Chapter 3

Potential Sources of Contamination

Metal mining operations routinely release metals and other chemicals into the surrounding environment from two distinct sources: the natural, mineralized rock and the large quantities of chemicals, fuels, and explosives that are used throughout the mining and mineral-extraction processes. Pollution of ground and surface waters from mines and associated mineral-processing facilities is a common occurrence.

The Environmental Protection Agency (EPA) compiled a summary of pollution case studies for mines and mineral-processing facilities in Arizona, Florida, Missouri, and Nevada that polluted ground and surface waters from 1990 to 1997 (USEPA 1997). These releases included metals like copper, mercury, cadmium, and lead; chemicals used in mineral processing, such as cyanide and acids; and radioactive materials. During that seven-year period, the EPA filed 91 environmental damage reports, of which 26 were for discharges from copper mines. In a more recent report, the EPA (USEPA 2004) identified 156 hard rock mining sites in the United States with past or potential Superfund liabilities of $1 million or more.

> *In productive Bristol Bay salmon streams, a major failure of a tailings storage facility could kill hundreds of thousands to millions of adult salmon and resident fish, depending on when and where the spill occurred.*
>
> —"An Assessment of Ecological Risk to Wild Salmon Systems from Large-Scale Mining in the Nushagak and Kvichak Watersheds of the Bristol Bay Basin" (Ecology and Environment, Inc. 2010)

Mining-related contamination of ground and surface waters frequently results from contact with mineralized rock in open pits and underground workings, discharge of process water, slurry pipeline breaks, spills of industrial chemicals, drainage from post-mining pit lakes, waste rock piles, underground workings, discharge and seepage from tailings storage facilities, and dust from blasting, hauling, and storing mine wastes (Figure 9). Other sources of contamination include settleable and suspended solids from related activities, such as blasting, construction, and maintenance of the pit and underground mines, roads, pipelines, and ports.

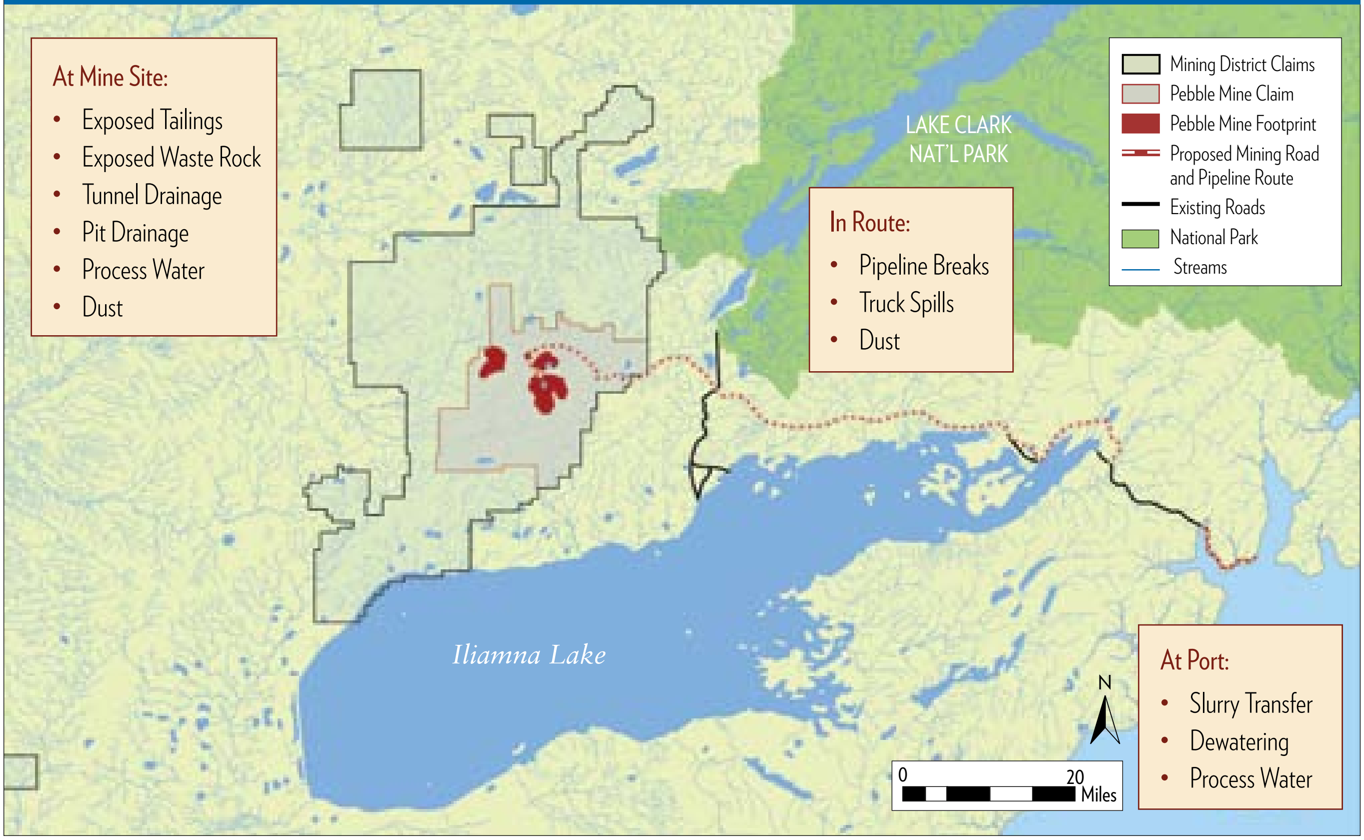
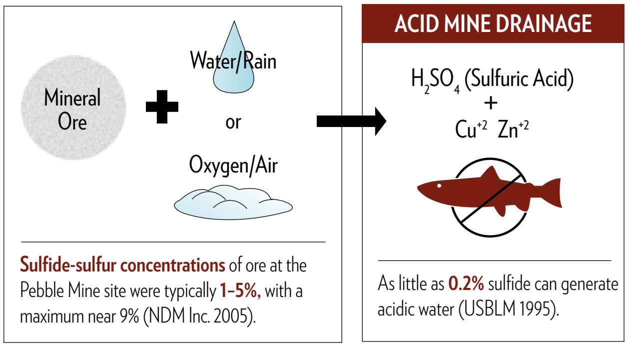


Figure 9. Contamination Risks at Mine Site and Along the Proposed Road and Slurry Pipeline. The Pebble Mine poses threats to salmon ecosystems not only at the mine site but also across its far-reaching infrastructure. This infrastructure may also facilitate additional proposals for mining operations in the Bristol Bay basin that were not previously feasible.

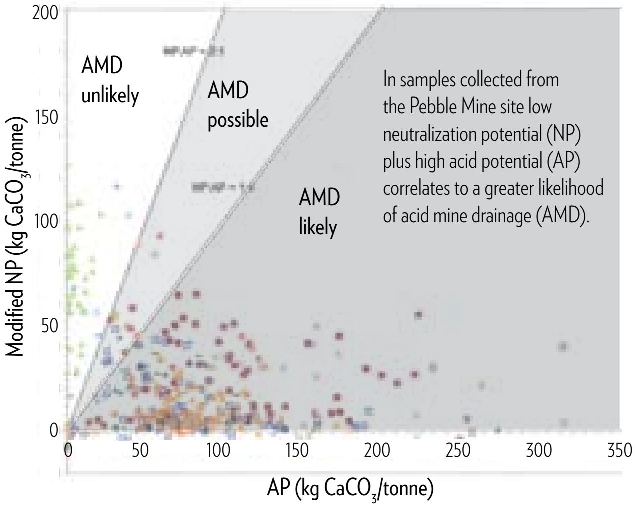
Figure 10a. Acid Mine Drainage. When metal sulfides are exposed to air and water, they react to form a sulfuric acid solution known as acid mine drainage (AMD), which is toxic to aquatic life.



Sulfide-sulfur concentrations of ore at the Pebble Mine site were typically **1–5%**, with a maximum near 9% (NDM Inc. 2005).

As little as **0.2%** sulfide can generate acidic water (USBLM 1995).

Figure 10b. Likelihood of AMD. The graph below depicts 399 samples from 65 holes drilled between 1988 and 2003 by Northern Dynasty at the Pebble Mine claim (NDM Inc. 2005).
NP = neutralization potential or concentration of calcium carbonate;
AP = acid potential or the concentration of sulfide–sulfur.



In samples collected from the Pebble Mine site low neutralization potential (NP) plus high acid potential (AP) correlates to a greater likelihood of acid mine drainage (AMD).

3.1 *Mine Rock-Water Interactions: Effluents*

Mining and preliminary physical ore processing—including blasting, crushing, and grinding—convert the rock from a solid into smaller particles that have much greater surface area. These processes facilitate chemical processing. However, increased surface area also increases the potential for undesirable chemical and bacteriological reactions between the rock minerals, water, and air. As a result, higher concentrations of soluble chemical constituents can be released from fine materials into local waters than would be released from the original, unbroken rock.

The most significant mine-related environmental and economic impacts generally result from the production of acid effluents, often called acid mine drainage (AMD), which is discussed in detail later in this chapter. Such acid effluents occur where the exposed rock contains significant sulfide concentrations. They are commonly released from waste rock piles, exposed surfaces in open pits and underground workings, tailings, road materials constructed with waste rock, etc.

Some mine wastes release alkaline or near-neutral pH effluents, either because of the alkaline composition of the original rock or due to the addition of alkaline process chemicals. The concentrations of many chemical constituents (metals, metalloids, non-metals, etc.) will increase greatly when in contact with acidic waters. Similarly, concentrations of some chemical constituents, especially those that form negatively charged anions in natural waters (e.g., aluminum, arsenic, antimony, selenium, manganese, molybdenum, vanadium, uranium, chromium, and nickel), will increase as the pH rises above about 8.5. Even when waters of nearly neutral pH react with mineralized geologic materials, concentrations of soluble constituents will increase when reacting with small rock particles.

Copper tailings discharges are often alkaline, having an initial pH between about 9.5 and 12.0. As the tailings age, and the solids react with the liquids and air, the liquid pH may over many years become acidic. Waste rock may also release initial discharges that have alkaline or near-neutral pHs, but as the alkaline rock minerals (e.g., feldspars and carbonates) decompose, the effluents can become acidic. It may be many years before the presence of acid discharges becomes obvious, and this may occur after mine closure.

Numerous types of mine rock-water interactions also increase the concentrations and loads of suspended sediment particles released into local waters.

3.2 *Waste Rock*

Waste rock is the mineralized, but uneconomic rock, which is removed to access the ore. Generally, it is stacked in large piles at the margins of the pit or underground workings, on land surfaces that lack any sort of underlying liner. Such waste rock accumulations are often the largest sources of acids and other toxic constituents at mine sites (USEPA 1997, 2004). Where waste rock contains significant concentrations of sulfide minerals, predominantly iron sulfide minerals such as pyrite or marcasite, chemical reactions between the rock minerals, water, air, and bacteria often generate acid effluents—acid mine drainage (Singer and Stumm 1970).

Mining processes invariably increase the concentrations of contaminants released into the aqueous environment, even when the rock mined (waste rock and ores) does not release acidic effluents (Moran 2007).

CASE STUDY: TUNNEL DRAINAGE

Holden Copper Mine (Washington)

Howe Sound Company mined the Holden deposit for copper, zinc, silver, and gold between 1938 and 1957, when the mine closed due to falling copper prices. Holden is an underground mine with 57 miles of tunnels penetrating a massive sulfide deposit. The tunnels create a huge reactive surface area of sulfide rock that produces acid mine drainage on contact with air and water (Day 2010). The mine also produces a steady stream of heavy metal pollution, including copper, that flows from the mine portals. Elevated levels of dissolved copper affect salmonids physically and also degrade salmonid habitat by reducing the fish's aquatic insect food supply. The presence of copper and aluminum may also increase the toxicity of other metals (e.g., lead, iron, nickel, cadmium, and manganese) and the effects of other environmental stressors (e.g., excess temperature, excess sediment) (Sayer et al. 1991). Reclamation of the mine is also a human health and safety priority with the village of Holden, a wilderness entry point near Lake Chelan, positioned right at the base of the mine.

Impact:

- The mining operation left **8.5 million tons of tailings** in piles that fill the narrow Railroad Creek valley floor. Heavy metals in soils and tailings near Holden exceed criteria for human contact. There is a risk that the unstable tailings pile may collapse into Railroad Creek during a flood or seismic event. The U.S. Forest Service has already tried to protect the creek from tailings erosion where it runs along the base of the tailings pile.
- The lower portions of the underground mine are flooded, and acid mine drainage flows from the mine portals and from beneath the tailings piles; the water is a milky white or orange color, depending on its chemical precipitate (aluminum hydroxides or iron). There is a direct connection between groundwater beneath the tailings pile and Railroad Creek.
- Iron, zinc, copper, and cadmium exceed criteria for the protection of aquatic life. A Washington State Department of Ecology study showed that the density of aquatic insects declined from over 3,000 individuals/m^2 above the mine site to just 50 individuals/m^2 below it, due to heavy metals pollution and the armoring of stream substrates by iron precipitates (creating *ferricrete*) (Johnson et al. 1997). Twelve miles downstream, where Railroad Creek empties into Lake Chelan, aquatic insect densities still only reached 361 individuals/m^2. The sediments composing Lucerne Bar, created by the plume of sediments carried into Lake Chelan by Railroad Creek, exceed the sediment criteria for zinc (Johnson et al. 1997) .

Mitigation: Though there were several attempts over the years to reduce the wind and water erosion from the tailings dump, it was only after Superfund designation, that a concerted effort has been made toward full reclamation and restoration of the mine area; Howe Sound Company's successor, Intalco, was directed to conduct a remediation study of the inactive Holden Mine under authority of the Superfund Act (Einan and Klasner 2010). A consortium of state and federal agencies and the mining company considered 14 alternative approaches (with citizen input) before settling on a mitigation strategy for protecting Holden Village and isolating Railroad Creek from the effects of Holden Mine (Day 2010, Einan and Klasner 2010):

- 8.5 million tons of exposed tailings
- Acid mine drainage leaks from the flooded tunnels and tailings piles to groundwater and nearby Railroad Creek
- Iron, zinc, copper, and cadmium exceed criteria for the protection of aquatic life, with aquatic insects reduced to less than 2% in areas
- $107 million for mitigation (20% of total mine earnings)

Above: Acid mine drainage from tailings leaked into groundwater and nearby Railroad Creek (photo by U.S. Forest Service).

Copper Creek will be put in a lined ditch where it passes through the tailings piles. Railroad Creek will be riprapped to protect it from tailings erosion. French drains will be constructed above the tailings and waste rock piles and maintained in perpetuity to reduce the amount of run-off that could contact the materials. Airflow restriction devices will be installed at the mine portals to reduce air contact with the mine tunnel walls and thereby reduce the production of acidic runoff. It will not affect the acidic groundwater already flowing from the flooded tunnels. Water-control structures will be placed at the mine portals to meter the flow of water leaving the mine.

One or more water-treatment plants will be required to treat the mine effluent before discharging it to Railroad Creek. It is not yet known where the best collection points will be for the multitude of surface and groundwater discharges from the mine. Significant electric power will be needed to maintain the site, particularly for the water-treatment plants. In this remote location, power generation will require multiple diesel generators. Water quality assessment and the many other components of mitigation will require monitoring, maintenance, and replacement forever.

Cost: The mitigation project which has been 10 years in planning will be built in stages over the next decade. The cost estimate for the chosen alternative, including costs for construction and the present value of long-term maintenance and water treatment, is **$107 million** (Day 2010). The Howe Sound Company earned $67 million from the Holden Mine by the time it closed in 1957. Considering that a 1957 dollar is worth $7.82 in 2010, Howe Sound's earnings would be $523,940,000 today in dollar equivalents plus the added present value of the mined metals. In other words, **mitigation of the Holden mine at $107 million is more than 20% of the total earnings of the mine's production over 19 years.**

Rio Tinto in Spain is very acidic (pH 2.0) with high concentrations of heavy metals as a result of mining (photo by Carol Stoker, NASA).

At metal-mine sites like Pebble, such waste rock routinely contains significant concentrations of dozens of chemical constituents that can be released into the environment, such as: aluminum, antimony, arsenic, chromium, copper, iron, lead, manganese, molybdenum, nickel, selenium, uranium, vanadium, zinc, and natural radioactive constituents.

Preliminary concepts for the Pebble (Knight Piesold Consulting 2006a, 2006b) suggest that contamination will be avoided by storing all or portions of the waste rock and all of the potentially acid-generating tailings under water in a tailings storage facility. Storing mine wastes underwater will only slow—not stop—the chemical reaction rates. Experience at hundreds of operating mine sites around the world indicates that all waste impoundments, liners, and dams leak to some extent, over time (Ripley et al. 1996, ICOLD 2001, IIED 2002, Lottermoser 2010). Thus, some volume of contaminants will continually be released into local ground and surface waters, even though most of the wastes remain inundated and contained. The inflowing water will eventually pass through, around, or under the tailings dam and into downstream systems and Iliamna Lake, mobilizing AMD, metals, metalloids, organic reagents, and so on.

It seems probable that effluents from the waste rock and tailings will require collection and active water treatment during operations and following mine closure, in perpetuity. Because mine wastes will remain on-site forever, these waste facilities will require perpetual physical maintenance to prevent erosion and release of the toxic contaminants—both solids and liquids.

Scenarios presented more recently (Ghaffari et al. 2011) indicate that waste rock not used for tailings dam construction would be stored in conventional waste rock piles near the pit, with the potentially acid-generating (PAG) material eventually processed at the end of mine life. In the 25-year scenario described in chapter 2, two billion tons of waste rock would be generated (Ghaffari et al. 2011). Segregating PAG from non-PAG waste has always been one of the most difficult things to predict and manage at a mine (Chambers and Moran 2007). Even when the PAG and non-PAG materials have been adequately defined, it is often difficult to actually separate them given that waste is defined on the basis of tests from small samples of large amounts of material, and the waste segregation is physically performed with massive, often imprecise, mechanical equipment (Chambers and Moran 2007).

Acid Mine Drainage

The Pebble deposit rocks contain significant concentrations of iron, copper, molybdenum, and other metal-sulfide minerals, such as chalcopyrite, pyrite, bornite, and molybdenite (Rebagliati 2007, Kelly et al. 2010). Some of these metal-sulfide minerals present a high risk of producing AMD (USEPA 1994a). When iron sulfide minerals (e.g., pyrite, pyrrhotite, and marcasite) and some other metal-sulfide minerals (e.g., enargite and arsenopyrite [Fey 2003]) are exposed to oxygen-rich water, the sulfide oxidizes to sulfate, the iron oxidizes to iron oxide or hydroxide, and sulfuric acid is released (USEPA 1994a). These processes are greatly accelerated when certain iron and sulfur bacteria are present. The increased acidity (lower pH) accelerates the dissolution of minerals in the pit walls, waste rock, and so on, releasing numerous rock constituents (e.g., aluminum, arsenic, antimony, copper, lead, nickel, zinc, and sulfate) into the surrounding environment in various mobile forms: dissolved, colloidal, and particulate (Singer and Stumm 1970, Moran and Wentz 1974). Many of the chemical constituents contained in these acidic effluents are toxic to aquatic life, especially coldwater fish, as described in chapter 5.

Thus, at mine operations, mineralized rock is exposed to air and water in numerous locations: open pit walls, underground workings, waste rock piles, exposed tailings, ore stockpiles, and roads. The originally solid rock is broken and crushed, creating much greater exposed surface area, which greatly increases the rates at which chemical reactions can occur. Chemical reactions of the broken or crushed rock with air, water, and bacteria yield effluents with elevated concentrations of several contaminants. Long-term, the most detrimental mine waste effluents have acidic pHs (often between 3.0 and 5.0, sometimes below 2.0), which mobilize elevated concentrations of the minerals in the rock, including numerous metals and metal-like constituents that may be toxic to humans and aquatic life—especially fish.

Pebble Limited Partnership has not released the detailed geochemical information necessary to adequately evaluate the sulfide content or long-term chemical reactivity of the ores, waste rock, and tailings. Nevertheless, the publicly available NDM/PLP data clearly show that much of the ore and waste rock contains elevated sulfide concentrations that will generate net acidity over time. For example, Northern Dynasty Inc. (2005) presented preliminary data from geochemical testing indicating that much of the site rock has geochemically significant concentrations of sulfide-sulfur. The authors state: "[S]ulfur concentrations in the pre-Tertiary rock types (comprising much of the ore and non-overburden waste) are typically between 1% and 5% sulfur up to maximum concentrations near nine percent" (NDM Inc. 2005). Significant volumes of rock containing 1% to 5% sulfur-as-sulfides indicate that AMD is likely to develop over the long term at the Pebble site (Morin and Hutt 1997, Price 1997, Lapakko 2003).

AMD has been documented at much lower sulfide-sulfur concentrations, including concentrations as low as 0.1% to 0.3% (Lapakko and Antonson 1994, Li 2000). At the Zortman-Landusky Mine, in Montana, waste rock having as little as 0.2% sulfide generated acidic water (USDOI 1995). (See the case study on pp. 88–89). In an industry-funded study of hundreds of metal-sulfide mines throughout North America, Todd and Struhsacker (1997) found that all sites exhibited some degree of water quality degradation, over time.

Once acid rock drainage develops, it is often a truly long-term problem. Davis, et al.(2000) report evidence that acid conditions have existed for thousands of years in the Rio Tinto region of southern Spain, the source of the corporate name of the Rio Tinto Group.

Mine Rock as Construction Material and Dust

Using mine waste rock as construction or road material carries great risk because it contains elevated, mobile metal/contaminant concentrations. Blasting, loading, and hauling ore and waste along mine roads and conveyors raise dust. The chemical composition of the dust may be of concern because of its metal content. Between 1989 and 2000, trucks hauling lead-zinc concentrate on the 55-mile long haul road from the Red Dog Mine in Northwest Alaska, contaminated over 143,000 acres of Cape Krusenstern National Monument with harmful levels of lead and cadmium (Hasselbach et al. 2005) (See case study pp. 78–79). High levels of dust contamination were also found at the port site on the Chukchi Sea and around the mine.

Data presented in NDM Inc. (2005) indicate that numerous metals/metalloids of potential concern (e.g., arsenic, copper, mercury, molybdenum, and lead) are present in the dust from the Pebble Mine. Employing state-of-the-art dust control will reduce the quantity of dust generated by mine operations, but some dust will escape the mine site and the haul road to contaminate surrounding lands and waters.

3.3 Tailings

At mines similar to the proposed Pebble operation, the ore is transported to a mill/process plant where it is crushed. Massive quantities of process chemicals and water are added to the ore to extract the commercial metals (see Section 2.3). The resulting waste is often a mix of approximately 50% liquid and 50% solid particles, called tailings (Ripley et al. 1996, Lottermoser 2007). This mix—a "chemical soup" containing literally hundreds of different potentially toxic compounds—is then discharged to a tailings impoundment, where the tailings are stored forever. Although modern mine operations attempt to collect and contain as much chemical waste as possible, all tailings impoundments, dams, and associated liners leak to some extent over time (Ripley et al. 1996, ICOLD 2001, IIED 2002, Lottermoser 2007).

The slow, semi-invisible seepage from tailings impoundments has contaminated nearby ground and surface waters and has generated the most costly long-term impacts at numerous metal-mining sites. Impacts from such chronic tailings seepage are much more common, statistically, than the impacts related to a catastrophic collapse of the tailings impoundment (see discussion below). Of greater concern, these impacts often take place over decades and may not become apparent until after an operation has closed and financial bonds have been returned to the operator.

The Pebble tailings storage facility would require perpetual maintenance of the physical structures to prevent release of the contaminated liquids and solids. Following site closure, either the state or some other operator will be required to collect and treat contaminated waters seeping from the TSF. Given the extremely-pure, salmon-laden waters, a high-technology water-treatment plant would be required to produce an effluent suitable for discharge into this environment. Such operations would likely continue forever, following mine closure, potentially creating long-term public liabilities. (See discussion in chapter 7).

Mine proponents may assert that compaction of the TSF's will mitigate the need for long-term site maintenance. However, no evidence exists in the mining technical literature to demonstrate that any similar, large-scale metal mine tailings/waste facility has ever been successfully closed, in a similarly fragile environment, without producing negative impacts to local/regional water quality over the long-term.

3.4 Process Water and Concentrates

At the Pebble site, the transport water that conveys mineral concentrates through the slurry pipeline to the port will also contain processing chemicals and other potentially toxic compounds. Filtrate—water remaining after the concentrate is dewatered at the port site—will be returned for reuse at the mine via a parallel pipeline. Pipelines will be engineered with leak-detection systems, shutoff valves, and other features to help contain any spillage, especially in the vicinity of stream crossings. While shutoff valves can limit the amount of spilled concentrate and wastewater, they do not prevent spillage. The material between the shutoff valve and the break could escape from a ruptured pipeline, even "a pipeline within a pipeline" as considered for stream crossings in the Preliminary Assessment (Ghaffari et al. 2011). While more modern systems employed at Pebble would undoubtedly trigger a faster shutoff response, the oil pipeline break beneath Montana's Yellowstone River in the summer of 2011 illustrates the potential impact of such a break on adjacent surface water. The potential impacts of pipeline failures are discussed below.

Precautions are also essential as the concentrates are loaded aboard ships at the port site. After they are dewatered, concentrates become more susceptible to wind-blown dispersal. Concentrates are normally stored in temporary storage sheds and then moved via conveyor along the loading dock and onto the ship. There are presently three ship-loading facilities for metal concentrates in Alaska: the Chukchi Sea port serving Red Dog Mine, the Greens Creek Mine port, and the Skagway ore-loading terminal, which handles ore concentrates from mines in the Yukon. Contamination has occurred at all three ship-loading facilities. For example, surface soil levels of 27,000 mg/kg (27 times the EPA industrial cleanup standard) were documented near the Red Dog port operational areas in a 1996 monitoring study (Hasselbach et al. 2005).

3.5 Post-mining Pit Lake

According to the Preliminary Assessment, upon completion of mining, the pit and underground tunnels will be allowed to flood, forming a post-mining pit lake (Ghaffari et al. 2011). Pit water quality will be affected by the rock composition and the chemical reactions between the water and the rock exposed in the pit and the tunnel walls and floors, especially the rubble that has been further exposed by fracturing. It will also be affected by the quality of inflowing ground water, the outflow of groundwater, precipitation, dissolution of metals, and evaporation (Higgins and Wiemeyer 2001). PLP states that the pit lake water level will be maintained as a groundwater sink, by pumping pit water to the water-treatment plant (Ghaffari et al. 2011).

Koktuli River wetlands (photo by Erin McKittrick).

Pit lake water quality is of concern for two reasons. First, if the hydrology of the site is such that water from the pit can migrate from the pit down-gradient to ground and surface waters, there will be long-term impacts to water off the mine site. Because the Pebble ore body is located at the hydrologic divide between Upper Talarik Creek and two branches of the Koktuli River, percolation or migration of pit water could affect both drainages. Second, assuming that pit water is of poor quality, both aquatic organisms that attempt to colonize the pit lake and terrestrial organisms utilizing it after mining will be adversely affected or killed.

Predicting water quality for pit lakes is an evolving science, traditionally exhibiting large margins of error. The U.S. Fish and Wildlife Service (USFWS) analyzed water samples from 12 pit lakes in Nevada (Higgins and Wiemeyer 2001). Of the 12 lakes sampled, four were slightly acidic, and all of the lakes contained at least one trace element at concentrations potentially toxic to aquatic life and terrestrial wildlife. Aquatic life concentration criteria were exceeded for arsenic, cadmium, and chromium in two lakes, copper in six lakes, mercury in four lakes, selenium in six lakes, and zinc in six lakes. At this point, there are no reported predictions for Pebble pit lake water quality, but there is no reason to expect that it will differ substantially from that associated with other metal mines.

3.6 Pipeline Failures

The four major pipelines running parallel to the 86-mile long road from the mine site to the port will be buried in a common trench except where they cross major surface waterways (Ghaffari et al. 2011). Pipelines will cross at least 89 creeks and rivers,

CASE STUDY: PIT LAKE FAILURE

Grouse Creek Gold Mine (Idaho)

In 1992, the U.S. Environmental Protection Agency (EPA), U.S. Forest Service (USDA FS), National Marine Fisheries Service (NMFS), and the state of Idaho granted permits to Hecla Mining Company of Coeur d'Alene, Idaho, allowing the company to build the Grouse Creek cyanide heap leach gold mine on Jordan Creek near Stanley, Idaho. Jordan Creek provides important habitat for endangered Chinook salmon, steelhead, and bull trout. The Challis National Forest Final Environmental Impact Statement **assured the public that no significant impacts to water quality were expected to occur from the mine** because the tailings impoundment was designed to be a zero discharge facility (USDA FS 1992). The mining newspaper *Northern Miner* called Grouse Creek a "state of the art" mine (Kilburn 1995), and in 1995, Idaho presented the Hecla Mining Company with two awards for environmental excellence in reclamation.

> *"The Grouse Creek project was developed to protect and, in certain cases, enhance the quality of the environment. During development of the mine, 80 acres of sedge wetlands were created or enhanced and 10 acres of historic gold dredge tailings were replaced with riparian wetlands and salmon habitat. The planned design of the facility will have a lasting positive impact on the surrounding area by reducing sedimentation to streams through an extensive stormwater runoff control system. In addition, all process water is stored in a double-lined tailings pond and recycled through the mill with none being discharged to the environment."*
>
> —Hecla Mining Company, 1994.

Failure: The plastic liner under the tailings impoundment failed **less than a year after the Grouse Creek Mine began producing its first gold** in 1994. Monitoring agencies also noted that in the late 1990s and early 2000s after the mine closed, the tailings impoundment filled faster than expected and threatened to overtop the dam (USDA FS and USEPA 2003).

Impact:

- The breach in the tailings pond released nearly **10,000 gallons of cyanide-bearing tailings and water** (USDA FS and USEPA 2003).
- Before the mine closed in 1997, two and a half years after opening, Hecla Mining had been cited for **258 violations** of its discharge permit (Earthworks 2004).
- Water quality violations continued after closure. Two years after the mine quit operating, cyanide was still flowing into Jordan Creek at over 12 times the levels at which chronic exposure to the chemical negatively affects fish and other aquatic organisms. Cyanide was detected in springs and seeps feeding Jordan Creek as well, indicating groundwater-surface water connectivity and contamination (USDA FS and USEPA 2003).
- In 2003, the EPA and the USFS declared the mine a **Superfund site** and the tailings impoundment an imminent threat, and the agencies ordered the dewatering of the tailings impoundment.

- 258 violations of discharge permit
- 10,000 gallons of cyanide-bearing toxins escaped, contaminating area groundwater and surface water
- Cyanide 12 times the level at which fish and aquatic life are negatively impacted
- Declared a Superfund site by the EPA
- Estimated reclamation costs: $60 million (original bond: $7 million)

Above: Grouse Creek Gold Mine (photo by Lynne Stone).

Mitigation: Cyanide-bearing waters have been contained in ponds or intercepted by groundwater wells and treated prior to release into Jordan Creek. The tailings impoundment will be reclaimed to serve as a floodway for storm water removal at one end and a passive water treatment facility at the other end. A sulfate-reducing bioreactor with aerobic polishing is expected to perform water treatment for most of the year except for spring runoff when lime treatment will have to be added to the process to accommodate the excess flow (Gross 2008).

Cost: Hecla Mining Company was required to post a typical and inadequate **$7 million bond**. The estimate for the tailings pond removal action is $1.7 million. An update of reclamation costs prepared in 2001 estimated **$60 million in land reclamation (finite) and water treatment in perpetuity** (SAIC 2001). Thus far, Hecla Mining has not abandoned the site nor ignored their financial responsibilities, as many other mining companies have done.

CASE STUDIES: PIPELINE FAILURES

Black Mesa Pipeline (Arizona)

Corrosion in the 273-mile-long Black Mesa coal slurry pipeline caused ruptures and seven spills between 1997 and July 1999 (Shafer 2002). Eight additional spills occurred in 2001–2002. The most recent incident occurred on January 19, 2002, when 500 tons of coal slurry spilled into Willow Creek, a tributary of the Big Sandy River in northwestern Arizona. Coal sludge in Willow Creek was eight inches deep. The company did not report the spill as required by the Comprehensive Environmental Response and Liability Act (CERCLA). The Arizona Department of Environmental Quality and the EPA say the pipeline, maintained by Black Mesa Pipeline, Inc., has leaked more than **half a million gallons of coal slurry** in **15 separate spills**. The pipeline company was fined $128,000 in 2001 for illegally discharging 485,000 gallons of coal slurry in seven spills between December 1997 and July 1999 (USJD 2001).

Century Mine (Ohio)

In 2005, more than **30,000 gallons of coal sludge** spilled from a pipeline in Ohio, killing most of the fish in Captina Creek. The spill resulted from a fist-sized hole in the three-mile-long pipeline that runs from American Energy Corporation Century Mine to a disposal area for slurry (OEPA 2011, OHC 2011).

Alumbrera Mine (Argentina)

An earthquake on September 17, 2004, measuring 6.5 on the Richter scale, caused a pipeline to break at the Alumbrera mine in Argentina, sending copper and gold concentrate into the Villa Vil River. An unknown amount of mineral concentrate filled approximately **two kilometers** of the river, which provides water for domestic consumption and irrigation to the municipality of Andalgalá in Catamarca Province. While the flood of concentrate, which reached 12 meters in height, left a layer of solids on top of the riverbed and river banks, the water component of the slurry penetrated up to two meters deep, carrying with it the toxic metals (Mining Watch 2005).

El Chino Mine (New Mexico)

Phelps Dodge Corporation paid a $42,150 civil penalty to the New Mexico Environment Department (NMED) over contamination resulting from pipeline spills at the company's Chino Mine in New Mexico (Guerriere 2003). The Phoenix-based copper producer also agreed to replace the pipeline and improve pipeline operating procedures. The settlement covered three spills of tailing slurry and process water from Chino pipelines: a **480,000-gallon spill** on December 8, 2000, an 18,000-gallon spill on December 21, 2000 and a 20,000-gallon spill on January 19, 2001. According to the NMED, **45 spills** occurred at the Chino Mine between 1990 and 2001.

Forty-five pipeline spills occurred at New Mexico's Chino Copper Mine over an 11-year period (photo by Eric Guinther).

14 of which have been designated as anadromous waters under the Catalog of Waters Important for the Spawning, Rearing or Migration of Anadromous Fish (Ecology and Environment, Inc. 2010), administered by the Alaska Department of Fish and Game. As shown in Figure 16 (pp. 48-49), 36 rivers, streams, and small tributaries enter the north shore of Iliamna Lake (Kvichak River basin) providing salmon and resident fish habitat, which could be severely affected by a pipeline failure. The streams identified in the Anadromous Waters Catalog include important sockeye, Chinook, and coho salmon producers, such as the Newhalen River, Knutson Creek, Canyon Creek, Chekok Creek, Pile Bay River, and Iliamna River. According to the Preliminary Assessment, pipelines will either be buried beneath these rivers and creeks or run along bridges —or, in the case of Iliamna Lake, a causeway—above them. Twenty bridges are projected, ranging in size from 40 to 600 feet, and almost 2,000 feet of causeway will cross the northwest portion of Iliamna Lake (Ghaffari et al. 2011).

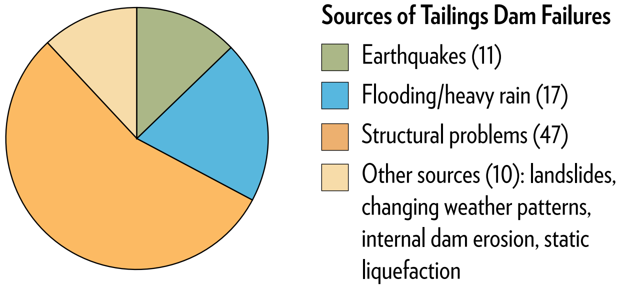
Although slurry pipelines are an economical way to transport large quantities of mineral to the port, there is risk that the pipeline carrying abrasive and corrosive copper-gold concentrate slurry (or any of the other three pipelines) may leak or break. According to Ecology and Environment Inc. (2010) "a pipeline break or spill could result in thousands of gallons of metal-laden slurry being deposited into sensitive anadromous streams." Most slurry pipeline breaks occur as the result of abrasion and corrosion, but earthquakes have caused at least one major spill (Mining Watch 2005). In Alaska, there is also a risk that the concentrate might freeze and break the pipe if the flow stopped because of a pump failure in the winter (Coulter 1976, McKetta 1992, Julien et al. 2002).

3.7 Tailings Dam Failures

In addition to the slow, chronic release of contaminants from the tailings and potential leakage into ground and surface waters, it is important to recognize the large-scale pollution events that could result from a tailings dam failure. Unlike a dam built to impound water, which can be drained if the dam loses structural integrity, tailings embankments must be built to function in perpetuity (Figure 13, p. 38). Despite the manifest need for perpetual stability, since 1970 the number of tailings dam failures has greatly exceeded the failures of dams used for water supply (ICOLD 2001). State and federal permits for all large mines in the United States specify construction standards to prevent the accidental discharge of toxic effluents and the catastrophic failure of mine dams. Nonetheless, several tailings dams have failed in the United States and elsewhere around the world (WISE 2011).

The International Commission on Large Dams (ICOLD) has compiled global data on reported tailings dams failures, breaches, and mudflows worldwide (ICOLD 2001, Cambridge 2005). ICOLD reported 72 tailings dam accidents in the United States and 11 in Canada between 1960 and 2000 (ICOLD 2001). Similarly, according to the World Information Service on Energy (WISE), 85 major mine tailings dams failed between 1960 and 2006 (WISE 2011). Twenty-four of the 85 tailings dams that failed were copper or gold mines (Figure 11), and failures occurred in all types of tailings dam construction (USSD 1994). The majority of failures happened at operating mines, and 39% of them occurred in the United States, indicating that failures are not merely a consequence of dated technology or limited regulation.

Figure 11. According to a study by the World Information Service on Energy (WISE), 85 major mine tailings dams failed between 1960 and 2006. Common causes included structural problems, flooding or rain, and earthquakes (WISE 2011).



Precipitation and Flooding

Rico et al. (2008) analyzed these and other data, categorizing the most common causes of tailings dam failure across Europe and the world. They found that the primary causes of failure related to meteorological events, such as unusual snow and rainfall events or periods. These accounted for 25% of the cases worldwide and 35% in Europe. Saturation of part or all of a tailings dam can lead to *static load-induced liquefaction*, which refers to the loss of strength in saturated material because of the build-up of pore water pressures unrelated to dynamic forces like earthquakes (Davies et al. 2002). Static load-induced liquefaction is much better understood today than it was even 10 years ago, and the engineering considerations required to avoid this type of failure are now routinely applied during the design of tailings dams. However, the risk of static liquefaction has not been fully eliminated.

CASE STUDIES: TAILINGS DAM FAILURES

Martin County Coal Corporation (Kentucky)

Failure: In 2000, a coal tailings dam failed, releasing slurry consisting of an estimated **250 million gallons of water and 155,000 cubic yards of coal waste** into local streams (American Geological Institute 2003).

Impact: About **75 miles** of rivers and streams turned an iridescent black, causing a fish kill along the Tug Fork of the Big Sandy River and some of its tributaries. At least 395,000 fish were killed, and towns along the Tug River were forced to turn off their drinking water intakes. The spill contained measurable amounts of metals, including arsenic, mercury, lead, copper, and chromium (but not enough to pose health problems in treated water).

Cost: **Over $46 million** (American Geological Institute 2003). The full extent of the environmental damage is not yet known, and estimates of the cleanup costs go as high as $60 million (WISE 2008).

Brewer Gold Mine (South Carolina)

Failure: In 1990, a tailings dam failed after heavy rains and spilled **10 million gallons of sodium cyanide solution** into Little Fork Creek (USEPA 2005).

Impact: Fish died in the Lynches River at least **49 miles** downstream (USEPA 1991).

Cost: The British mining company that operated the mine **abandoned the site** in 1999, and EPA declared it a Superfund site in 2004 because of heavy metals pollution and acid mine drainage.

Buffalo Creek Valley (West Virginia)

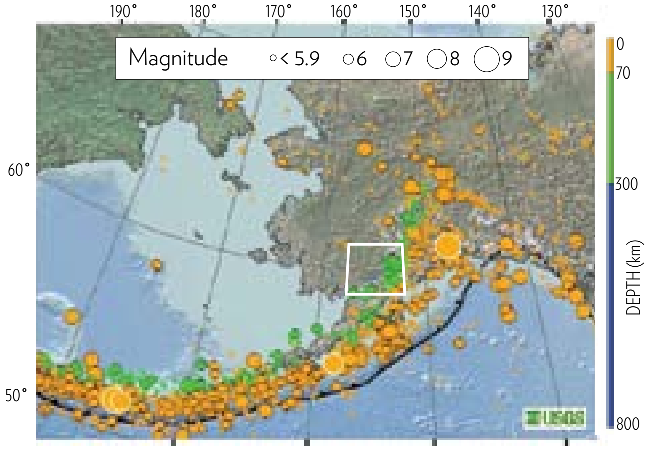
Failure: In 1972, a coal waste impoundment at the head of Buffalo Creek failed.

Impact: 125 people killed, 500 homes destroyed, water quality degradation.

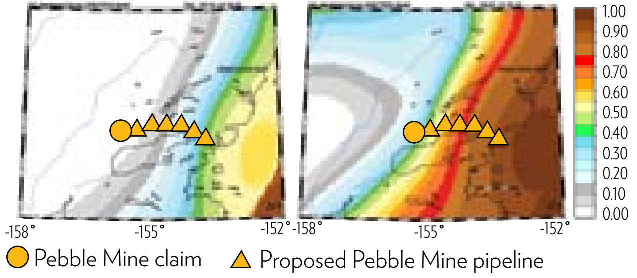
Cost: **Over $400 million** (ASDO, 2007).

Figure 12. Seismic activity between 1990 and 2009; probability of future earthquakes; and major fault lines in and around the mining district (Higman and Mattox 2009, USGS 2010a, 2010b). Since 1899, there have been numerous 6.0-6.9 earthquakes and three 7.0+ earthquakes within 125 miles of the Pebble site.

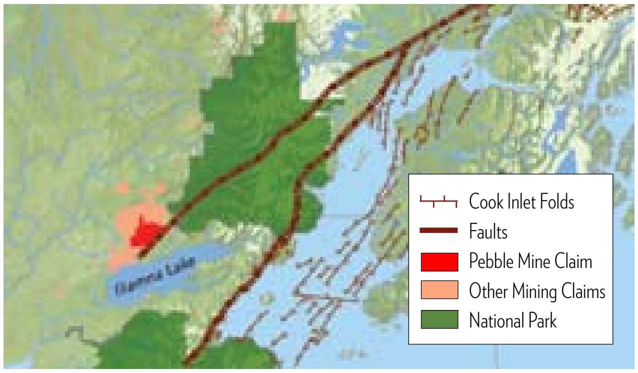
Seismic Activity in Alaska 1990–2009



Probability model of 6.0 magnitude earthquake


100 years **1000 years**

Major and minor faults near proposed Pebble Mine



In addition to liquefaction, rain and snow events may also lead to flooding. Precipitation and flood models are used to inform dam design, but the limited streamflow and weather data available for the Pebble Mine site may not yield accurate predictions of 100, 500, or 1,000-year flood events in the area. At the Red Dog Mine in the Brooks Range north of Kotzebue, Alaska, wastewater was released when unanticipated levels of snowmelt and rainfall threatened to overtop the dam the year after the mine opened (Ott and Scannell 1993). Flood projections also may not accurately account for climate changes predicted to produce heavier and more frequent rainfall and increased rain-on-snow events (IPCC 2007). United States Geological Survey (USGS) predictions of 100-year or greater flood flows for the Kenai Peninsula—where three floods exceeding USGS 100-year flood predictions have occurred in a 20-year period—may have to be revised because of rapidly melting glaciers and more severe rainstorms (Eash and Rickman 2004). Long-term climate change and likely impacts to formerly frozen or partially frozen ground will impact many assumptions concerning water management and the stability of facilities at the Pebble site.

Earthquakes

Seismic liquefaction has been identified as the second most common cause of tailings dam failure worldwide (Rico et al. 2008). The Pebble tailings dams will be constructed on top of glacial till and fractured bedrock (Knight Piesold Consulting 2006a, 2006b) in a seismically active area (Haeussler et al. 2005). The design of the dams, constructed of waste rock and overburden, is based in part on current understanding of the location of local faults and the potential force of future earthquakes. (Figure 12 summarizes recent seismic activity and future earthquake probabilities in the Bristol Bay region.) The Preliminary Assessment recognizes two seismic zones that could affect the Pebble Project, including the large Pacific Plate–North American Plate subduction zone located offshore, and the Lake Clark Fault (Ghaffari et al. 2011).

Dams are engineered to withstand overtopping from the probable maximum flood and shaking resulting from large earthquakes, but in each of these instances, assumptions must be made as to the magnitude of these "maximum" events. While the Preliminary Assessment characterizes as "conservative" the parameters used to determine seismic events—and the seismic design of the tailings storage facility—assumptions made in determining both the location and return period (which influences the calculation of the force) of future seismic events call into question just how conservative these determinations may be (Chambers et al. 2011). For example, although Northern Dynasty consultants estimated the Lake Clark Fault to be 18 miles from the Pebble Mine site (Knight Piesold Consulting 2006a), according to Chambers et al. (2011) "the location of the Lake Clark Fault is not known, and it is possible that it runs directly through the area of proposed development at Pebble." It is worth noting that the 2002 magnitude 7.9 Denali Fault earthquake revealed an unknown fault now named the Susitna Glacier Fault (Crone et al. 2004).

According to Woody and Higman (2011), "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.....Hydrologic exchange patterns between ground and surface waters in alluvial systems can be highly complex and difficult to map and predict." Such complex interactions between surface and groundwater systems exacerbate the significant challenge of controlling mining related contamination (photo by Erin McKittrick).

If one earthquake in the next 1,000 years is stronger than the maximum predicted, or if a previously undetected fault extending into the mine area triggers a significant earthquake, the tailings storage dams may fail and release the stored waste into the Nushagak and/or Kvichak watersheds. With the largest dam potentially reaching a height of 740 feet (Knight Piesold Consulting 2006a) and the Bristol Bay region experiencing 5.0-magnitude earthquakes an average of once per year, it is possible that a seismic event could cause a tailings dam failure of very large proportions (Haeussler and Plakfer 1995, AA 2009a, USGS 2009a, 2009b, 2009c). The probability of such a massive failure is relatively low in the short term, but the consequences (discussed later in this section) should it occur could be catastrophic. The longer a tailings dam is in place, the greater the probability of catastrophic failure.

An earthquake would not have to destroy the dams to release the toxic materials into the groundwater and into adjacent salmon-spawning streams. If an earthquake opened cracks in the bedrock below the dam or cracked the seepage-collection system, it could allow the hundreds of billions of cubic feet of contaminated water stored in the facility to leak into ground and surface waters.

Deterioration of Infrastructure

Man-made structures deteriorate as they age, and Rico et al. (2008) identified several types of infrastructure failure as causes of tailings dam failure. Over time, the complex system of liners, pipes, drains, and pumps necessary to control leakage under a mine waste—and maintain the stability of a dam—deteriorate and fail in the corrosive environment and under the crushing weight of millions—or in the case of the Pebble Mine—billions of tons of fluid tailings. Pollutions control structures placed in or under tailings impoundments or earth-fill dams are extremely expensive and logistically challenging to repair or replace. And unlike work in a typical reservoir, operators cannot simply release water contaminated by acid mine drainage before making repairs.

Impacts of Failure

A failure of one of the massive tailings dams planned for the Pebble Mine would have devastating short and long-term consequences for the receiving waters. Even a relatively small event could release a torrent of polluted water downstream, burying the receiving water body in a sludge of mine wastes. Further downstream, silt could clog stream gravels and turn the clear streams turbid, eliminating critical salmon habitat. The failure of the much smaller tailings dam at the Brewer Gold Mine in South Carolina killed all of the fish in the Lynches River for 49 miles downstream (USEPA 2005). In Kentucky, the failure of the Martin County Coal Corporation's tailings dam, which contained 250 million gallons of liquid waste and 155,000 cubic yards of solids, contaminated 75 miles of the Big Sandy Fork River (see the sidebar on p. 35). These are small spills, however, in comparison to the billions of gallons of water and over 10 billion tons of waste that could be released in a failure at the Pebble site.

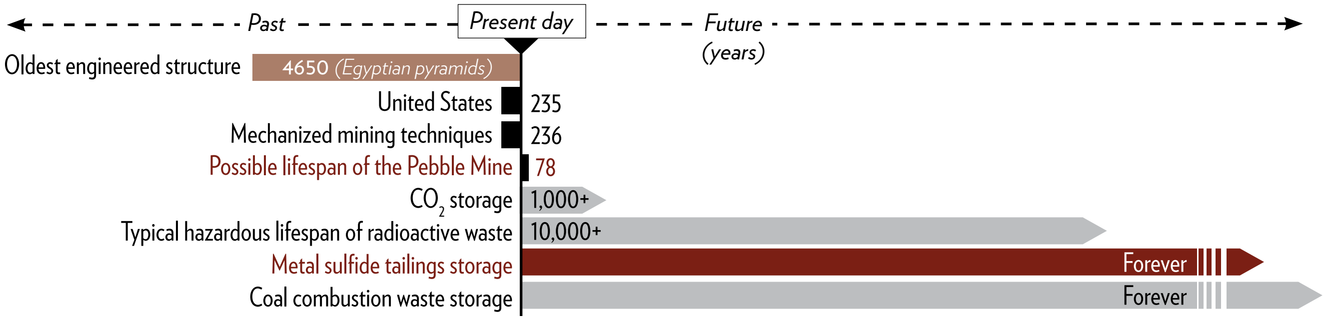
A major tailings dam failure due to an earthquake, flood, structural flaw, or any combination of these could release billions of tons of mine waste into the North or South Fork of the Koktuli River. This material would then flow downstream into the Nushagak or Kvichak River drainages. Mine tailings washed downstream would expose the pyritic tailings to oxygen, potentially leading to acid waters. Introduction of acid waters into streams would extirpate salmon at least in the upper reaches (Parsons 1977, Ledin and Pedersen 1996, Levings et al. 2004, Dubé et al. 2005); the lower reaches of the streams would see elevated contaminant concentrations and reduced prey for salmon consumption (Levings et al. 2004).

If acid waters reached Lake Iliamna, some percentage of the billions of fry that rear in the lake could be harmed, potentially removing generations of production. In British Columbia, exposure of juvenile Chinook salmon to waters mixed with acid mine drainage led to 100% mortality within just two days (Barry et al. 2000). In the extraordinarily productive Bristol Bay tributaries, a major failure of a tailings storage facility could kill hundreds of thousands to millions of adult salmon and resident fish, depending on when and where the spill occurred. Furthermore, fish production might be permanently eliminated or impaired in the streams directly affected by the spill, and salmonid migrations would be impaired until the toxic tailings are removed (Ecology and Environment, Inc. 2010). According to Hughes (1985), in some instances, the effects of toxic sediments resulting from tailings dam accidents are still being reported over a century after the incident took place.

The sizes and locations of tailings storage facilities required for the Pebble Mine, coupled with the need for these facilities to remain intact and fully functional for thousands of years after the mine is closed, present a substantial threat to downstream fish populations. In the short term, the risk that the tailings dams will leak or fail in any given year may be small. Over the long time span that these dams must contain their toxic contents in place, however, the probability that a release will occur becomes much higher.

Even if accurate projections of earthquake location, frequency, and force coupled with conservative tailings dam designs allow wastes to be fully controlled over the long term, it is worth noting that "human management/operation" and "unknown causes" ranked as the third and fourth highest causes of tailings dam failure worldwide and in Europe (Rico et al. 2008). This point requires little discussion. Over the long term, technology and engineering are only as reliable as the inevitably flawed humans who apply them.

Figure 13. Engineering for Perpetual Storage. The longest time horizon formally considered for the active life of the Pebble Mine is 78 years (Ghaffari et al. 2011). The mine's pollution-control facilities, however, must function forever to protect the aquatic resources of the Bristol Bay basin. Unlike a dam built to impound water, which can be drained if the dam loses its structural integrity, tailings dams must be built to function in perpetuity (Higman 2010).



Adapted from Higman 2010

Bristol Bay fisherman (photo by Bob Waldrop).