Chapter 5

Potential Effects of the Pebble Mine on Salmon

Unlike many mine sites, the proposed Pebble project is in a largely pristine, unimpacted region. Typical spring and surface waters contain extremely low concentrations of dissolved minerals. The introduction of even small amounts of additional dissolved mineral contaminants into the Pebble waters can produce significant changes in the water chemistry, more significant than would be expected in waters that have higher dissolved mineral content.

All salmon species require suitable freshwater habitats during their life cycles (Meehan 1991, Groot and Margolis 2001). Due to the narrow habitat requirements of salmon, any activities that directly or indirectly alter water quality, water quantity, physical habitat structure, food supply, flow regime, or fish passage can alter fishery productivity (Meehan 1991, Spence et al. 1996). Historically, as a result of metal mining, even very small increases in contaminants, sediment, and turbidity and decreases in stream-flow and pH have resulted in dramatic decreases in salmon and their macroinvertebrate prey (Hughes 1985, Clements et al. 2000, Maret and MacCoy 2002, Maret et al. 2003). Large increases in these parameters have completely eliminated salmon from the affected habitats (Hughes 1985). Although salmon are resilient, it takes many generations and several human lifetimes for adaptation to occur in response to fundamental ecosystem changes, if they can occur at all.

The single greatest threat to salmon and salmon habitat in the Nushagak and Kvichak River drainages from the proposed Pebble Mine is from acid mine drainage (AMD). Acid mine drainage impacts water quality in two critical ways. First, it lowers pH (increases acidity), and second, it increases the presence of dissolved metals, potentially to toxic levels. In addition to AMD and its effects on water quality, the cumulative effects of habitat loss, altered flows, increased sedimentation, turbidity, and increased water temperature resulting from mining also threaten salmon populations.

Although AMD is the primary threat, Pebble waters may become toxic to salmon and other aquatic life even without the development of AMD. Given the chemical "fragility" of these waters, relatively small increases in the concentrations of several metals/metalloids and other contaminants, (e.g., arsenic, antimony, copper, selenium, zinc, and ammonia) could negatively impact salmon populations. The extremely low Aquatic Life Water Quality Criteria promulgated by both the EPA and the State of Alaska lend support to this statement (ADEC 2003).

> *Surface water becoming groundwater becoming surface water again is one of the features of the country north of Iliamna Lake—and it's why sockeye favor this body of water. Springs replenish the gravel-bottomed shores of the lake's islands with highly oxygenated water, which salmon eggs need to mature. Any accidental acid mine drainage into this intricately connected natural system could be disastrous.*
>
> —"Alaska's Choice: Salmon or Gold" (Dobb 2010)

5.1 Acid Mine Drainage and Changes in pH

As described in chapter 3, the Pebble Mine presents a high risk of developing AMD because the deposit is composed primarily of metal-sulfide ores (USEPA 1994a, NDM Ltd. 2007). The AMD from a mine's pit, tunnels, waste rock/ore piles, and tailings storage facilities is the primary source of mining-related pH changes in ground and surface waters (USEPA 1994a).

Numerous chemical reactions release ionized hydrogen, H+, into the environment. Elevated concentrations of free H+ ions render the water *acidic*. Low concentrations of H+, together with the presence of other compounds, especially carbonate constituents (CO_2-HCO_3-CO_3) in fresh waters, produce waters referred to as alkaline (basic). Variations in the hydrogen ion content (activity) of waters (and soils) are measured using the pH scale, which reports the negative logarithm of the hydrogen ion concentration (Hem 1985, Mazor 1991).

The pH scale for most solutions is from 0 to 14.0, but it can extend both higher and lower. Waters with a pH of 7.0 are considered to be neutral, those with a pH below 7.0 are considered to be acidic, and those with a pH greater than 7.0 are considered to be basic (alkaline). A solution at pH 6.0 contains 10 times more hydrogen ions than at pH 7.0 (Lewis and Bamforth 2007). Thus, pH 4.0 waters are ten times more acidic than those at pH 5.0, and 100 times (10 times 10) more acidic than those at pH 6.0. The pH of a waterbody is important because too much acidity or alkalinity will reduce or eliminate fish and other aquatic life from the water body.

Effects of pH on Salmon

AMD-induced changes in the pH of surface waters are dependent on several factors, including the flow

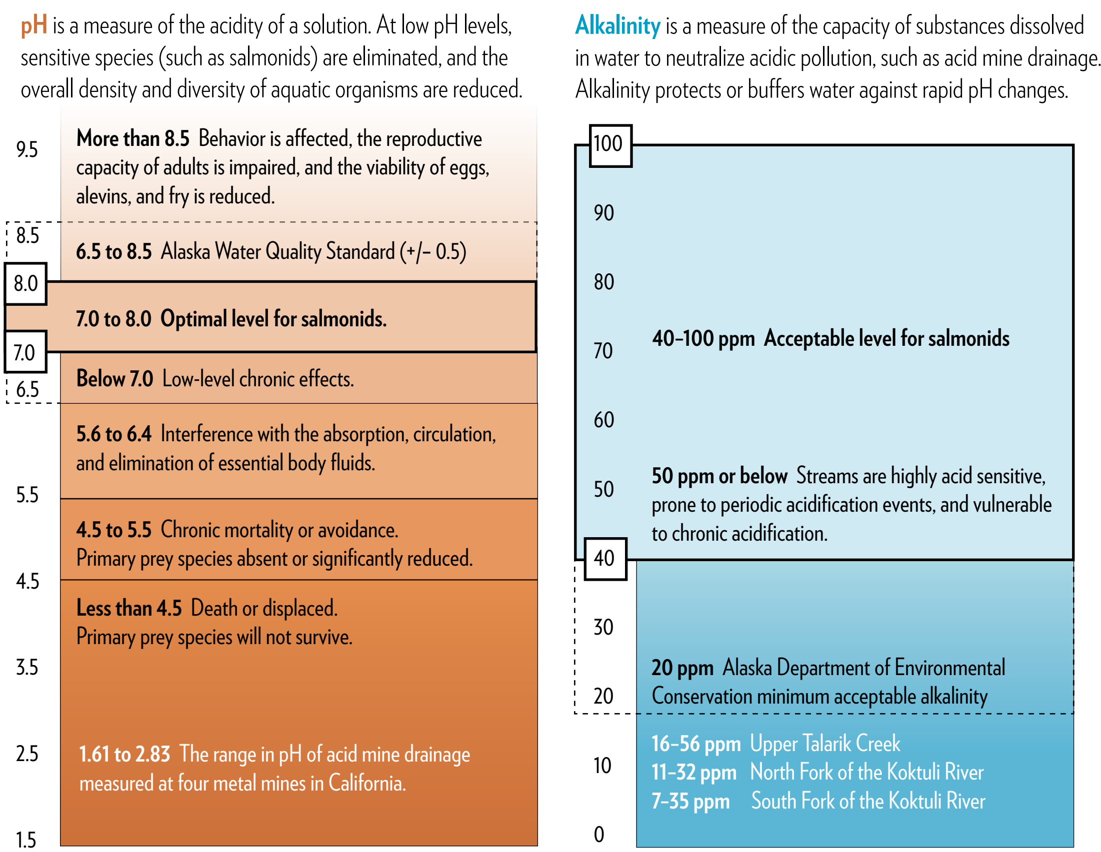
Acid mine drainage from dumping high-sulfide material, Formosa Copper Mine (photo by Umpqua Watersheds Inc., Frances Eatherington).

rate, the amount of dilution, and the alkalinity of the receiving waters (USEPA 1994a, Earle and Callaghan 1998). At low pH, sensitive species such as salmon may be completely eliminated, while less sensitive species such as northern pike and sticklebacks may proliferate (Meehan 1991). At higher pH (5.5–6.5), fish behavior is affected, the reproductive capacity of adults is impaired, and the viability of eggs, alevins, and fry is reduced.

Salmon populations are adversely impacted by both acute and chronic exposure to low pH. For salmon and many other aquatic organisms, pH levels of 7.0 to 8.0 are considered optimal to maintain a productive ecosystem (Figure 17). Low pH harms fish because it causes an imbalance of the sodium and chloride ions in the blood (Morris et al, 1989). If pH falls below the tolerance range even for a short period, death can occur due to respiratory or osmoregulatory failure (Kimmel 1983). Acid water also increases the permeability of fish gills to water, adversely affecting gill function. Ionic imbalance in fish may begin at a pH of 5.5 or higher, depending on species tolerance (Potts and McWilliams 1989). The author of a study of the physiological reactions of rainbow trout (*Oncorhynchus, mykiss*) to low pH and varied calcium ion concentrations concluded that the extinction of fish populations in waters acidified by AMD or acid rain usually occurs through reproductive (recruitment) failure (Nelson 1982). Low pH caused decreased cardiac rate, ossification, slower growth, less pigmentation, delayed hatching, and increased mortality.

Acidification affects fish assemblages in a number of ways and is dependent on several biotic and abiotic

Figure 17. The effects of pH and alkalinity on aquatic life (Mills 1985, Rosseland 1986, DeWalle et al. 1987, Eshleman 1988, Schindler 1988, Kaufmann et al. 1991, Meehan 1991, Wurts 1993, ADEC 2003, NDM, Inc. 2005, ADEC 2006, HDR Alaska and CH2M Hill 2008, Zamzow 2011).



CASE STUDY: ACID MINE DRAINAGE

- Numerous violations of permit, including dumping of high-sulfide material into mine tunnels, leading to acid mine drainage
- Developer abandoned site after failed attempts at reclamation; EPA declared it a Superfund site
- 18 miles of fish habitat destroyed
- Significant decline of macroinvertebrates (up to 98%)

Formosa Copper Mine (Oregon)

The Formosa copper mine is located in the Siskiyou Mountains in southwestern Oregon. The site was initially mined between 1926 and 1937. Formosa Exploration Inc. (FEI, a partnership of Canadian and Japanese companies) reopened the mine in 1990. Between 1990 and 1993, FEI mined 350 to 400 tons per day of copper and zinc. The copper concentrate was sent to Japan. Because zinc prices were low at the time, the ore was stored on-site and remains there today (Throop 1995). The mine covers the headwaters of Middle Creek which drains into Cow Creek, the water source for the town of Riddle, Oregon.

Failures:

- Inadequate inspections and monitoring by state agencies from 1990 to 1993.
- In 1993, Oregon's Department of Geology and Mineral Industries (DOGAMI) issued a Notice of Violation to FEI for numerous violations of permit conditions, such as illegal dumping of waste rock and storage of acid-producing pyrite. By August 1993, DOGAMI issued a Closure Notice for failing to correct the problems within the 30-day compliance period (USEPA 2009a).
- Dumping of high-sulfide material back into the mine tunnels. The underground workings are reported to contain large quantities of highly reactive acid-generating rock and tailings (ODHS 2010).
- Incomplete reclamation between 1994 and 1996, costing about **$1 million**.
- Failure of the drainage system throughout the 1990s and 2000s to present.

Impact:

- At least **5 million gallons of acid mine drainage**, heavy with toxic metals, were leaked into the creeks annually, through both ground and surface waters (USEPA 2007a). Acid rock drainage formed in the network of underground workings and flowed out of the lower mine adits (shafts) and into the headwaters of Middle Creek (Throop 1994).
- Water draining from the mine to Middle Creek had high concentrations of cadmium, copper, and zinc; concentrations of heavy metals fluctuate as groundwater levels rise or fall seasonally (USEPA 2009a). Mine drainage was stained bright orange with iron or blue-green with copper deposits.
- **Eighteen miles of fish habitat** downstream from the mine has been destroyed. The Middle Creek watersheds were historically productive fisheries for salmonids, including coho salmon and steelhead. Upper Middle Creek and South Fork Middle Creek have not supported spawning runs since the mine reopened in 1990; heavy metal pollution and poor flow characteristics now limit the use of these important spawning grounds (USEPA 2009a, ODHS 2010).
- A Bureau of Land Management/Oregon Department of Environmental Quality survey in 1999 found a correlation between increasing concentrations of zinc in the surface water and the decline of macroinvertebrate (aquatic insect) abundance in the Middle Creek watershed. Comparisons of 1999 data with data from pre-mining surveys found that at two sites the total density and numbers of sensitive **macroinvertebrate species were reduced by 96% and 98%**. Data from Cow Creek downstream from the Cow Creek and Middle Creek confluence also indicates that macroinvertebrate communities have experienced stress at lower elevations due to the releases of heavy metals (USEPA 2009a).

Mitigation: The mining company FEI, state agencies, and the Bureau of Land Management cooperated in major reclamation activities in 1994, removing tailings dumps and backfilling the material into the underground mine tunnels. Twenty tons of tailings were also removed from Middle Creek (USEPA 2009a). FEI filled in the former tailings pond with the ore and waste rock and capped it with a bentonite/geotextile composite and drainage layer. The mine owners sealed the portals with limestone rock and concrete and installed drains, although the drains soon failed (ODHS 2010).

After FEI abandoned the site, the state of Oregon did not have enough money to reclaim the mine site and could only repair the most critical failures. In the 2000s, pipelines draining the mine were repeatedly found to be crushed, plugged, or severed, sending mine drainage directly into Middle Creek. Sumps and water-collection systems overflowed. A limestone channel built to reduce the acidity of the mine drainage became encrusted with iron scale and ceased to function (USEPA 2009a). In 2007, the EPA placed the Formosa Mine Superfund Site on the National Priorities List. Plans for removal of the most reactive tailings dumped in the underground tunnels are hampered by limited knowledge of the extent of the tunnel network.

Cost: The bond money originally requested in the 1990 operating permit was inadequate for restoration at the site after closure. The reclamation bond administered by DOGAMI was eventually increased from $500,000 to $980,000 (Throop 1995), but **the bond was inadequate to pay the cost of cleanup, perpetual treatment, and monitoring**. Taxpayer funding of the reclamation costs began in 1996 when FEI abandoned the mine and it became an orphan site. An estimate of the Superfund cleanup costs to remove underground tailings and to construct an acid drainage collection and treatment system is not possible until the local hydrology is better understood and a more thorough mapping of the underground tunnel complex is completed.

factors. The most important biotic factors are fish species, development stages, and spawning strategy (Rosseland 1986). While recruitment failure has been identified as the primary source of population decline, the life stage that is most affected differs from one population to another, even within the same species. Eggs and alevins are believed to be the most sensitive life stages, but significant mortality has occurred in post-spawning adults (Rosseland 1986). Salmon are particularly vulnerable to low pH during the physiological changes that occur during salmon smolts' transitions from freshwater to salt water and adult spawners' transitions from salt water to freshwater.

Stress, gill damage, ionic imbalance, and other effects of low pH can act in concert with other harmful agents such as metals and diseases to increase mortality in salmon populations. Acid water often increases the toxicity of other pollutants (such as metals) to fish that are already under stress from low pH conditions. At low pH levels (<5.0), metals contained in waste rock or suspended sediments may be released, adding other toxic pollutants to the aquatic system (Sorenson et al. 1971). Rainbow trout under low pH conditions acquired heavy infections of the gill parasite, *Trychophyra intermedia,* which was not related to mechanical gill damage (Balm et al. 1996). This suggests that the parasite may have a primary effect on gill function under acid conditions.

In addition to physiological responses to acid water, salmon also exhibit behavioral changes that impact reproductive success. Japanese scientists who studied the effects of acidification on salmon found that a pH of 5.8 completely inhibited the migratory homing behavior of landlocked sockeye salmon (*Oncorhynchus nerka*), and slight acidification (around pH 6.0) inhibited their spawning behavior (Ikuta et al. 2001). Sub-lethal acid stress at pH 5.0 and lower stimulated avoidance of acidic areas or induced failure of endocrine-related immune and reproductive functions. Ikuta et al. (2003) studied the upstream migratory behavior and redd-digging behavior of mature sockeye salmon, brown trout, and Japanese char (*Salvelinus leucomaenis*) in response to low pH. Digging and upstream behavior were significantly inhibited in weakly acidic water (pH 5.8-6.4). Of the three species, sockeye salmon were the most sensitive to changes in pH.

Although acidification affects fish assemblages differently, salmon exhibit predictable responses to pH values at certain thresholds and within general ranges. According to Trasky (2008), the following responses can be expected:

- pH less than 4.5: All salmon and other fish species will die or be displaced from a water body. Primary prey species will not survive.
- pH 4.5 to 5.5: Salmon will be severely distressed from ionic imbalance or toxic synergistic effects with metals or disease and will likely be absent because of chronic mortality or avoidance. Primary prey species will be absent or present in low numbers. Acid-tolerant species, such as northern pike and sticklebacks, may be present.
- pH 5.6 to 6.4: Salmon may be present, though dissolved metals are present. Salmon will be under stress resulting from interference with the absorption, circulation, and elimination of essential body fluids. These pH levels inhibit homing and spawning behavior in sockeye salmon. A pH of 6.0 is toxic to juvenile Chinook and chum salmon if dissolved metals are present. Sensitive macroinvertebrate prey species will begin to decline as pH drops below 7.0.
- pH 6.5 to 8.5: Salmon can persist. However, low-level chronic effects on salmon and habitat may begin to occur as pH levels decline below 7.0.

While acidification has significant effects on salmon, waters with higher pH also have predictable effects. High pH can kill adult fish and invertebrate life directly and can damage developing juvenile fish. When the pH of freshwater becomes highly alkaline, the effects on fish may include death; damage to outer surfaces like gills, eyes and skin; and an inability to dispose of metabolic wastes. High pH may also increase the toxicity of other substances. For example, the toxicity of ammonia is ten times more severe at pH 8.6 than at pH 7.0 (Lenntech 2011).

Effects of pH on Salmon Habitat

Water bodies with low pH are poor salmon habitat. Acid waters have fewer invertebrate species and lower abundance and biodiversity than near neutral waters (Earle and Callagan 1998). As pH levels rise in waters with AMD, the precipitation of iron, aluminum, and other metals can coat substrate and smother aquatic life (Martin and Platts 1981). Hoehn and Sizemore (1977) studied a Virginia stream in which AMD had eliminated all benthic macro-invertebrates over a six mile reach below the point of discharge. The natural low alkalinity of the stream (>25 mg/l) was reduced to less than 5mg/l (the role of alkalinity is discussed later), and the pH was reduced from 7.2 to 6.3. Increased concentration of iron from less than 0.01 mg/l to more than 4.0 mg/l was accompanied by the deposition of a coating of iron hydroxide on the stream bed, a phenomenon most likely responsible for the absence of macroinvertebrates. In a study of 34 stream sites differing in pH and invertebrate species richness, Hildrew et al. (1984) found that the pool of locally available, suitably adapted species was smaller in acid streams. Diversity of feeding categories

CASE STUDY: ACID MINE DRAINAGE

Mount Washington Copper Mine (British Columbia)

A small open pit copper mine operated on Mount Washington, on Vancouver Island, from 1964 to 1967 prior to going bankrupt after only four years of operation. The site was abandoned, leaving an open scar on the hillside above the Comox Valley and the Tsolum River.

In the past, the Tsolum River supported large populations of steelhead and resident rainbow trout, sea-run cutthroat trout, and coho, pink, and (to a lesser extent) chum salmon (BCME 2011).

Failures:

- The abandoned mine site generated toxic copper leachate (acid mine drainage) through the 1980s.

Impact:

- By 1993, Tsolum River was barely able to support any fish or other aquatic life; 18 miles of fish habitat were destroyed.
- In 2000, the Department of Fisheries and Oceans (DFO) declared the Tsolum River dead.
- Tsolum River did not meet water quality standards.

Acid mine drainage from the Mount Washington copper mine is considered the primary reason fisheries have declined in the basin. There are other potential contributing factors, including the reduction of summer low flows by irrigation withdrawals, over-fishing, logging, and gravel extraction. However, the neighboring Puntledge River which has experienced these same disturbances with no mine present, has continued to support strong salmon and trout populations (BCME 2011). In late spring and fall, when snowmelt and heavy rains add volume to the Tsolum River, lethal copper leaching increases.

Mitigation: In 1987, federal and provincial agencies funded studies monitoring and on-site projects to address the problem. Mediation work began in 1988. Partial covers, segregated drainage, and other steps were taken to reduce the volume of toxic concentrations of copper entering and impacting the Tsolum River ecosystem. A partial cap was placed over a consolidated pile of volatile rock, at a cost of $1.5 million, but was declared a failure. Though work completed over this period was successful in reducing the levels of copper in the water, fish populations continued to decline and water quality did not significantly improve.

In 1999, the Outdoor Recreation Council declared the Tsolum River the most threatened river in British Columbia. A 2000 report published by SRK Consultants on remediation options for the Mount Washington mine recommended that to achieve full remediation, the site itself would require an engineered cover to provide source control. Partners agreed that it was the right solution, but the estimate of $6 to 10 million was beyond their resources.

It was determined that with the limited funds available, low flows, habitat restoration, stock enhancement, community awareness, and protection of the watershed would be the focus, while lobbying for source control continued.

- Developer went bankrupt after only four years of operation
- Department of Fisheries and Oceans (DFO) declared the Tsolum River dead
- Salmonid stocks in the Tsolum River had all but become extinct; 18 miles of fish habitat destroyed
- $1.5 million spent to date on failed cap; true cost not yet known

Above: Mount Washington Copper Mine (Google Earth).

In 2003, a partnership committee was formed between industry, government and the public with a goal to seek long-term solutions to address copper leaching impacts from the abandoned open pit mine site. In 2006, a grant allowed the Tsolum River partners to undertake an engineering study to select and design a viable remediation plan to address decades of acid rock drainage impacting the Tsolum River ecosystem. In 2007, detailed cost and site-specific designs for the remediation work were produced.

Costs:

- $1.5 million for the failed partial cap.
- $50,000 for engineering study to design remediation
- Estimated $6 to 10 million to implement remediation.

increased with species richness, indicating that a greater range of food resources was available in the less acid, more species-rich communities.

The current Alaska water quality standard requires a pH between 6.5 and 8.5, which may not vary by more than 0.5 pH units from natural conditions (ADEC 2006). This standard may not adequately protect salmon. If a stream with a background pH of 6.5 were allowed to decline by 0.5 pH units to 6.0, it would be acidic enough to inhibit salmon homing, spawning, and osmoregulation. Prey species may be present in low numbers or absent.

Alkalinity in the Pebble Mine Area

Alkalinity is a measure of the capacity of substances (usually bicarbonate and carbonate) dissolved in water to neutralize acidic pollution such as AMD. The measurement is important because high-alkalinity protects or buffers water against rapid pH changes that are harmful to fish and other aquatic life. When acid is introduced, the pH levels in low-alkalinity streams can drop to a point that eliminates fish and acid-intolerant forms of aquatic life. Conversely, high-alkalinity streams can offset the effects of introduced acid water. Moon and Lucostic (1979) reported that a mitigating alkaline discharge downstream from a mine releasing AMD kept stream pH between 5.8 and 7.0 for 18 months. It should be noted that although pH was maintained above lethal levels, the benthic macroinvertebrate assemblage was smothered by ferric hydroxide, which precipitated out with the increase in alkalinity. This illustrates how AMD can impact salmon habitat even when acidity is ameliorated by the input or presence of alkaline water.

An acceptable alkalinity level for salmon culture is in the 40 to 100 ppm range (Wurts 1993). The Alaska Department of Environmental Conservation (ADEC) states that alkalinity should be at least 20 ppm calcium carbonate equivalent (ADEC 2003). This may be minimally adequate to maintain aquatic life and function under normal conditions; however, 20 ppm is insufficient to protect a water body from detrimental pH changes if it receives AMD.

Typical spring and surface waters in the Pebble Mine area contain extremely low concentrations of dissolved minerals, as is demonstrated by the very low field specific conductance measurements reported by both Northern Dynasty (NDM Inc. 2005) and the U.S. Geological Survey (Eppinger et al. 2009). The median specific conductance measurement for these waters reported by the USGS was 48 microS/cm, which would convert to a total dissolved solids concentration of approximately 30 to 35 mg/L, indicating that these are extremely dilute waters. The Northern Dynasty (NDM Inc. 2005) data showed that minor and trace constituent concentrations were consistently low or nondetectable in these waters and that pHs were typically near neutral, unless in contact with exposed ores. Northern Dynasty recorded alkalinity concentrations in the Pebble Mine study area ranging from 11 to 32 ppm for the North Fork of the Koktuli River; 7 to 35 ppm for the South Fork of the Koktuli River; and 16 to 56 ppm for Upper Talarik Creek (NDM Inc. 2005, HDR Alaska and CH2M-Hill 2008).

Testing water quality of an inlet to Frying Pan Lake. Although dissolved copper would likely be the most significant metal contaminant produced from the Pebble Mine, many other heavy metals and elements are present, including antimony, arsenic, cadmium, chromium, lead, mercury, nickel, selenium, and zinc. The introduction of even small amounts of additional dissolved mineral contaminants into the Pebble waters can produce significant changes in the water chemistry, more significant than would be expected in waters that have higher dissolved mineral content (photo by Wild Salmon Center).

Although the pH range reported for sampled Pebble Project area streams falls within the acceptable range for salmon established under Alaska state water quality standards, these data indicate that the acid-neutralizing capacity of Pebble area streams is limited. Streams with alkalinities of less than 50 ppm are considered highly acid sensitive, prone to periodic acidification events, and vulnerable to chronic acidification (DeWalle et al. 1987, Eshleman 1988, Schindler 1988, Kaufmann et al. 1991).

5.2 Acid Mine Drainage and Copper Toxicity

Copper (Cu) is essential to the growth and metabolism of fish and other aquatic life, but it can cause irreversible harm at levels slightly higher than those required for growth and reproduction (Eisler 2000). As a result, copper is a serious pollutant in the aquatic environment, and its toxicity to a variety of species has been well studied (Sorenson 1991, Eisler 2000). Elevated levels of dissolved copper have acute toxic effects on all life stages of salmonids. As detailed in Trasky (2008), acute toxic effects of dissolved copper on adult and juvenile salmon occur from 17 to 54 ug/l, and adverse sub-lethal effects of dissolved copper on salmonid metabolism, growth, reproduction, migration, prey location, and avoidance of toxic situations occur at concentrations between 0.7 and 23 ug/l. Consequently, the current Alaska criteria (ADEC 2003) for exposure of aquatic life to dissolved copper (acute/one-hour exposure: 3.8 to 52 ug/l; chronic 96-hour exposure: 2.9 to 30 ug/l) may not protect salmonids from the chronic or behavioral effects of copper. Additionally, these criteria fail to consider synergistic effects between copper and other metals or other likely co-occurring stressors.

Effects of Copper on Salmon

Very low concentrations of dissolved copper (in the low parts per billion to high parts per trillion range) can have acute and chronic toxic effects on fish and their prey (Hamilton et al. 1990, Eisler 2000, USEPA 2007b, Tierney et al. 2010). In adults, acute exposure to copper causes ionoregulatory and respiratory problems. Wilson and Taylor (1992) found that exposure to 49 ppb of dissolved copper for 24 hours caused a rapid decline in blood sodium, chloride, and oxygen tension, while increasing heart rate and arterial blood pressure rate in rainbow trout, conditions that eventually led to death. Researchers in juvenile salmonids at the EPA's Corvallis Environmental Research Laboratory found that dissolved copper was acutely toxic to juvenile Chinook salmon and steelhead trout at levels of 17 to 38 ppb. Steelhead trout were more sensitive than Chinook salmon, and salmon fry and smolts were more sensitive than newly hatched alevins (Chapman 1978). They also found that copper was acutely toxic to adult male coho salmon and adult male steelhead at 46 and 57 ppb, respectively (Chapman and Stevens 1978). Table 3 highlights copper toxicity levels for salmonids and other aquatic organisms based on USEPA (2007b) data.

Giattina et al. (1982), observed that at sub-lethal concentrations of copper (6.4 ppb), rainbow trout avoided contaminated water, but as levels gradually increased, individuals were attracted to higher concentrations that are considered lethal (330–390 ppb). Pedder and Maly (1985) found that when exposed to lethal concentrations of copper (0.5 to 4.0 ppm) without the gradual increase, there was an initial attraction period and then subsequent avoidance, indicating that individual behavior subsequent to copper discharges contributed to high mortality. These results suggest that environmental impacts predicted on the basis of toxicity tests alone do not reflect potentially important behavioral changes caused by chronic and sub-chronic concentrations of copper.

Table 3. Dissolved Copper Toxicity to Salmonids and Other Aquatic Organisms. Note: 1 ug/l = 1 part per billion (ppb) assuming comparable densities; 1 ppb = approximately 1 second in 100 years (USEPA 2007b).

	COPPER TOXICITY		
Taxon	*Acute Toxicity (ug/l)*	*Behavioral Effect (ug/l)*	*Chronic Toxicity (ug/l)*
Water fleas	6	8.96	
Amphipods	9.6		
Coho adults	22.93		
Brook trout adults		60.4	
Chinook adults	25.02		6.9–23
Bull trout	25.02	19.7	
Rainbow trout adults	22.19–49	2.2–14	1.6–6.4
Sockeye adults	54.82		

According to Trasky (2008), studies revealed that when fertilized sockeye and pink salmon eggs were exposed to copper, the incipient lethal level was between 37 and 78 ppb for sockeye salmon and between 25 and 55 ppb for pink salmon during the egg-to-fry stage. Copper inhibited the softening of egg capsules, but associated mortalities during hatching occurred only at concentrations also lethal to eggs and alevins. Copper was concentrated by eggs, alevins, and fry in proportion to exposure concentrations. Several studies found that dissolved copper levels toxic to salmon fry, smolts, and adults were lower than levels toxic to developing eggs (Trasky 2008).

Exposure to sublethal levels of copper increases the susceptibility of salmon to disease and infections. According to Baker et al. (1983), exposure to sublethal levels of copper increased the susceptibility of Chinook salmon and rainbow trout to *Vibrio anguillarum* infections. *Vibrio* is a serious and often fatal disease of fish. At exposure levels of 9% (parts per trillion range) of copper LC50 (i.e., the dose that will kill one-half of the population) for 96 hours, vibriosis mortality was greater in fish exposed to copper than in those exposed to just *Vibrio*. Likewise, rainbow trout stressed by copper required 50% fewer pathogens to induce a fatal infection than did non-exposed fish (Baker et al. 1983). Similar results were observed by Hetrick et al. (1979), who found that the exposure of rainbow trout to sublethal levels of copper in water increased their susceptibility to the infectious hematopoietic necrosis (IHN) virus. In most instances, the percent mortality was twice as great in the copper-stressed groups compared with those groups that were not stressed but received the same virus dose.

Juvenile salmon appear to be the most sensitive to the effects of dissolved copper, most likely due to physiological changes related to growth and smolting (Hecht et al. 2007). In a study of juvenile coho, individuals exposed to sublethal levels of aqueous copper (one-quarter and one-half of the LC50 dose over four days) ceased growing or showed decreased rates of growth (Buckley et al. 1982). National Marine Fisheries Service researchers found that a three-hour exposure to <10 mg/l dissolved copper reduced or eliminated juvenile coho salmon's neurophysical and behavioral responses to an alarm pheromone (Baldwin et al. 2003). Similarly, a 20 mg/l concentration of dissolved copper inhibited coho salmon olfaction by 80% (McIntyre et al. 2008).

In addition to physiological impacts, exposure to sublethal levels of copper and other heavy metals may also cause serious damage to the life processes of salmonids (Baatrup 1991). As described in Trasky (2008), fish depend on an intact nervous system, including their sensory organs, to locate food, recognize predators, migrate, communicate, and orientate. The nervous system is very vulnerable to damage from metallic pollutants, and injury may drastically alter the behavior and subsequently the survival of fish. Metals' affinity for a number of ligands and macromolecules in the nervous system makes them potent neurotoxins, which affect the integrity of the fish nervous system structurally, physiologically, and biochemically. The interaction of copper and other metals with chemical stimuli in the nervous system may interfere with communication between the fish and the environment.

Synergistic Effects

Dissolved copper may be the most significant metal contaminant produced by the Pebble Mine. However, water samples from the Pebble Mine area indicate the presence of many of the other metals and chemical constituents on the EPA's list of priority pollutants, including antimony, arsenic, cadmium, chromium, lead, mercury, nickel, selenium, and zinc. While these other metals are also toxic to salmon and other aquatic life at very low concentrations (Eisler 2000), copper also produces negative synergistic effects with them. The cumulative effects of interactions between and among metals and water quality variables such as temperature, alkalinity, and acidity are important because many variables concurrently influence fish growth and survival (Molony 2001). For example, copper becomes more toxic to salmon as pH and alkalinity decrease (Waiwood and Beamish 1978, Chakoumakos et al. 1979, Lauren and McDonald 1985, Welsh et al. 2000). Because alkalinity levels in Upper Talarik Creek and Koktuli River watersheds are low, copper (and other metal/metalloid) toxicity is likely to be high.

Pebble operations are likely to release concentrations of several other non-metallic constituents known to be potentially toxic to salmon and other aquatic life. These include nitrates, ammonia, sulfate, fluoride, chloride, and process chemicals. For example, xanthates are reported to be toxic to fish and aquatic invertebrates (Alto et al. 1977, Australian Government Publishing Service 1995)

5.3 Whole Effluent Toxicity and Community Effects

Mine and mineral-processing wastes include complex combinations of inorganic and organic compounds. The constituents released from mines, waste rock, tailings, and spoil pits are essentially a chemical soup. When contaminants are released into nearby ground or surface waters, they can be toxic not only to salmonids but also to aquatic and riparian organisms, like macroinvertebrates, if present in toxic concentrations. Like the examples described earlier for copper and pH, the additive and synergistic effects of these compounds are much more complex than the effects of any one component. For example, mine effluents that enter nearby surface waters from point or diffuse sources chemically react to produce insoluble substances that settle to the river bottoms. These precipitates are predominantly composed of aluminum, iron, and manganese compounds, but also include other metals and metalloids (e.g., antimony, arsenic, cadmium, copper, lead, mercury, and zinc) that can coat substrates and smother aquatic life (Moran 1974, Martin and Platts 1981). These precipitates may be consumed by aquatic bottom-dwelling organisms, which are in turn consumed by fish, resulting in potentially toxic biological accumulations (Clements et al. 2000, Maret et al. 2003).

One can get a sense of potential chemical contaminants in waters downstream of the Pebble Mine site by examining data from other copper mines. Table 4 shows actual constituent concentrations from waters at three copper mine sites: Kennecott Utah Copper in Utah, the Globe-Miami area in Arizona, and Southern Peru Copper in Peru. All of the examples in Table 4 had unlined tailings impoundments or no tailings impoundment, and their lithologies and metals differed somewhat from one another and from those likely to be proposed for the Pebble Mine. However, all concentrations shown in Table 4 and many of those in waste effluents at other copper mines far exceed their water quality criteria and standards.

Metals in aquatic ecosystems can impair the algae food base of lake and stream-dwelling salmon. Many studies have demonstrated that phytoplankton, such

Table 4. Water Contamination. Actual constituent concentrations from waters at three copper mine sites: Kennecott Utah Copper, Utah; the Globe-Miami area, Arizona; and Southern Peru Copper, Peru. These data are included for comparative purposes and to indicate concentrations that have been released into the environment via water pathways. Their inclusion is not intended to imply that the future Pebble Mine waste waters will have these concentrations. These examples include only a few of the chemical constituents actually present in the site waters; many constituents were not determined or the data were not made public (photo by Tim Jarrett).

	Kennecott Copper (UT)[2]			Globe-Miami (AZ)[3]	Southern Copper (Peru)[4]
CONTAMINANT[1] (water quality criterion)	Groundwater (down-gradient of waste rock)	Groundwater (near tailings)	Tailings Waters	Wells	Tailings Waters
Arsenic (10)	4–200	87–281	3,100–13,000	190–2,500	5–162
Cadmium (0.1)	70–380			100–1,000	0.5–6.4
Chromium (24)			19,200–39,400		5–46
Copper (1.5)	112,000–128,000	40	227,000–456,000	18,000–150,000	5–11,300
Nickel (16)	20,000–22,200			870–3,000	5–46
Selenium (4.6)	70-170	5,000-10,000			13–33
Silver (0.32)	30				3–23
Lead (0.54)			3,400–9,800		2–243
Aluminum-D (87)				16,000–230,000	
Cobalt-D (50)				1,600–10,000	
Iron-D (300)				130,000– 2,710,000	30–144,000
Manganese-D (50)				42,000–670,000	1.0–4,120
Molybdenum (10)					279–826
Zinc-D (36)				2,900–24,000	28–1,010
Sulfate (mg/L)				7,000–9,000	231–1,930
Chloride (mg/L)				220–440	49–115
Ammonia (32–49)					2,000–9,000

1. Water quality criteria are shown in parentheses for each contaminant. Data are from either aquatic toxicity criteria from USEPA or ADEC or drinking water standards from these agencies (ADEC 2003, USEPA 2006, 2007a). Criteria are in ppb, unless otherwise noted. D = dissolved.
2. Data are from USEPA (1994b) and represent ground waters down-gradient of waste rock piles; ground waters near the tailings; and tailings waters.
3. Data are from USGS (1990) and represent ground waters contaminated by waste rock drainage and possible tailings effluents that have migrated into the local ground waters.
4. Data are from Woodward Clyde (1994) and come from tailings waters.

CASE STUDY: GROUNDWATER CONTAMINATION

Bingham Canyon Mine (Utah)

Bingham Canyon Mine (also pictured in the table above) is owned by Kennecott Utah Copper Corporation. With a pit over 0.75 miles deep, 2.5 miles wide, and covering 1,900 acres (Rio Tinto 2007) it is currently the largest mine in North America. According to Earthworks (2010), pollution from the mine has contaminated 60 square miles of groundwater near Salt Lake City, making water unusable for at least 4,300 households. Kennecott, a subsidiary of Rio Tinto, built a multi-million-dollar water-treatment facility, the largest of its kind in the United States, to treat an estimated 2.7 billion gallons of polluted water annually for at least the next 40 years. As of 2006, "Kennecott had spent $370 million on cleanup and source control, and will be required to pump and treat aquifer water for at least the next 40 years" (Earthworks 2010). The Bingham Canyon Mine contains an ore body roughly half the size of Pebble.

Right: Bingham Canyon Mine as seen from the International Space Station (Johnson Space Center).

- Contaminated 60 square miles of groundwater, making it unusable for 4,300 households, and must treat 2.7 billion gallons annually
- $370 million spent on cleanup and source control as of 2006

as diatoms, are highly sensitive to metal exposure (Hollibaugh et al. 1980, Franklin et al. 2002, Nayar et al. 2004). Copper and mercury are particularly toxic to plankton, although other metals (such as nickel, cadmium, lead, and zinc) are also known to inhibit the growth of some species (Hollibaugh et al. 1980, Thomas et al. 1980, French and Evans 1988, Enserink et al. 1991, Balczon and Pratt 1994, Dahl and Blanck 1996, Nayar et al. 2004). Metal concentrations in parts per billion released from contaminated sediments have been associated with reductions in phytoplankton production, phytoplankton abundance, and chlorophyll concentration (Nayar et al. 2004).

Zooplankton species, which are the key prey for lake-dwelling sockeye salmon juveniles, vary in their sensitivities to different metals (Enserink et al. 1991, Jak et al. 1996). For instance, EC50 (halfway between baseline and maximum response concentration) values for growth inhibition in the water flea *Daphnia magna* were demonstrated to vary from 1.3 ppb for mercury, 16.1 ppb for copper, 570 ppb for zinc, and 3,200 ppb for arsenic (Enserink et al. 1991). Other common zooplankton species were shown to be more sensitive to metals than *D. magna*, whereas copepods were less sensitive and rotifers were about as sensitive (Jak et al. 1996). Such trace metal concentrations could change zooplankton assemblage structure and reduce the salmon food supply, resulting in lower salmon production in Iliamna Lake (Walsh 1978).

Aquatic insects form the major prey base for juvenile salmon. Particular aquatic insect species respond across a broad spectrum of tolerance or intolerance to acid mine drainage and excess metal concentrations. However, many major salmonid prey species occur in the taxonomic orders *Ephemeroptera*, *Plecoptera*, and *Trichoptera* (mayflies, stoneflies, and caddisflies, respectively), which contain many sensitive aquatic insect species. A Washington Department of Ecology survey conducted in 1996 found a precipitous decline in aquatic insects above and below the Holden Copper Mine near Lake Chelan in north central Washington State (Johnson et al. 1997). (See the case study p. 29). The average density of aquatic insects reached a high of 3,130 organisms per square meter above the mine at the Glacier Peak Wilderness boundary and fell to just 50 organisms per square meter at a site on Railroad Creek just below the mine's tailings pile three miles farther downstream. Results showed a small recovery in numbers (to 361 organisms per square meter) at the mouth of Railroad Creek near its outflow at Lake Chelan, eight miles below the mine. However, only insect species tolerant of excess metals were reestablished in the eight miles of stream below the mine, and insect taxa known to be sensitive, such as those in the genera *Epeorus, Megarcys,* and *Pteronarcys* (mayflies and stoneflies), did not reappear at all.

5.4 Water Appropriations

The Pebble operations would require a tremendous volume of water. This water would be used for processing ore, slurrying as much as 10.8 billion tons of mine waste from the mill to the waste-storage facilities, and slurrying concentrate along the 86-mile pipeline from the mine to the port (Ghaffari et al. 2011). Northern Dynasty has applied for all of the ground and surface waters within the boundaries of the mine area, upgradient of the downstream limit of water extraction (Table 5). These appropriations, which were requested in water rights applications submitted in 2006, would eliminate or reduce flow in sections of Upper Talarik Creek (a tributary of the Kvichak River) and the North and South Forks of the Koktuli River (tributaries of the Mulchatna River, which feeds the Nushagak) (NDM Inc. 2006a, 2006b, 2006c). Waters would be removed via pumping, gravity, and channeling.

Maintaining stream flows is one of the most important measures in maintaining salmon habitat and populations (Trasky 2008). Loss of salmon and resident fish habitat resulting from reduced and altered stream and groundwater flows is well documented in the scientific literature and is a major cause of salmon declines in the Pacific Northwest (Heggnes et al. 1996, NRC 1996). Appropriation of all water in a stream would eliminate all fish habitat. Reductions in stream flow would reduce the amount of available stream habitat, alter critical stream temperature regimes, impact stream velocity and morphology, and lower the quality and carrying capacity of salmon habitat (Berg and Northcote 1985, Poff et al. 1997, Madej et al. 2006, Poff et al. 2010).

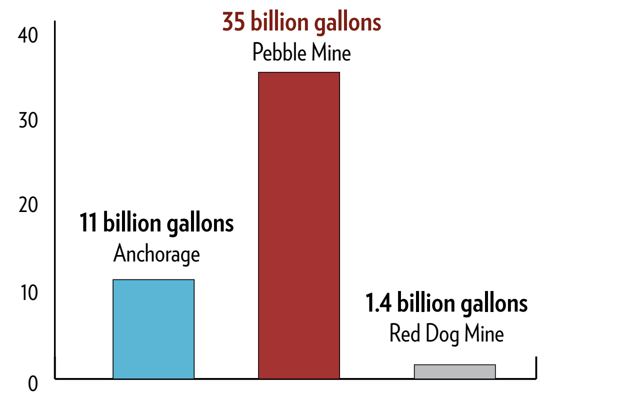
Table 5. Water Appropriation for the Pebble Mine (NDM, Inc. 2006a, 2006b, 2006c).

Location	Surface Water	Groundwater
South Fork Koktuli	12.0 billion	2.8 billion
North Fork Koktuli	8.0 billion	0.2 billion
Upper Talarik Creek	6.8 billion	1.7 billion

Surface Water

Fish absorb oxygen through their gills, and any disruption in the water supply can result in increased stress and mortality. Some fish may survive short-term disruptions in water supply by taking refuge in remaining pools, but when their medium for life is diverted for other purposes, mortality occurs (Gillilan and Brown 1997). The surface water appropriation for the mine and tailings storage facilities would eliminate all flow

Figure 18. Estimated Pebble Mine water usage in billions of gallons per year (NDM Inc. 2006, Moran and Galloway 2007, ADNR 2008a).



and fish habitat in the upper main stem of the South Fork Koktuli and its headwater tributaries, a tributary to the North Fork Koktuli, and the tributaries to Upper Talarik Creek (NDM Inc. 2006a, 2006b, 2006c). In the mine area, dewatering lakes and streams will result in the permanent loss of fish that currently use those habitats.

Below the mine, stream flow would be reduced, and fish habitat would be dried up or diminished downstream. Headwater catchments produce about 55% of the flows in large rivers (Alexander et al. 2007), so loss of headwater streams and the groundwater that produce them will alter flows and water quality downstream. According to Northern Dynasty's surface water rights applications, the net reductions in stream flow projected for each of the three surface water bodies are as follows: 8% on the North Fork Koktuli, 18 miles downstream; 16% on the South Fork Koktuli, 12 miles downstream; and 9% on Upper Talarik Creek, 18 miles downstream (NDM Inc. 2006a, 2006b, and 2006c).

Loss of flow in the most severely affected areas could affect upstream salmon migration. Fish migrating upstream must have stream flows that provide suitable water depth and velocities for successful upstream passage (Bjornn and Reiser 1991). Baxter (1961) reported from a study in Scotland that salmon need 30% to 50% of the average annual flow for passage through the lower and middle reaches of rivers, and up to 70% for passage up headwaters streams.

Stream flow also dictates the amount of spawning area available in any stream by regulating the area covered by water and the velocities and depths of water over the gravel beds (Bjornn and Reiser 1991). Decreasing stream flow exposes more gravel and reduces the area suitable for spawning. A number of studies have documented the importance of stream flow in the amount of available spawning habitat (Collings 1972, Collings 1974, Boehne and House 1983). The reduction of habitat (stream width and depth) from mine appropriations could substantially reduce available spawning and rearing habitat particularly during the summer low flow period when Chinook, sockeye, and chum salmon are spawning. Similarly, reduced flows would diminish the amount of available over wintering habitat for juvenile salmon during critical low winter flows. Englund and Malmqvist (1996) also found that reductions in stream-flow or alteration of stream-flow patterns reduced the productivity of stream habitat, including the productivity of aquatic invertebrates that comprise the primary food source for juvenile salmon.

Groundwater

The abundant wetlands, lakes, and ponds present in the proposed Pebble Mine area indicate high groundwater levels and interconnected ground and surface waters. According to Trasky (2008), groundwater directly affects the productivity of salmon-bearing streams by (1) sustaining stream base flows and moderating water level in groundwater-fed lakes and streams; (2) providing stable temperature regimes and refugia; (3) providing nutrients and inorganic ions; and (4) providing stable spawning habitat. In 2006, Northern Dynasty submitted separate groundwater applications for 19.4 cubic feet per second (cfs) from the Upper Talarik Creek drainage, 11.78 cfs from the South Fork Koktuli watershed, and 12 cfs from the North Fork Koktuli River drainage (NDM Inc. 2006d, 2006e, 2006f). These groundwater withdrawals create a clear potential for substantially decreased flows and water levels in the interconnected streams and lakes common in and around the Pebble Mine site (Ecology and Environment, Inc. 2010).

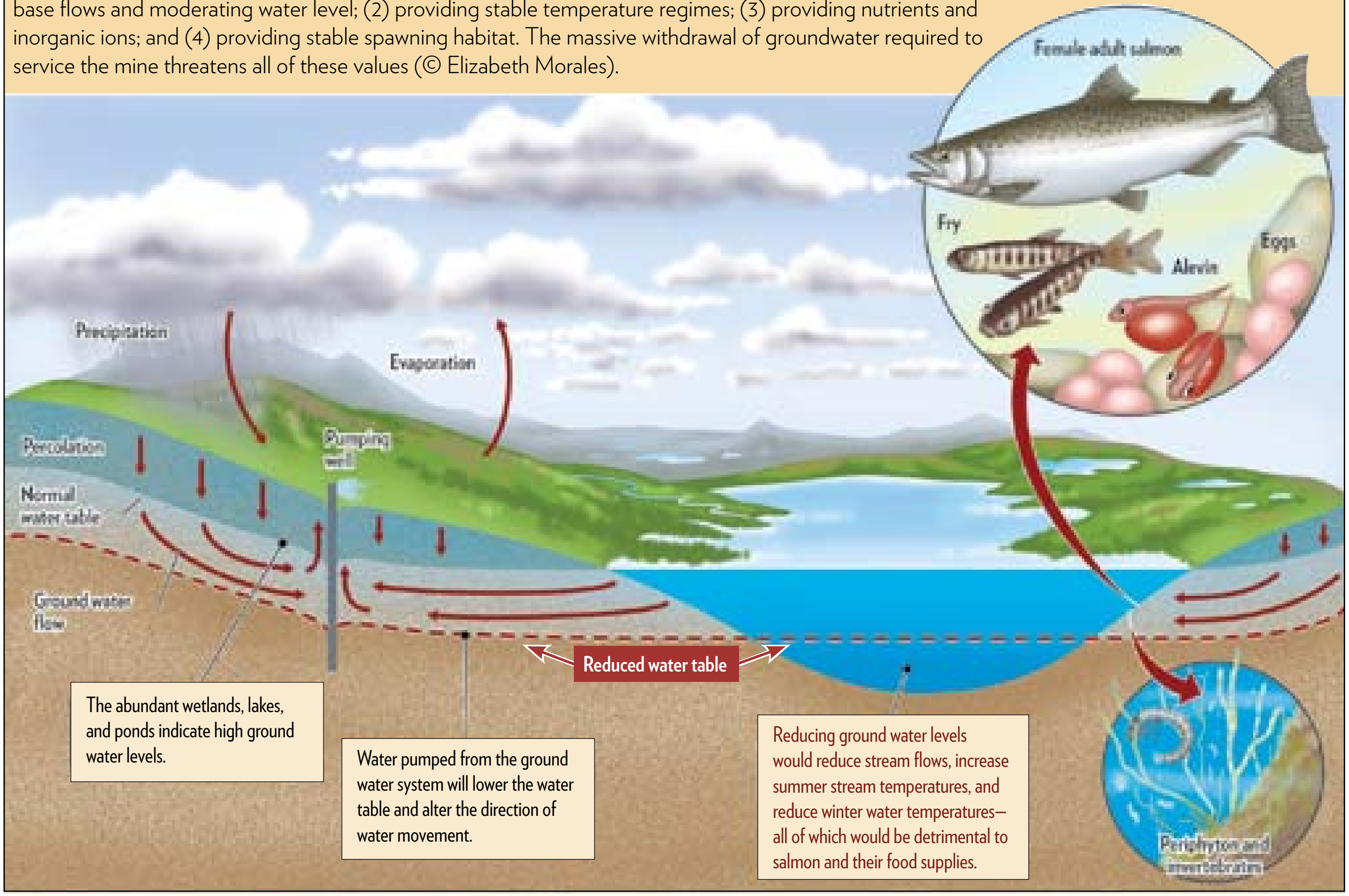
The groundwater system in the area is recharged by precipitation that flows to lakes and streams through the groundwater system (USGS 2008a). Water pumped from the groundwater system to service mine operations and to prevent flooding of the pit and tunnels will lower the water table and alter the direction of water movement, as illustrated in Figure 19 (Moran 2007, USGS 2008b). Water that currently flows to the Upper Talarik Creek and the North and South Forks of the Koktuli River from this area would no longer do so. Heavy pumping may also draw water from adjacent streams, such as Upper Talarik Creek, into the groundwater system, further reducing the amount of stream flow (USGS 2008a, Stratus 2009).

Groundwater flowing down-gradient from the mine area appears to provide the majority of flow to the North and South Forks of the Koktuli River and Upper Talarik Creek during July and August (NDM Inc. 2005) when Chinook, chum, and sockeye salmon are spawning (ADFG 2008b). From January through March, when surface runoff slows or stops, groundwater is the primary source of critical winter flows for incubating salmon eggs and over-wintering juveniles. The temperature of groundwater is very stable compared to surface water and is equal to the average annual temperature of the ground surface, which in turn is approximately equal to the mean annual air temperature (Douglas 2006). Removing or reducing groundwater would reduce summer and winter stream flows, increase summer stream temperatures, and reduce winter water temperatures—all of which would be detrimental to salmon and their food supplies.

Groundwater from the mine area is the source of many of the seeps and upwelling areas in streams currently used by spawning salmon (NDM Inc. 2005). Sites with upwelling groundwater are preferentially selected by salmon for spawning (Garrett et al. 1998, Baxter and McPhail 1999, Malcolm et al. 2004). In northern rivers, low surface flows, low temperatures, and freezing are threats to egg and alevin survival, and salmon seek areas of upwelling for spawning (Leman 1993). For example, upwelling groundwater was detected in nearly 60% of Taku River (Alaska) sockeye salmon redds (Leman 1993). Egg-to-fry survival in kokanee salmon redds in areas of groundwater upwelling was significantly higher (84%) than in redds where no groundwater was detected (66%)(Garrett et al. 1998). Temperatures in upwelling sites 2.4° to 2.6° C above stream temperature accelerated rates of development, protected embryos from freezing, and increased fry survival. Bull trout (*Salvelinus confluentus*) select zones of upwelling within the stream reaches they inhabit, although when spawning, females dig redds in areas with down-welling (Baxter and Hauer 2000).

Over the life of the mine, Northern Dynasty has applied to take a total of approximately 136 cfs of ground and surface waters from the three watersheds that drain the site (NDM Inc. 2006a, 2006b, 2006c). Under the 78-year scenario considered in Ghaffari et al. (2011), this could add up to over 300 billion cubic feet of water during that period. Predicting the effects of such a massive reduction in headwater water quantity on fish production at a broader scale is complex and imprecise. However, there is little question that the total loss of fish habitat in the mine area, coupled with reduced availability of ground and surface waters below the mine and tailings ponds, will reduce spawning and rearing habitat, as well as fish production. An ecological risk assessment completed by The Nature

Figure 19. Effects of Groundwater Pumping. Groundwater directly affects the productivity of salmon-bearing streams by: (1) sustaining stream base flows and moderating water level; (2) providing stable temperature regimes; (3) providing nutrients and inorganic ions; and (4) providing stable spawning habitat. The massive withdrawal of groundwater required to service the mine threatens all of these values (© Elizabeth Morales).



Conservancy (Ecology and Environment, Inc. 2010) summarized the impacts of ground and surface water withdrawals, which would include 33 square miles of drainage area lost, including 68 miles of stream (14 of which are designated in the Anadromous Waters Catalog), plus an additional 78 stream miles that would "exhibit some form of flow reduction in the three watersheds evaluated."

Finally, as highlighted throughout this report, if there is no discharge from the mine as planned, all of the water withdrawn, minus evaporation, would ultimately be stored in the tailings storage facilities along with billions of tons of mine waste. However, as stated earlier, the technical literature fails to provide any examples of metal-mine tailings impoundments/storage facilities that have not leaked some volumes of contaminants over the long-term (Ripley et al. 1996, IIED 2002, Lottermoser 2007, Moran 2007).

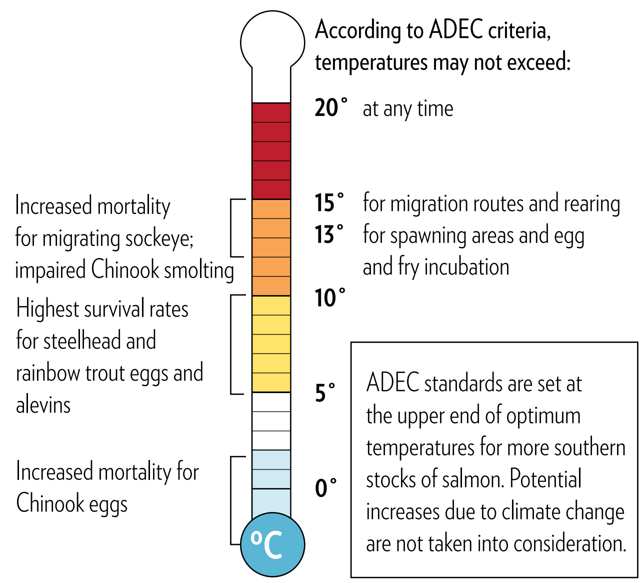
Temperature

Changes in water temperature as a result of proposed surface and ground water appropriations are also likely to affect salmon habitat in Upper Talarik Creek and the North and South Forks of the Koktuli River. Water temperature is one of the most important factors governing the well-being of stream ecosystems and salmon populations (Spence et al. 1996, Myrick and Cech 2004). Salmon body temperatures are the same as the temperature of the ambient water, and they are adapted to the relatively narrow temperature regimes in their home stream habitats (Knudsen et al. 1999). Temperature affects the timing of adult and juvenile salmon migrations, spawning, egg incubation, metabolism rate, food consumption, growth rates, behavior, and resistance to disease and parasites (Spence et al. 1996). The temperature of an aquatic ecosystem also affects the amount of dissolved oxygen in the water, the rate at which algae and aquatic plants photosynthesize, and the rates at which terrestrial litter becomes suitable as a food source for aquatic macroinvertebrates.

Water temperature affects the egg incubation, metabolism rate, food consumption, growth rate, maturation, resistance to disease and parasites, and emergence timing of aquatic insects (Hynes 1970). Thus, temperature is an important factor governing the number and types of food organisms available for salmon. Temperatures above or below normal home stream temperature ranges can add biological, physical, or chemical stresses, possibly resulting in habitat avoidance, reduced growth, greater susceptibility to disease, and lower survival.

Additional temperature increases associated with climate change should also be considered when determining allowable water temperatures resulting from development of the Pebble Mine. Because salmon in

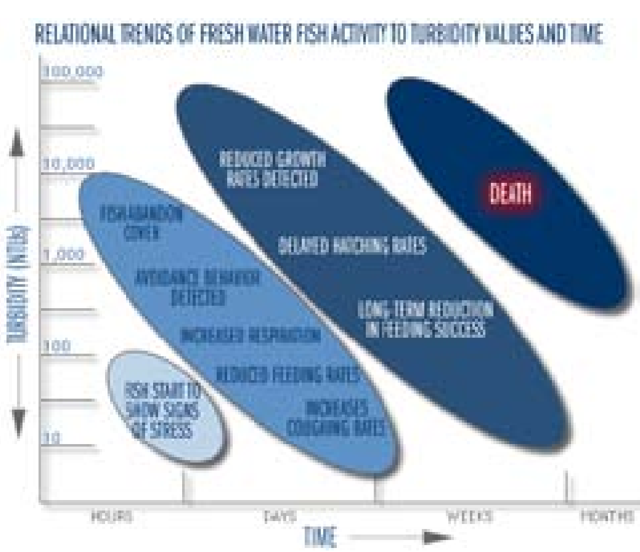
Figure 20. Effects of water temperature on salmonids (McCullough et al. 2001, Myrick and Cech 2004, ADEC 2006).



Bristol Bay are genetically adapted to a cold temperature regime, even small water temperature increases as a result of mining, coupled with projected temperature increases of 3° to 9°C from climate change, could markedly reduce salmon survival and production in affected streams (Rouse et al. 1998, Kyle and Brabets 2001, Perry et al. 2007). Climate change is projected to significantly diminish the ranges of many populations of anadromous and resident salmonids in the conterminous United States and has already altered many species' ranges globally (Parmesan and Yohe 2003, Flebbe et al. 2006, Battin et al. 2007, Rieman et al. 2007).

The ADEC (2006) temperature criteria do not provide a high level of protection for salmon. The criteria state that "[temperatures] may not exceed 20°C at any time. The following maximum temperatures may not be exceeded, where applicable: migration routes 15°C, spawning areas 13°C, rearing areas 15°C, and egg and fry incubation 13°C." Maximum allowable temperatures under this standard are all at the upper end of optimum temperatures for more southern stocks of salmon, which have genetic adaptations for higher water temperatures. Some life functions that are particularly sensitive to temperatures are not addressed. For example, temperatures above 12° to 15°C have been reported to impair Chinook salmon smolting (McCullough et al. 2001). In addition, Chinook eggs have been reported to survive temperatures between 1.7° and 16.7°C, but mortality greatly increases near the temperature extremes. The ADEC criterion for fry and egg incubation is 13°C; however, the highest survival rates for steelhead and rainbow trout eggs and alevins occur between 5° and 10°C, and mortality is

Figure 21. Effect of turbidity on freshwater fish. Newcombe and MacDonald (1991) reviewed the scientific literature on suspended sediment effects and concluded that the effect of turbidity on salmonids is related to both the concentration of suspended sediment and the duration of exposure. In addition, the frequency of pollution episodes, ambient water quality, species and life history, life stage, and the presence of disease organisms may all affect the toxicity of suspended solids (Newcombe and MacDonald 1991).



significantly increased at the extremes (Myrick and Cech 2004). Mortalities to returning adult salmon from sockeye salmon virus are high at temperatures from 12.2° to 15°C, but the ADEC standard for adult migration routes allows increases up to 15°C (Figure 20).

5.5 *Sediment and Turbidity*

Numerous studies have shown that mining can produce significant sources of bedload sediment and can cause suspended solids to enter aquatic ecosystems (Moran and Wentz 1974, Martin and Platts 1981, Jennings et al. 2008). As preliminarily proposed, the Pebble Mine and it's associated facilities would generate and be required to manage a tremendous amount of sediment from land clearing and gravel extraction associated with virtually all of the major elements of the plan, including construction of: the tailings storage facilities and open pit mine; roads, pipelines, the mill, power plant, housing, and other infrastructure; the Cook Inlet deep-water port facilities; and several miles of large earth-fill dams to enclose the tailings reservoirs (NDM Inc. 2005, Knight Piesold Consulting 2006a, 2006b, Ghaffari et al. 2011). Although it is assumed that modern sediment control measures would be required, sediment levels throughout streams in the mine area and road/pipeline corridor would increase during mine construction and operation (Martin and Platts 1981, Ruediger and Ruediger 1999). The eventual spills and leaks resulting from human error, floods, landslides, and earthquakes would add to those sediment levels.

Sediment enters water bodies naturally in undisturbed watersheds at moderate levels and at a wide range of particle sizes that contribute to increased salmon habitat complexity. However, major disruptions of aquatic ecosystems occur when the sediment deposition rates or volumes of suspended sediment become excessive or chronic (Martin and Platts 1981, Bryce et al. 2008, 2010). For salmon specifically, increased sediment levels impair life functions and reduce survival and production over time (Crouse et al. 1981, Reeves et al. 1993). Very high concentrations of sediment can kill adult salmon, eggs, and larvae. Lower concentrations increase mortality rates and cause adverse behavioral effects (Newcombe and MacDonald 1991), including adverse effects on feeding, predator avoidance, and reproduction (Figure 21) (Birtwell 1999).

Turbidity affects salmon by altering their physiology, behavior, and habitat, all of which may lead to physiological stress and reduced survival rates (Bash et al. 2001). Based on a review of the scientific literature by Trasky (2008) and as summarized in Table 6, acute toxic effects of suspended solids on adults, juveniles, eggs, and larvae have been reported within an extremely large range (20 to 202,000 ppm). Death occurred within 1 to 504 hours, depending on concentration, duration, life stage, and species. Chronic effects, such as growth reduction, stress, and gill tissue damage, have been reported for suspended sediment concentrations in the 3 to 1,500 ppm range. Detrimental effects occurred within three to 42 days of exposure to elevated levels of suspended sediments. Behavioral effects, such as avoidance of turbid areas, interference with homing behavior, and reduced feeding, occurred as the result of exposures in the 5 to 650 ppm range.

Suspended and deposited sediments also have direct behavioral effects on (acute or chronic) biota and reduce the productivity of salmon habitat (USEPA 2006). Sedimentation rates above natural levels

Table 6. Effects of Suspended Sediment on Salmonids (Trasky 2008).

Suspended particles (parts per million)	SUSPENDED SEDIMENTS	
	Effects	*Interval*
20–202,000 ppm	**Acute toxic effects** on adults, juveniles, eggs, and larvae	Death occurred within 1–504 hours
3–1,500 ppm	**Chronic effects** such as growth reduction, stress, and gill tissue damage	Detrimental effects within 3–42 days
5–650 ppm	**Behavioral effects** such as avoidance of turbid areas, interference with homing behavior, and reduced feeding	

Beaver pond at the headwaters of the Kvichak River (photo by Erin McKittrick).

decrease the carrying capacity of lakes and streams by clogging spawning gravels, smothering food organisms, and changing the species composition of benthic communities (Hall 1986, Waters 1995, Reiser and White 1998, Zweig and Rabeni 2001, Kaller and Hartman 2004, Carlisle et al. 2007, Fudge et al. 2008, Bryce et al. 2010). Excess fine sediments were reported to be a major stressor of fish and macroinvertebrate assemblages in the western United States and of macroinvertebrates nationally (Stoddard et al. 2005, Paulsen et al. 2008). Two of the most important indirect effects of elevated levels of suspended sediment are the loss of epiphyton (attached algae) through shading and the loss of epiphytic invertebrates due to abrasion and clogging (Berry et al. 2003). The scientific literature indicates that the invertebrates that stream-dwelling salmon feed on are more sensitive to turbidity than juvenile and adult salmon. Benthic invertebrate populations declined 50% to 77% when exposed to increases of 8 to 62 ppm suspended solids (Rosenberg and Wiens 1978, Wagener and LaPerriere 1985). In addition, elevated levels of suspended solids often shift invertebrate populations from preferred grazing to burrowing taxa that are less available to salmon. A large decline in primary production and food organisms as a result of turbidity will be reflected in a decline in salmon populations, even though the fish may not be directly harmed.

The current Alaska Water Quality Standard for sedimentation reads: "In no case may the 0.1 mm to 4.0 mm fine sediment range in those gravel beds exceed a maximum of 30% by weight." This standard does not provide sufficient protection to salmon. In a study of Atlantic salmon spawning habitat in a Scottish river, researchers found that when fine sediment less than 2 mm in diameter reached 20% by mass (for this purpose, mass and weight can be considered the same), egg mortalities reached as high as 85% (Soulsby et al. 2001). Weaver and Fraley (1993) found an inverse relationship between fry emergence success in westslope cutthroat trout (*Oncorhynchus clarki*) and the percentage of substrate material less than 6.35 mm in redds. Following current USEPA guidance, Bryce et al. (2010) determined that for salmon, minimum-effect levels were 5% for percent fines (≤0.06 mm) and 13% for percent sand and fines (≤2 mm), both expressed as a real percentage of the wetted streambed surface (Cantilli et al. 2006). For chief salmon prey organisms (aquatic macroinvertebrates that live on stream bottoms and are thus more sensitive to sedimentation), the minimum-effect levels for the two sediment size classes were 3% and 10%, respectively (Bryce et al. 2010). The Alaska criterion also does not address behavioral or synergistic effects between sediment and other stressors on salmon.

Similarly, the ADEC (2006) criterion for turbidity, which states, "[Turbidity] may not exceed 25 NTU (nephelometric turbidity units) above natural conditions; for all lake waters, may not exceed 5 NTU above natural conditions," does not provide a sufficient level of protection for salmon and salmon habitat. Harmful effects to both salmon and benthic organisms have been documented at levels below the 25 NTU increase allowed in streams (Bash et al. 2001). Many other states, including Minnesota, Washington, and California, allow much smaller increases in turbidity in cold-water salmon streams than Alaska does. Minnesota allows 10 NTU above background. California's standard states, "[W]here natural turbidity is between 1 and 5 NTU, increases shall not exceed 1 NTU. Where natural turbidity is between 5 and 50 NTU, increases shall not exceed 20%." Washington only allows "6 NTU over background turbidity when the background turbidity is 50 NTU or less or more than a 10% increase in turbidity when the background turbidity is greater than 50 NTU" (ODEQ 2005).

Even with modern erosion-control measures, sediment and turbidity in streams in the Pebble Mine area, road/pipeline corridor, and port site are likely to increase. Suspended solids that enter streams from any of these sites may contain other organic and inorganic materials that are harmful to salmonids and aquatic life (Lenhardt and Lehman 2006). These include hydrocarbons; nitrates from blasting; heavy metals from dust, mineral processing, and tailings storage areas; chemicals used in processing ore and oil; and grease from machinery and fuel spills. Elevated levels of turbidity and suspended solids may act in concert with other pollutants such as disease pathogens, heavy metals, and hydrocarbons, to increase harmful effects above that of each individual pollutant (Berry et al. 2003, Moran 2007). Because settleable and suspended solids usually enter surface waters from non-point sources, the effects will be difficult to measure and control.

5.6 Predictions versus Performance in Maintaining Water Quality

The past history of other recently-permitted sulfide mines and data from Northern Dynasty indicate two things: (1) the Pebble Mine will produce acid mine drainage and other forms of water quality contamination, and (2) substantial releases of contaminated effluents into local waters will occur during operations or after closure (NDM Inc. 2005, Kuipers et al. 2006, Moran 2007). Such incidents could take numerous forms; acid and other mine drainages from the mine pit and underground workings could contaminate groundwater and seep into the South Fork Koktuli or Upper Talarik Creek, or pollutant-laden water could leak from tailings dams into the North or South Fork of the Koktuli River. These or numerous other scenarios could eliminate aquatic life for many kilometers downstream; the extent of the damage varying with the volume and toxicity of the discharge. As described in this chapter, even small increases in copper and other metal levels in streams draining the Pebble Mine site could reduce or eliminate salmon and resident fish populations or cause secondary effects, such as habitat avoidance, reduced resistance to disease outbreaks, or habitat degradation. Because of the size of the Pebble Mine and the amount of waste stored on site, the effect of a large-scale release from a tailings dam failure could extend as far as the main-stem Nushagak River or Iliamna Lake (Ecology and Environment, Inc. 2010). Long-term experience from actual metal-mine operations indicates, however, that the most costly impacts are likely to result from the slow, semi-invisible, chronic seepage of contaminants from the wastes that will be stored on-site forever.

Pebble Limited Partnership has promised to employ considerable safeguards to control acid mine drainage and other adverse impacts at the site. Nevertheless, the mining industry has a poor history of accurately predicting its performance. Kuipers et al. (2006) investigated the industry's success in predicting water quality outcomes from mining operations. They compared the actual impacts of mining on water quality with the mine developers' earlier predictions of expected performance in environmental impact statements and related analyses.

The authors of this study concluded the following:

- 100% of the mines predicted compliance with water quality standards before operations began (assuming pre-operations water quality was in compliance).
- 76% of the mines that were studied in detail (25 mines) exceeded water quality standards due to mining activity.
- Mitigation measures predicted to prevent water quality exceedances failed at 64% of the mines studied in detail.
- 85% of the mines near surface water with elevated potential for acid drainage or contaminant leaching exceeded water quality standards.
- 93% of the mines near groundwater with elevated potential for acid drainage or contaminant leaching exceeded water quality standards.
- Of the sites that did develop acid drainage, 89% had predicted low acid drainage potential initially or offered no information on acid drainage potential.

This research tracked actual impacts *years and decades* after the developers' assessments. To ensure the continued health of one of the world's most productive salmon ecosystems, PLP will have to maintain one of the largest toxic impoundments in the world *in perpetuity.* In considering the PLP's projections of "no net loss" of fisheries over this time frame, strong consideration should be given to the industry's demonstrated inability to accurately project water quality impacts over far shorter horizons (Todd and Struhsacker 1997, NRC 2005, Kuipers et al. 2006, Septoff 2006).

Confluence of the Nushagak and Mulchatna Rivers (photo by Erin McKittrick).

Sockeye salmon in Bristol Bay (photo by Ken Morrish, Fly Water Travel).