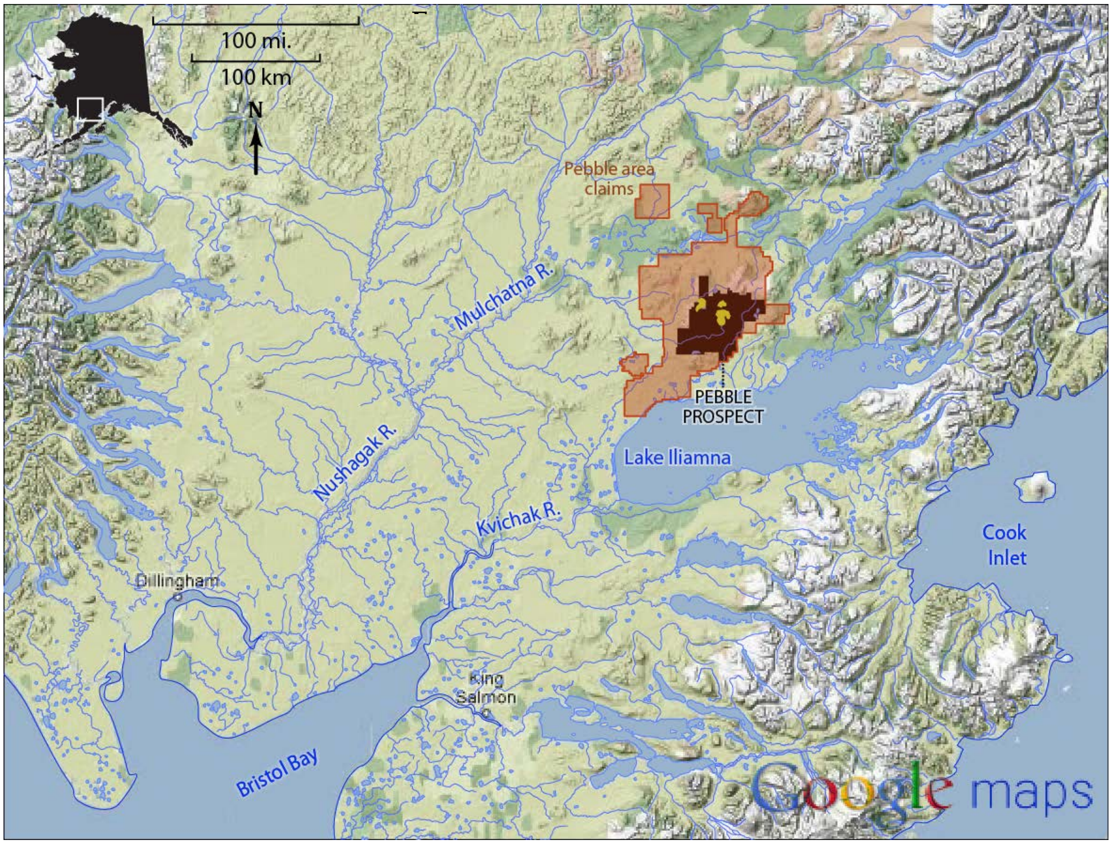


Figure 1. Map of Bristol Bay, Alaska, depicting Nushagak and Kvichak watersheds, state mine leases (red) and Pebble prospect claims (black).

Ground and Surface Water: A Single Resource

At least four glacial advances left their imprint on Bristol Bay in the form of coarse, porous, layers of alluvial sediments, which can both store and transmit large volumes of groundwater (Figure 2; Detterman and Reed 1973, Stilwell and Kaufman 1998, Power et al. 1999). In Bristol Bay, groundwater aquifers are typically recharged during annual spring and fall flood events (Figure 3). When dry conditions prevail in summer and winter, stream water levels drop below the water table and stored groundwater contribution to surface stream flow increases. Groundwater can comprise most or all water feeding surface streams and rivers during low flow periods, especially in Alaskan alluvial systems (Winter et al. 1998, Reynolds 1997, Power et al. 1999). Baseflow conditions exist when dry or freezing conditions persist and groundwater provides all flow to surface streams.

Baseflow is a major determinant in the fate of aquatic organisms. Only streams with adequate baseflow can sustain fish and aquatic communities during prolonged droughts and freezing. The amount of baseflow a stream receives is closely linked to hydraulic conductivity within a watershed. Valleys with extensive alluvial sediments, such as headwaters of the Nushagak and Kvichak rivers, store large volumes of water. Because sediments are permeable, they discharge and recharge with seasonal cycles (Figure 3) and this supports aquatic communities, including salmon, through drought and freezing (Malcolm et al. 2004, Gilbert et al. 1990). Hydrologic exchange patterns between ground and surface waters in alluvial systems can be highly complex and difficult to map and predict. For example, research at the Pebble Prospect (Figures 1 and 2) shows sediment layers with high permeability throughout substrata and the transmission of groundwater between watersheds via permeable substrata (Florio 2007, Smith and McCreadie 2008).

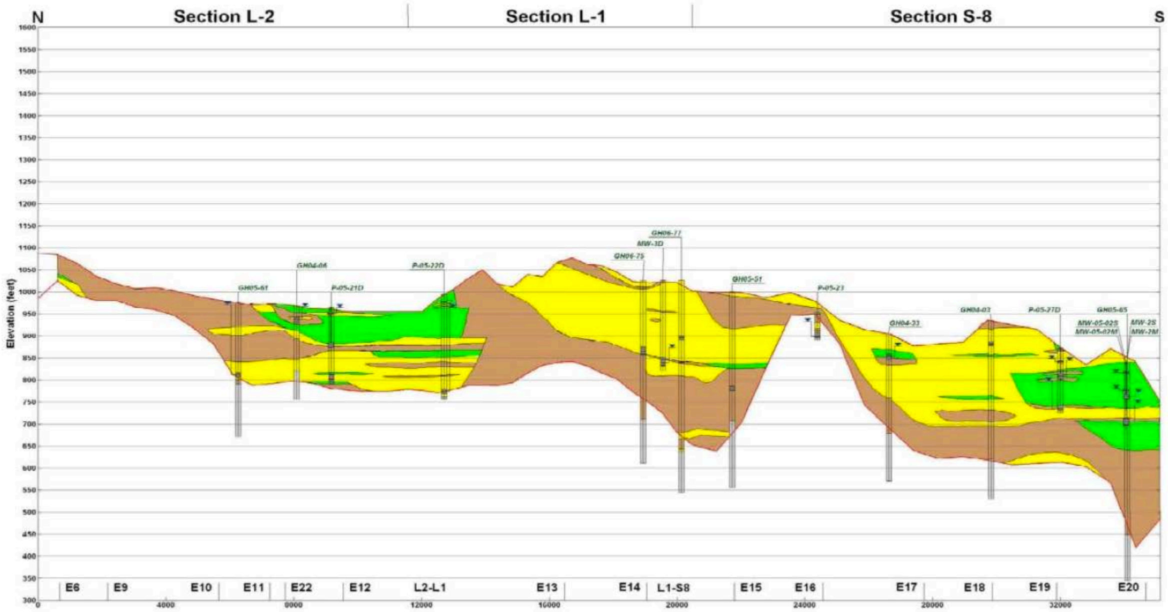


Figure 2. Hydrogeologic cross section from the Pebble prospect mine lease illustrates complexity of subsurface sediment layers, which influence groundwater flow paths. Colors represent different sediment layers with: brown = sand or silty sand; green = clay or silty clay, and yellow = gravel and gravelly sand. Graphic from Smith and McCreadie (2008).

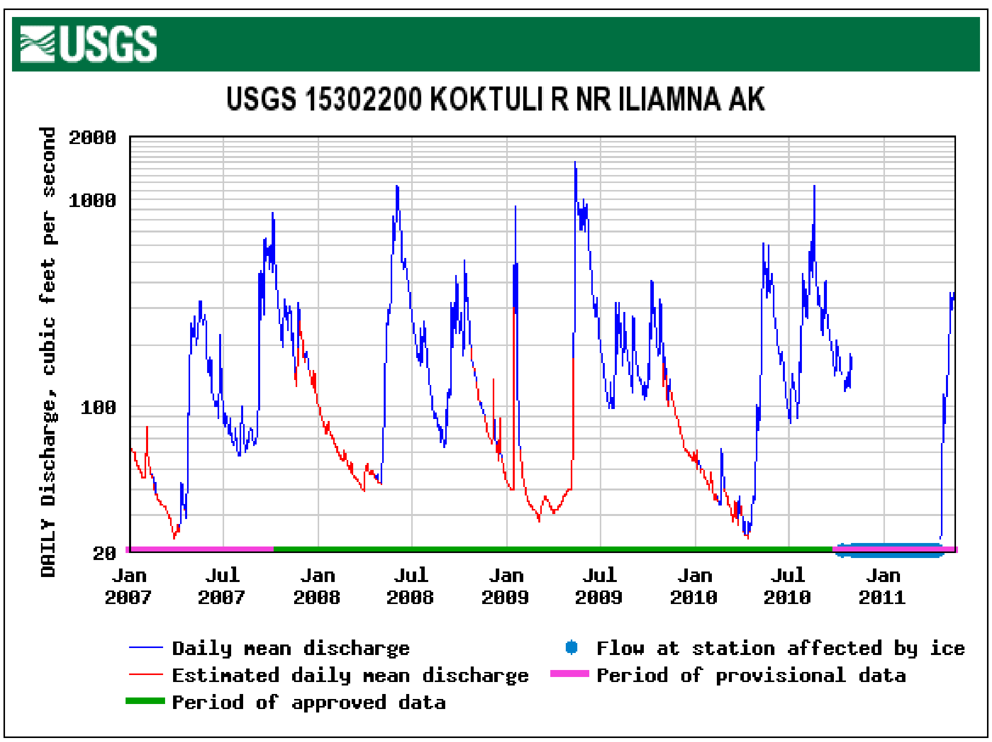


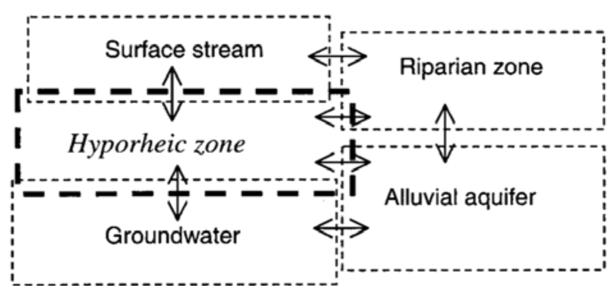
Figure 3. Typical annual flow patterns for the South Fork Koktuli River, Nushagak River system during 2007 to 2010. Graph depicts mean daily discharge. Note low flow periods during summer and winter where baseflow or groundwater contribution is greater than 20 cfs. Data from USGS National Water Information System at http://waterdata.usgs.gov/nwis.

The Hyporehic Zone

The interaction between surface and groundwater strongly influences biodiversity, structure and function of aquatic communities (Gilbert et al. 1990). Ground and surface water mix below the riverbed in the hyporheic zone, a region of active exchange of life, nutrients, ions, oxygen, and heat (Figure 4; Dahm et al. 1996, Acuña and Tockner 2008). The hyporheic zone provides habitat to diverse aquatic communities including fish eggs and juvenile fish, insects, fungi and bacteria (Stanford and Gaufin 1974, Ward et al. 1998, Hester and Gooseff *in press*) and it influences watershed ecosystem processes including nutrient cycling, pollutant buffering and thermal regimes (Acuña and Tockner 2008, Mulholland and Webster 2010, Hester and Gooseff *in press*). In alluvial systems the hyporheic zone extent has been documented over 10 meters down below the streambed (Marmonier et al. 1992, Stanford and Ward 1988) and laterally away from the stream up to three kilometers (Stanford and Gaufin 1974, Stanford and Ward 1988, Ward et al. 1998).

Within state mineral leases in the Nushagak and Kvichak watersheds of Bristol Bay (Figure 1), the hyporheic zone is appears extensive due to permeable alluvial substrates that facilitate surface and groundwater exchange pathways (personal observation by authors). The interconnected nature of surface and groundwater in this region supports fish and the food web they rely on and allows movement of invertebrates and fish among aquatic habitats. For example, salmon were documented in spring-fed pools with no visible outlet to an anadromous river in the Koktuli River watershed; salmon may have migrated there underground through larger alluvial substrates in the hyporheic zone, or perhaps arrived during a flood event (Woody and O'Neal 2010). Burbot were also documented in spring-fed pools in August 2009, with an obvious, but temporarily dry connection to the Stuyahok River (Woody and O'Neal 2010). The presence of healthy fish in these groundwater-fed regions indicates not all fish in ponds and habitats without an obvious outlet to a stream are stranded and suffer mortality. Some fish may survive and thrive, and move among habitats via the hyporheic zone or during high water.

Figure 4. Schematic diagram showing hyporheic linkages among surface stream, groundwater, alluvial aquifers and the riparian or streamside systems (after Boulton 2000)



Groundwater as Essential Salmon Habitat

Groundwater-fed streams and rivers are among the most important freshwater fish habitats in Alaska because groundwater determines the volume and extent of ice-free winter habitats in flowing waters (Reynolds 1997, Power et al. 1999, Bellino 2009). In Bristol Bay below freezing conditions can extend over 5 months (Iliamna Airport 2011) with groundwater playing a key role in overwinter survival of salmon and the aquatic communities upon which they depend.

Aquatic species have evolved specialized adaptations to exploit groundwater resources and salmon exhibit a variety of such behaviors. Sockeye, Chinook, and chum salmon preferentially spawn in upwelling groundwater (Lorenz and Eiler 1989, Leman 1993, Geist and Dauble 1998, MacLean 2001), whereas coho prefer downwelling surface to groundwater regions (Mull 2005). Groundwater protects developing fish embryos from freezing during winter incubation (Curry et al. 1995, Reynolds 1997, Power et al. 1999, Brown et al. 1994) and, after hatching, ice-free groundwater allows salmon to move both down and laterally into the hyporheic zone to absorb yolk sacs, after which they emerge from substrates to become free-swimming fry (Godin 1982).

Groundwater provides overwintering juvenile fish, such as rearing coho and Chinook salmon, refuge from ice in tributaries (Swales et al. 1986, Bradford et al. 2001). Brown et al. (1994) found trout overwintering in frozen streams with just 8 cm of ice-free groundwater near stream substrates. Roussel et al. (2004) found fish avoided freezing conditions by staying under anchor ice formation where microtemperatures were warmer than in nearby areas. Winter researchers have observed young salmonids burrowing into stream substrates or hiding under ice formations, effectively hiding them from predators (Cunjack 1996, Cunjack 1998, Power 1999, Bradford et al. 2001, Hillman et al. 1992, Huusko et al. 2007). In light of extended harsh Alaskan winters, groundwater represents a valuable fisheries resource that influences salmon spawning behavior, incubation success, and availability of overwintering habitat, all of which can influence salmon survival (Reynolds 1997, Power et al. 1999, Huusko et al. 2007).

Groundwater Influences Salmon Biodiversity

High salmon biodiversity has been linked to long-term Bristol Bay salmon productivity and sustainability (Hilborn et al. 2003, Schindler et al. 2010). Within Bristol Bay, hundreds of small unique spawning populations adapted to natal sites within each watershed create a diverse “salmon stock portfolio” (Hilborn et al. 2003, Ramstad et al. 2004, Ramstad et al. 2010, Schindler et al. 2010). Similar to a diverse asset “stock portfolio”, high biodiversity ameliorates extreme salmon production fluctuations that would occur if biodiversity were reduced (Schindler et al. 2010). Reductions in biodiversity can lead to increased fishery closures and threaten long-term sustainability of fisheries (Schindler et al. 2010).

Groundwater influences salmon biodiversity. Sockeye salmon that bury embryos in colder incubation regimes spawn earlier than sockeye salmon that bury embryos in warmer incubation regimes, and since early and late spawning populations do not interbreed, genetic differences can evolve (Brannon 1987, Sheridan 1962, Woody 1998, Hendry et al. 2007). Spawn time differences among breeding populations has resulted in evolution of genetically distinct populations (Tallman 1986, Woody et al. 2000, Hendry et al. 2007), and salmon spawning in groundwater-influenced areas represent a unique evolutionary component that contributes to overall salmon biodiversity.

Salmon and Groundwater in Nushagak and Kvichak Headwaters

Salmon Presence in Nushagak and Kvichak Headwaters

Rivers and lakes in Bristol Bay produce prolific salmon runs due, in part, to diverse abundant salmon spawning and rearing habitat fed by groundwater. While salmon abundance data for the hundreds of tributaries feeding the Nushagak or Kvichak is limited, salmon presence has been documented in 3 of every 4 headwaters of less than 10% gradient on state mining leases, excluding the Chulitna drainage (Woody and O'Neal 2010). Data indicate tributaries draining state mineral leases provide essential spawning, incubation, rearing and migration habitat to sockeye, Chinook, coho and chum salmon (ADFG 2011b), and to subsistence fish species which have been documented in 96% of area streams (Woody and O'Neal 2010).

Limited spawning abundance data (Table 1) on mine leases (Figure 1) indicate hundreds of thousands of salmon can spawn there. Because these species preferentially spawn in groundwater-influenced habitats, and because juvenile coho and Chinook overwinter in flowing waters, their persistence in these systems underscores the importance of groundwater in this region.

Table 1. Upper range of estimated escapement during 2004 to 2007 for three rivers draining state mining leases, Bristol Bay, Alaska. All data from HDR (2006) except the sockeye salmon estimate denoted by the asterisk from McLarnon (2007).

River	Sockeye	Chinook	Coho	Chum
North Fork Koktuli	9,200	12,500	4,900	4,000
South Fork Koktuli	14,800	13,900	8,100	4,800
Upper Talarik Creek	120,000*	320	35,500	0
Total	144,000	26,720	48,500	8,800

Groundwater:Salmon Links in Nushagak and Kvichak Headwaters

To document groundwater upwelling on state mine leases, streams were surveyed for evidence of open ice-free water on 11 March 2011 (methods detailed Appendix I). Average temperatures during March 2011 ranged from a high of 0.2^{o}C to -11.4^{o}C and averaged -5.9^{o}C (Iliamna Airport 2011) and open water was assumed indicative of groundwater. Over 282 linear km (175 miles) of open or partially open water was documented during the March 2011 survey (see detail Figure 5) in both rivers and smaller headwater streams. These observations agree with previous studies that documented spring-fed high gradient tributaries (Woody and O'Neal 2010) and over 4,500 upwelling springs in this region (Smith and McCreadie 2008). Upwelling groundwater is ubiquitous in state mine leases based on the March 2011 survey and unpublished reports by Pebble Limited Partnership (Florio 2007, Cathcart 2008, Smith and McCreadie 2008).

Geo-referenced salmon spawning habitats (ADFG 2011b) were generally coincident with or downstream from open and partially open waters, with some notable exceptions (Figure 5). The approximately 15 km open water reach in North Fork Koktuli indicates groundwater presence and potential spawning habitat, however, spawning salmon presence data is lacking (Figure 5). Because spawning and habitat surveys are limited for Bristol Bay headwaters, it is unclear if the lack of known spawning salmon simply reflects limited survey effort or if habitat is actually unsuitable for spawning. Although spawning salmon have not been documented in all upwelling regions, rearing salmon are documented throughout the watershed and may use these regions for overwintering. Further studies would provide data to verify or negate salmon presence in these regions.

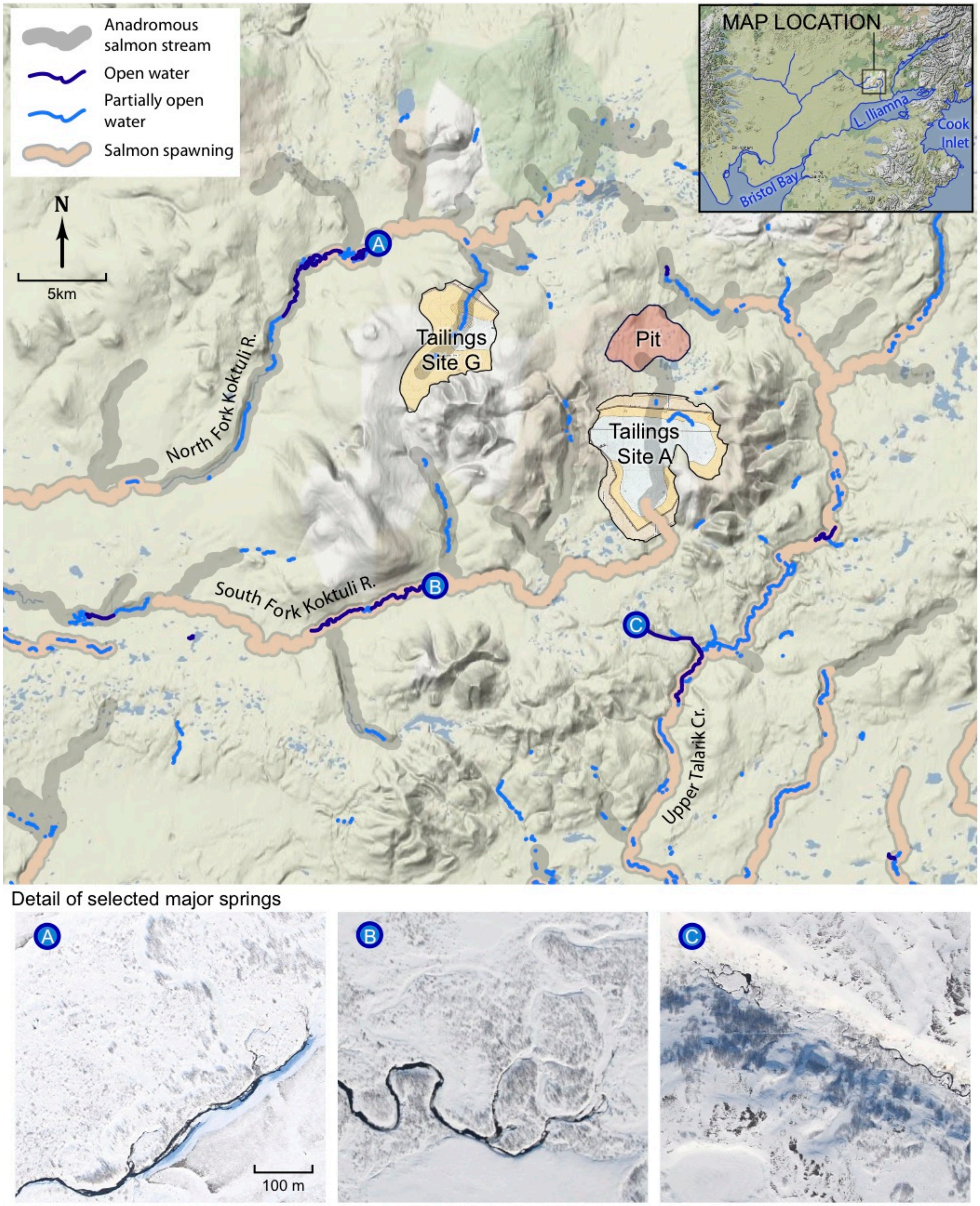


Figure 5. Map of open water survey results for 11 March 2011 including documented salmon distributions for the North and South Fork Koktuli rivers (Nushagak) and Upper Talarik Creek (Kvichak). Pebble prospect ore body and tailings plans (DNR 2011) included for reference.

The area depicted in photograph "C" (Figure 5) highlights the interconnectedness of drainages. This photo illustrates where about 25 cfs of groundwater migrates from the South Fork Koktuli through permeable sediments into a stream feeding a salmon spawning area in Upper Talarik Creek (Smith and McCreadie 2008, ADFG 2011b).

Our results appear to agree with unreleased results from other studies in the region documenting the ubiquity of upwelling groundwater and that open or partially open water in winter is indicative of upwelling groundwater presence (Florio 2007, Cathcart 2008, Smith and McCreadie 2008).

Mining and Potential Risks to Groundwater Quantity and Quality

Mining generally impacts natural water systems and effects can occur throughout the mine life cycle from exploration to after mine closure (Ripley et al. 1996). While in some cases mine water can be used for beneficial purposes (Banks et al. 1996), adverse impacts such as dewatering of streams, and aquifers (Siegal 1997, Fetter 2001) and water contamination can occur and persist for decades to millennia (Errington and Ferguson 1987, Davis et al. 2000, Woody et al. 2010). Mining induced changes in water flow patterns and chemistry can disrupt hydrologic exchange pathways and directly contaminate ground and surface waters (Mestrov and Lattinger-Penko 1981, Hancock 2002, Kasahara et al. 2009). Contaminants related to mining can include heavy metal influxes, chemical pollution, increased acidity or alkalinity, and increased suspended sediment, all of which can adversely affect aquatic communities (Melard et al. 1994, Hancock 2002, Woody et al. 2010).

Water Quantity Issues and Mining

Dewatering is a technique used to access open pit and underground mine excavations. Depending on the scale of the operation, dewatered areas can range from hundreds of meters to many square kilometers (Younger 2002). As a mine is excavated, concurrent pumping of groundwater prevents flooding of the excavation and allows access to the ore; the pumping creates a "cone of depression" in the natural water table (Figure 6; Strobel 2011). The cone of depression can significantly lower the water table below natural stream or lake levels, can cause land subsidence or sinking (Bai 1994) and can reduce water flows into streams, the hyporheic zone, riparian areas and wetlands (Scott et al. 1999, Hancock 2002).

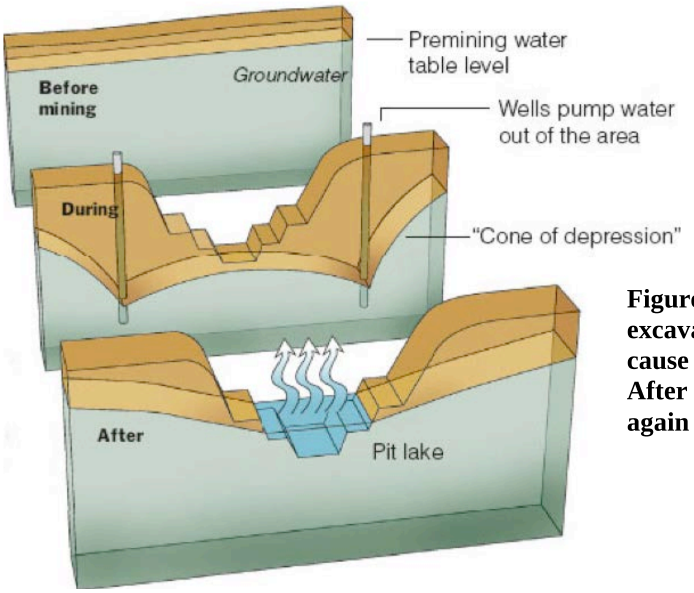


Figure 6. Illustration of how pumping water from an excavation as occurs during mining during mining can cause a cone of depression in the surrounding water table. After mining ceases, pumping stops and the excavation fills again but remains lower due to evaporation.

One prospect in Bristol Bay (Pebble Prospect) submitted water use permit applications in 2006 (DNR 2011) for about 144 cfs annually (about 34 billion gallons per year). Hydrographs for tributaries draining Pebble indicate winter baseflows can be as low as 124 cfs (USGS 2011). If the mine requires 144 cfs for operations throughout the year, there will be increased reliance on groundwater to support operations during winter since surface waters will be frozen. Use of 144 cfs of groundwater could significantly reduce groundwater flows into salmon incubation habitats, fish overwintering habitats, and the hyporheic zone, which supports invertebrates upon which overwintering salmon feed. It is currently difficult to assess impacts of such mine water withdrawals on natural groundwater flow patterns to salmon habitat and the watershed ecosystem since no details are publically available as to how water will be used, treated, and returned to the watershed nor have hydrologic data, water balance models, drill logs, or other necessary data been released to the public.

Water Quality Issues and Mining

Documented surficial geology (Detterman and Reed 1973, Stilwell and Kaufman 1998), subsurface stratigraphy (Figure 2; Smith and McCreadie 2008), and interconnections between ground and surface water in mine lease areas (Smith and McCreadie 2008) suggest multiple pathways through which water contamination can occur should mining proceed. The Pebble prospect is a 10.78 billion ton low-grade porphyry copper deposit (Cooke et al. 2005) with a high waste to ore ratio and relatively high potential for acid mine drainage (NDM 2005, Day 2006). If acid drainage develops, then metals in the ore such as copper, zinc, arsenic, cadmium and lead can be mobilized into water (Wireman 2001). These metals can be toxic to aquatic life as well as terrestrial species (Eisler 2000). Due to its low alkalinity and low dissolved organic carbon concentrations, waters of this region have limited ability to ameliorate toxic effects of increased metal concentrations from mining (Craven et al. *In Review*). Copper is one of the most abundant metals in Pebble and is also one of the most toxic elements to aquatic life, including salmon (Hall et al. 1988, Eisler 2000, Baldwin et al. 2003, Hansen et al. 1999, Tierney et al. 2010).

Copper (Cu) is a documented neurotoxin in fish (Thompson and Hara 1977, see reviews by Sorenson 1991, Eisler 2000 and Tierney et al. 2010), which can impair olfaction in salmon and other fish at concentrations in the part per billion (ppb). For example, Sandahl et al. (2007) demonstrated that coho salmon exposure to just 2 ppb of Cu for 3 hours significantly impaired olfactory detection of predator alarm cues and caused a 50% decline in normal predator avoidance response; an impaired ability to detect and avoid predators can be lethal. Salmon olfactory receptors also receive and trigger critical physiological and/or behavioral responses in fish (Tierney 2010), such as sperm production, predator recognition and avoidance (Brown and Smith 1997, Hirovan et al. 2000), food location (Hara 2006) kin recognition (Quinn and Busack 1986), recognition of conspecifics (Brown and Smith 1997, Hirovan et al. 2000), migration (Groot et al. 1986), homing (Hasler and Schlotz 1983) and reproduction (Moore and Waring 1996, Waring et al. 1996). Impairment of salmon olfaction from increased copper concentrations due to industrial copper mining in this area is a significant risk and has potential to adversely affect salmon productivity, biodiversity and long-term sustainability.

Multiple pathways for potential groundwater contamination from proposed open pit mining exist at Pebble, and prevention will be a significant challenge. For example, large springs (photograph "A" Figure 5) along southeast side-channels of the North Fork Koktuli River show an area that could be impacted by the proposed Pebble project. Tailings Site 'G' is partly bounded by a large hill that is uphill of and presumably the source of these springs. The spring is evidence that the hill is both porous and permeable. If a tailings facility were built here, any leakage on its northwestern edge would enter the groundwater and emerge from these springs. During winter months when these springs are likely the major portion of stream water, such contamination would be particularly concentrated and could impact salmon. Another region of concern is proposed tailings storage facility ‘A’ (Figure 5). Highly permeable soils have been documented in this area and it is proximate to the region of interbasin groundwater exchange that upwells into documented salmon spawning habitat (photograph ”C” Figure 5). If contaminants leached from this tailings facility into groundwater, they could move from the Nushagak watershed to the Kvichak watershed into documented spawning habitat and then down to Iliamna Lake (Figure 1) where millions to billions of sockeye fry rear one to two years prior to seaward migration (Burgner, 1991).

Recent studies (Kuipers et al. 2006) indicate that development of mines with high potential for acid mine drainage or contaminant leaching and near ground and surface water resources pose a high risk of exceeding water quality standards, despite predictions to the contrary.

Conclusion

Due to significant interaction between ground and surface water in the Pebble prospect, the size and type of the Pebble ore body, the relatively high potential for acid mine drainage, and reliance of salmon on groundwater resources, mining of this prospect has potential to significantly impact salmon productivity, biodiversity, and sustainability through loss of habitat and water contamination.

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APPENDIX I. Methods for Documenting Groundwater Presence on State Mine Leases

To document groundwater upwelling presence in headwaters of the Nushagak and Kvichak river drainages, we surveyed streams on state mine leases (detail Figure 5) for evidence of open ice-free water on 11 March 2011. Average temperatures during March 2011 ranged from a high of -0.2^{o}C to -11.4^{o}C and averaged -5.9^{o}C (Iliamna Airport 2011). Assuming open water in March is a strong indicator of upwelling groundwater presence, stream courses were flown, photo-documented and geo-referenced using a digital SLR equipped with an image-stabilizing 30 mm lens attached to an airplane wing. Flying at about 120 mph and 2000 m altitude, the camera was programmed to take a photo every 10 seconds or about every 536 m. Each photo was geo-referenced and oriented by interpolating between GPS track-points. Raw images were processed into jpegs, then located, rotated, scaled, and linked to a Google Earth kml file (see detail; Figure 5). Open water was categorized as open or partially open and assumed to be evidence of groundwater contribution to streams.

The presence of salmon in the region was mapped using georeferenced salmon spawning data downloaded from Alaska Department of Fish and Game databases and added to the kml file (Figure 5). Location of the Pebble prospect ore body and proposed tailings facilities were mapped for reference based on permit applications submitted in 2006 to DNR (2011).

Spawning habitat surveys are ongoing in this region and when complete this paper will be updated and published in Transactions of the American Fisheries Society.