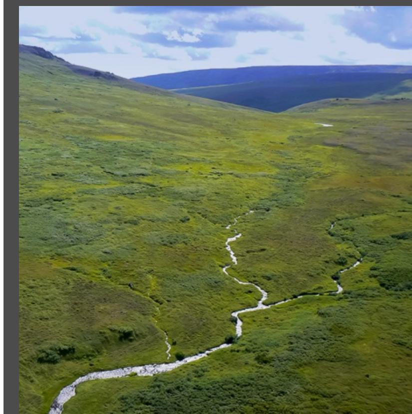


EXECUTIVE SUMMARY

The Bristol Bay watershed in southwestern Alaska supports the largest sockeye salmon fishery in the world, is home to 25 federally recognized tribal governments, and contains significant mineral resources. The potential for large-scale mining activities in the watershed has raised concerns about the impact of mining on the sustainability of Bristol Bay's world-class commercial, recreational, and subsistence fisheries and the future of Alaska Native tribes in the watershed, who have maintained a salmon-based culture and subsistence-based way of life for at least 4,000 years.

The U.S. Environmental Protection Agency (USEPA) launched this assessment to determine the significance of Bristol Bay's ecological resources and evaluate the potential impacts of large-scale mining on these resources. It uses the well-established methodology of an ecological risk assessment, which is a type of scientific investigation that provides technical information and analyses to foster public understanding and inform future decision making. As a scientific assessment, it does not discuss or recommend policy, legal, or regulatory decisions, nor does it outline or analyze options for future decisions.

This assessment characterizes the biological and mineral resources of the Bristol Bay watershed. It is intended to increase understanding of potential impacts of large-scale mining on the region's fish resources and serve as a technical resource for the public and for federal, state, and tribal governments as they consider how best to address the challenges posed by mining and ecological protection in the Bristol Bay watershed. It will inform ongoing discussions of the risks of mine development to the sustainability of the Bristol Bay salmon fisheries and thus will be of value to the many stakeholders in this debate.

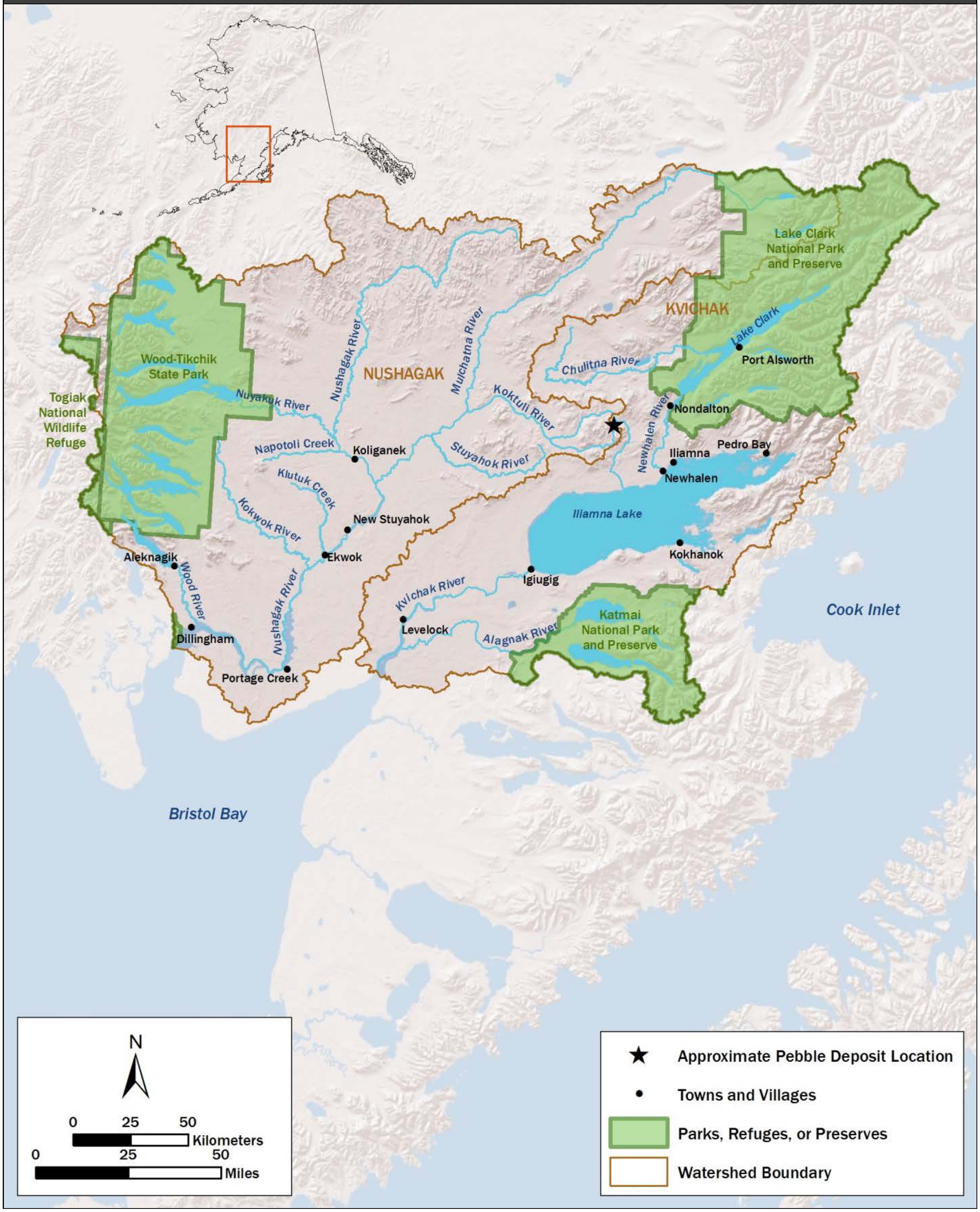
The assessment also will inform the consideration of options for future government action, including, possibly, by USEPA, which has been petitioned by multiple groups to address mining activity in the Bristol Bay watershed using its authority under the Clean Water Act (CWA). Should specific mine projects reach the permitting stage, the assessment will enable state and federal permitting authorities to make informed decisions to grant, deny, or condition permits and/or conduct additional research or assessment as a basis for such decisions. USEPA conducted this assessment consistent with its authority under the CWA Section 104(a) and (b).

Scope of the Assessment

This assessment reviews, analyzes, and synthesizes information relevant to potential impacts of large-scale mine development on Bristol Bay fisheries and consequent effects on wildlife and Alaska Native cultures in the region. Given the economic, ecological, and cultural importance of the region's key salmonids (sockeye, Chinook, coho, chum, and pink salmon, as well as rainbow trout and Dolly Varden) and stakeholder and public concern that a mine could affect those species, the primary focus of the assessment is the abundance, productivity, and diversity of these fishes. Because wildlife in Bristol Bay are intimately connected to and dependent on these and other fishes, changes in these fisheries are expected to affect the abundance and health of wildlife populations. Alaska Native cultures have strong nutritional, cultural, social, and spiritual dependence on salmon, so changes in salmon fisheries are expected to affect the health and welfare of Alaska Native populations. Therefore, wildlife and Alaska Native cultures are also considered as assessment endpoints, but only as they are affected by changes in salmonid fisheries.

The assessment considers multiple geographic scales. The largest scale is the Bristol Bay watershed, which is a largely undisturbed region with outstanding natural, cultural, and mineral resources. Within the larger Bristol Bay watershed, the assessment focuses on the Nushagak and Kvichak River watersheds (Figure ES-1). These are the largest of the Bristol Bay watershed's six major river basins, containing about 50% of the total watershed area, and are identified as mineral development areas by the State of Alaska. Given its size and extent of characterization, the Pebble deposit is the most likely site for near-term, large-scale mine development in the region. Because the Pebble deposit is located in the headwaters of tributaries to both the Nushagak and Kvichak Rivers, both of these watersheds are subject to potential risks from mining. The third geographic scale is the watersheds of the three tributaries that originate within the potential footprint of a mine on the Pebble deposit: the South Fork Koktuli River, which drains the Pebble deposit area and converges with the North Fork west of the Pebble deposit; the North Fork Koktuli River, located to the northwest of the Pebble deposit, which flows into the Nushagak River via the Koktuli and Mulchatna Rivers; and Upper Talarik Creek, which drains the eastern portion of the Pebble deposit and flows into the Kvichak River via Iliamna Lake, the largest undeveloped lake in the United States (Figure ES-1). The mine footprints in the three realistic mine scenarios evaluated in the assessment make up the fourth geographic scale. These scenarios—Pebble 0.25, Pebble 2.0, and Pebble 6.5—define three potential mine sizes, representing different stages in the potential mining of the Pebble deposit. The final geographic scale is the combined area of the subwatersheds between the mine footprints and the Kvichak River watershed's eastern boundary that would be crossed by a transportation corridor linking the mine site to Cook Inlet.

Figure ES-1. The Nushagak and Kvichak River watersheds of Bristol Bay.



The assessment also addresses two periods for mine activities. The first is the development and operation phase, during which mine infrastructure would be built and the mine would be operated. This phase may last from 20 to 100 years or more. The second is the post-mining phase, during which the site would be monitored and maintained. Water treatment and other waste management activities would continue as necessary and any failures would be remediated. Because mine wastes would be persistent, this period could continue for centuries and potentially in perpetuity.

We began the assessment with a thorough review of what is known about the Bristol Bay watershed, its fisheries and wildlife populations, and its Alaska Native cultures. We also reviewed information about copper mining and publicly available information outlining proposed mine operations for the Pebble deposit. The Pebble deposit has been the focus of much exploratory study and has received significant attention from groups in and outside of Alaska. With the help of regional stakeholders, we developed a set of conceptual models to show potential associations between salmon populations and the environmental stressors that might reasonably result from large-scale mining. Then, following the USEPA's ecological risk assessment framework, we analyzed the sources and exposures that would occur and potential responses to those exposures. Finally, we characterized the risks to fish habitats, salmon, and other fish populations, as well as the implications of those risks for the wildlife and Alaska Native cultures that use them.

This is not an in-depth assessment of a specific mine, but rather an examination of potential impacts of reasonably foreseeable mining activities in the Bristol Bay region, given the nature of the watershed's mineral deposits and the requirements for successful mine development. The assessment analyzes mine scenarios that reflect the expected characteristics of mine operation at the Pebble deposit. It is intended to provide a baseline for understanding potential impacts of mine development, not just at the Pebble deposit but throughout the Nushagak and Kvichak River watersheds. The mining of other existing porphyry copper deposits in the region would be expected to include the same types of activities and facilities evaluated in this assessment for the Pebble deposit (open pit mining and the creation of waste rock piles and tailings storage facilities [TSFs]), and therefore would present potential risks similar to those outlined in this assessment. However, because the region's other ore bodies are believed to be much smaller than the Pebble deposit, those mines would likely be most similar to the smallest mine scenario analyzed in this assessment (Pebble 0.25).

This assessment considers many but not all potential impacts associated with future large-scale mining in the Bristol Bay watershed. Although the mine scenarios assume development of a deep-water port on Cook Inlet to ship product concentrate elsewhere for smelting and refining, impacts of port development and operation are not assessed. The assessment does not evaluate impacts of the one or more large-capacity electricity-generating power plants that would be required to power the mine and the port. We recognize that large-scale mine development would induce the development of additional support services for mine employees and their families, vacation homes and other recreational facilities, and transportation infrastructure beyond the main corridor (i.e., airports, docks, and roads). The assessment describes but does not evaluate the effects of induced development resulting from large-scale mining in the region. Direct effects of mining on Alaska Natives and wildlife are not assessed. The assessment also does not include a cost-benefit analysis and does not compare mining to other ongoing activities such as commercial fishing.

Ecological Resources

The Bristol Bay watershed provides habitat for numerous animal species, including at least 29 fish species, more than 40 terrestrial mammal species, and more than 190 bird species. Many of these species are essential to the structure and function of the region's ecosystems and current economies. The Bristol Bay watershed supports several wilderness compatible and sustainable economic sectors, such as commercial, sport, and subsistence fishing; sport and subsistence hunting; and non-consumptive recreation. Considering all these sectors, the Bristol Bay watershed's ecological resources generated nearly $480 million in direct economic expenditures and sales in 2009 and provided employment for over 14,000 full- and part-time workers.

Chief among these ecological resources are world-class commercial and sport fisheries for Pacific salmon and other salmonids. The region's commercial salmon fishery generates the largest component of economic activity. The watershed supports production of all five species of Pacific salmon found in North America: sockeye (*Oncorhynchus nerka*), coho (*O. kisutch*), Chinook (*O. tshawytscha*), chum (*O. keta*), and pink (*O. gorbuscha*) (Figure ES-2). These fishes are anadromous, meaning that they hatch and rear in freshwater systems, migrate to sea to grow to adult size, and return to freshwater systems to spawn and die. Because no hatchery fish are raised or released in the watershed, Bristol Bay's salmon populations are entirely wild.

The most abundant salmon species in the Bristol Bay watershed is sockeye salmon. The watershed supports the largest sockeye salmon fishery in the world, with approximately 46% of the average global abundance of wild sockeye salmon (Figure ES-3). Between 1990 and 2009, the annual average inshore run of sockeye salmon in Bristol Bay was approximately 37.5 million fish. Annual commercial harvest of sockeye over this same period averaged 25.7 million fish. Approximately half of Bristol Bay's sockeye salmon production is from the Nushagak and Kvichak River watersheds, the main area of focus for this assessment (Figure ES-3).

Chinook salmon are also abundant in the region. Chinook returns to the Nushagak River are consistently greater than 100,000 fish per year and have exceeded 200,000 fish in 11 years between 1966 and 2010, frequently placing Nushagak River Chinook runs at or near the world's largest. This is noteworthy given the Nushagak River's small watershed area compared to other Chinook-producing rivers such as the Yukon River, which spans Alaska and much of northwestern Canada, and the Kuskokwim River in southwestern Alaska, just north of Bristol Bay.

Figure ES-2. Reported salmon (sockeye, Chinook, coho, pink, and chum combined) distribution in the South and North Fork Koktuli River and Upper Talarik Creek watersheds. Designation of species spawning, rearing, and presence is based on the Anadromous Waters Catalog (Johnson and Blanche 2012). Life-stage-specific reach designations are believed to be underestimates, given the challenges inherent in surveying all streams that may support life-stage use throughout the year.

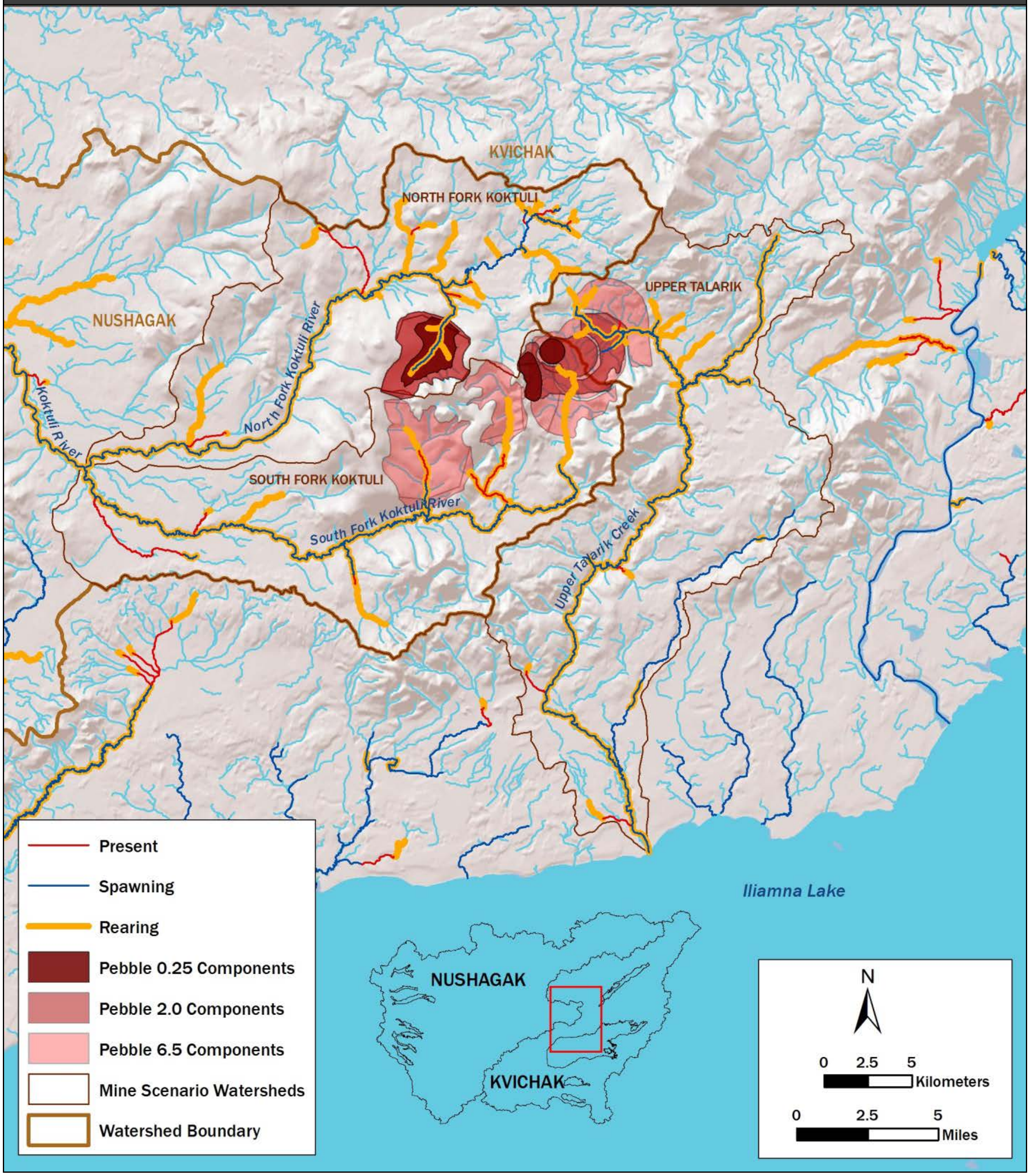
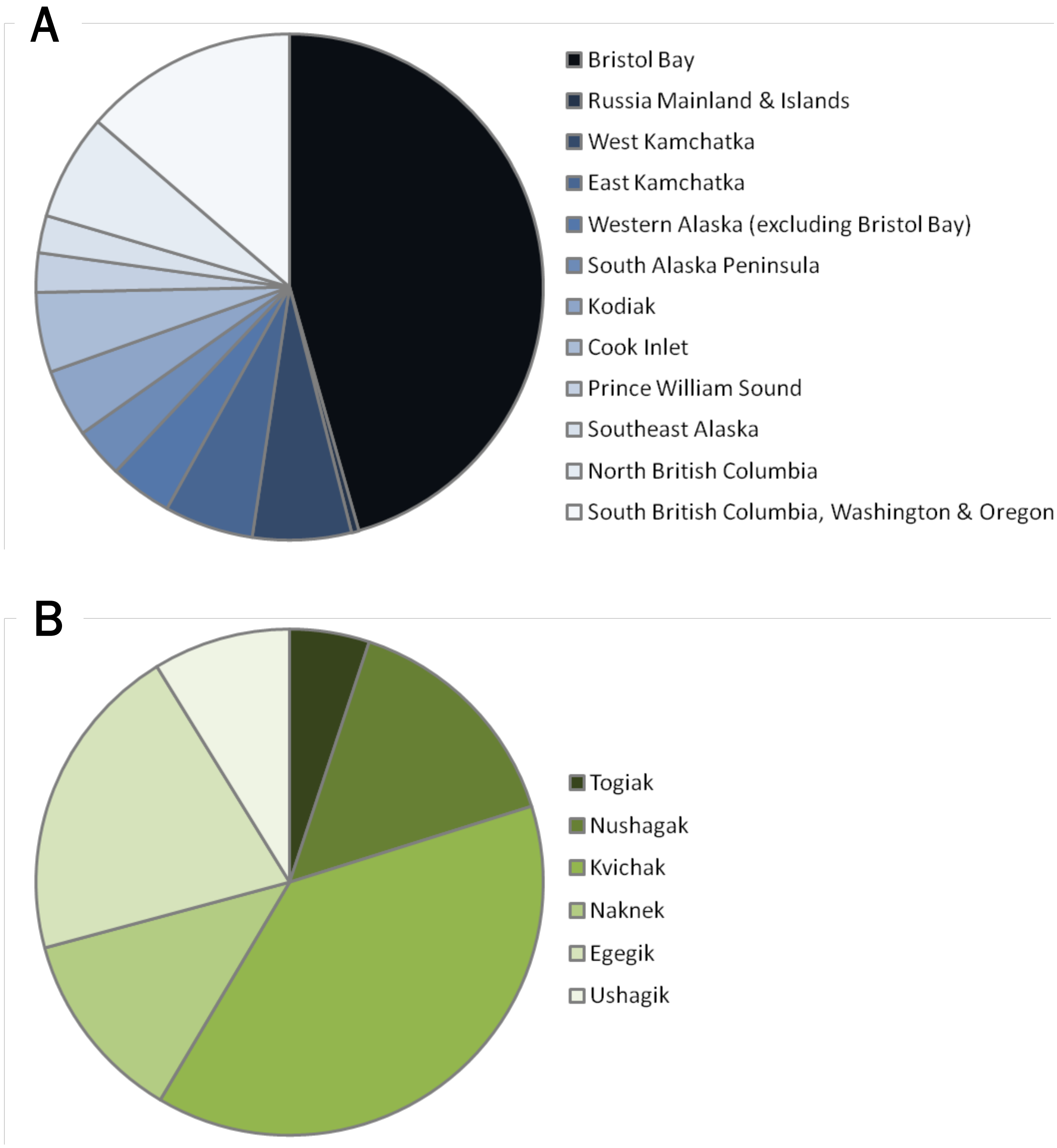


Figure ES-3. Proportion of total sockeye salmon run sizes by (A) region and (B) watershed in the Bristol Bay region. Values are averages from (A) 1956 to 2005 from Ruggerone et al. 2010 and (B) 1956 to 2010 from Baker pers. comm.



The Bristol Bay watershed also supports populations of non-salmon fishes that typically (but not always) remain in the watershed's freshwater habitats throughout their life cycles. The region contains highly productive waters for sport and subsistence fish species, including rainbow trout (*O. mykiss*), Dolly Varden (*Salvelinus malma*), Arctic char (*S. alpinus*), lake trout (*S. namaycush*), Arctic grayling (*Thymallus arcticus*), northern pike (*Esox lucius*), and humpback whitefish (*Coregonus pidschian*). These fishes occupy a variety of habitats in the watershed, from headwater streams to wetlands to large rivers and lakes. The Bristol Bay region is especially renowned for the size and abundance of its rainbow trout: between 2003 and 2007, an estimated 183,000 rainbow trout were caught in the Bristol Bay Management Area.

The exceptional quality of the Bristol Bay watershed's fish populations can be attributed to several factors, the most important of which is the watershed's high-quality, diverse aquatic habitats unaltered by human-engineered structures and flow management controls. Surface and subsurface waters are highly connected, enabling hydrologic and biochemical connectivity between wetlands, ponds, streams, and rivers and thereby increasing the diversity and stability of habitats able to support fish. These factors all contribute to making the Bristol Bay watershed a highly productive system. High aquatic habitat diversity also supports the high genetic diversity of fish populations. This diversity in genetics, life history, and habitat acts to reduce year-to-year variability in total production and increase overall stability of the fishery.

The return of spawning salmon from the Pacific Ocean brings marine-derived nutrients into the watershed and fuels both aquatic and terrestrial foodwebs. Thus, the condition of Bristol Bay's terrestrial ecosystems is intimately linked to the condition of salmon populations, as well as to almost totally undisturbed terrestrial habitats. The watershed continues to support large carnivores such as brown bears (*Ursus arctos*), bald eagles (*Haliaeetus leucocephalus*), and gray wolves (*Canis lupus*); ungulates such as moose (*Alces alces gigas*) and caribou (*Rangifer tarandus granti*); and numerous waterfowl and small mammal species. Brown bears are abundant in the Nushagak and Kvichak River watersheds. Moose also are abundant, particularly in the Nushagak River watershed where felt-leaf willow, a preferred forage species, is plentiful. The Nushagak and Kvichak River watersheds are used by caribou, primarily the Mulchatna caribou herd. This herd ranges widely through these watersheds, but also spends considerable time in other watersheds.

Alaska Native Cultures

The predominant Alaska Native cultures present in the Nushagak and Kvichak River watersheds—the Yup'ik and Dena'ina—are two of the last intact, sustainable, salmon-based cultures in the world. In contrast, other Pacific Northwest salmon-based cultures are severely threatened by development, degraded natural resources, and declining salmon resources. Salmon are integral to these cultures' entire way of life via the provision of subsistence food and subsistence-based livelihoods, and are an important foundation for their language, spirituality, and social structure. The cultures have a strong connection to the landscape and its resources. In the Bristol Bay watershed, this connection has been maintained for at least 4,000 years and is in part both due to and responsible for the continued undisturbed condition of the region's landscape and biological resources. The respect and importance given salmon and other wildlife, along with traditional knowledge of the environment, have produced a sustainable subsistence-based economy. This subsistence-based way of life is a key element of Alaska Native identity and serves a wide range of economic, social, and cultural functions in Yup'ik and Dena'ina societies.

There are 31 Alaska Native villages in the wider Bristol Bay region, 25 of which are located in the Bristol Bay watershed. Fourteen of these communities are within the Nushagak and Kvichak River watersheds, with a total population of 4,337 in 2010. Thirteen of these 14 communities have federally recognized tribal governments and a majority Alaska Native population. Many of the non-Alaska Native residents in the watersheds have developed cultural ties to the region and they also practice subsistence. Virtually every household in the watersheds uses subsistence resources. In the Bristol Bay region, salmon constitute approximately 52% of the subsistence harvest; for some communities this proportion is substantially higher.

The subsistence-based way of life in many Alaska Native villages is augmented with activities that support cash economy transactions, including commercial fishing. Alaska Native villages, in partnership with Alaska Native corporations and other business interests, are considering a variety of economic development opportunities. Some Alaska Native villages have decided that large-scale mining is not the course they would like to pursue, whereas a few others are seriously considering this opportunity. All are concerned with the long-term sustainability of their communities.

Geological Resources

In addition to significant and valuable ecological resources, the Nushagak and Kvichak River watersheds contain considerable mineral resources. The potential for large-scale mine development in the region is greatest for copper deposits and, to a lesser extent, for intrusion-related gold deposits. Because these deposits are low-grade—meaning that they contain relatively small amounts of metals relative to the amount of ore—mining will be economic only if conducted over large areas and will necessarily produce large amounts of waste material.

The largest known and most explored deposit is the Pebble deposit. If fully mined, the claim holder estimates that the Pebble deposit would produce more than 11 billion tons of ore, which would make it the largest mine of its type in North America. A mine at the Pebble deposit could ultimately generate revenues between $300 billion to $500 billion over the life of the mine, as well as provide more than 2,000 jobs during mine construction and more than 1,000 jobs during mine operation.

Although the Pebble deposit represents the most imminent site of mine development, other mineral deposits with potentially significant resources exist in the Nushagak and Kvichak River watersheds. Ten specific claims with more than minimal recent exploration (in addition to the Pebble deposit claim) have been filed for copper deposits. Most of these claims are near the Pebble deposit. The potential impacts of large-scale mining considered in this assessment are generally applicable to these other sites.

Mine Scenarios

Like all risk assessments, this assessment is based on scenarios that define a set of possible future activities and outcomes. To assess mining-related stressors that would affect ecological resources in the watershed, we developed realistic mine scenarios that include a range of mine sizes and operating conditions. These mine scenarios are based on the Pebble deposit because it is the best-characterized mineral resource and the most likely to be developed in the near term. The mine scenarios draw on preliminary plans developed for Northern Dynasty Minerals, consultation with experts, and baseline data collected by the Pebble Limited Partnership to characterize the mine site, mine activities, and the surrounding environment. The exact details of any future mine plan for the Pebble deposit or for other deposits in the watershed will differ from our mine scenarios. However, our scenarios reflect the general characteristics of mineral deposits in the watershed, modern conventional mining technologies and practices, the scale of mining activity required for economic development of the resource, and the infrastructure needed to support large-scale mining. Therefore, the mine scenarios evaluated in this assessment realistically represent the type of development plan that would be anticipated for a porphyry copper deposit in the Bristol Bay watershed. Uncertainties associated with the mine scenarios are discussed later in this executive summary.

The three mine scenarios evaluated in the assessment represent different stages of mining at the Pebble deposit, based on the amount of ore processed: Pebble 0.25 (approximately 0.25 billion tons [0.23 billion metric tons] of ore over 20 years), Pebble 2.0 (approximately 2.0 billion tons [1.8 billion metric tons] of ore over 25 years), and Pebble 6.5 (approximately 6.5 billion tons [5.9 billion metric tons] of ore over 78 years). The major parameters of the three mine scenarios are presented in Table ES-1, and their layouts are presented in Figure ES-4. The major components of each mine would be an open mine pit, waste rock piles, and one or more TSFs. Other significant features include plant and ancillary facilities (e.g., a water collection and treatment system, an ore-processing facility, and other facilities associated with mine operations) and the groundwater drawdown zone (the area over which the water table is lowered due to dewatering of the mine pit). An underground extension of the mine, which could increase the size of the mine to 11 billion tons of ore, is not included in this assessment.

Each of these mine scenarios includes a 138-km (86-mile) transportation corridor; 113 km (70 miles) of the corridor would fall within the Kvichak River watershed (Figure ES-5). This corridor would include a gravel-surfaced road and four pipelines (one each for product concentrate, return water, diesel fuel, and natural gas).

The assessment considers risks from routine operation of a mine designed using modern conventional design, practices, and mitigation technologies, assuming no significant human or engineering failures. The assessment also considers various types of failures that have occurred during the operation of other mines and that could occur in this case, including failures of a wastewater treatment plant, a tailings dam, pipelines, and culverts.

Table ES-1. Mine scenario parameters.

Parameter	Mine Scenario		
	Pebble 0.25	Pebble 2.0	Pebble 6.5
Amount of ore mined (billion metric tons)	0.23	1.8	5.9
Approximate duration of mining (years)	20	25	78
Ore processing rate (metric tons/day)	31,100	198,000	208,000
Mine Pit			
Surface area (km^2)	1.5	5.5	17.8
Depth (km)	0.30	0.76	1.24
Waste Rock Pile			
Surface area (km^2)	2.3	13.0	22.6
PAG waste rock (million metric tons)	86	580	4,700
NAG waste rock (million metric tons)	320	2,200	11,000
TSF 1[a]			
Capacity, dry weight (billion metric tons)	0.25	1.97	1.97
Surface area, exterior (km^2)	6.8	16.1	16.1
Maximum dam height (m)	92	209	209
TSF 2[a]			
Capacity, dry weight (billion metric tons)	NA	NA	3.69
Surface area, exterior (km^2)	NA	NA	22.7
TSF 3[a]			
Capacity, dry weight (billion metric tons)	NA	NA	0.96
Surface area, exterior (km^2)	NA	NA	9.82
Total TSF surface area, exterior (km^2)	6.8	16.1	48.6

Notes:
[a] Final value, when TSF is full.
PAG = potentially acid-generating; NAG = non-acid-generating; TSF = tailings storage facility; NA = not applicable.

Figure ES-4. Major mine components for the three scenarios evaluated in the assessment. Pebble 0.25 represents 0.25 billion tons of ore; Pebble 2.0 represents 2.0 billion tons of ore; Pebble 6.5 represents 6.5 billion tons of ore. Each mine footprint includes the mine components shown here, as well as the drawdown zone and the area covered by plant and ancillary facilities. Light blue areas indicate streams and rivers from the National Hydrography Dataset (USGS 2012) and lakes and ponds from the National Wetlands Inventory (USFWS 2012); dark blue areas indicate wetlands from the National Wetlands Inventory (USFWS 2012).

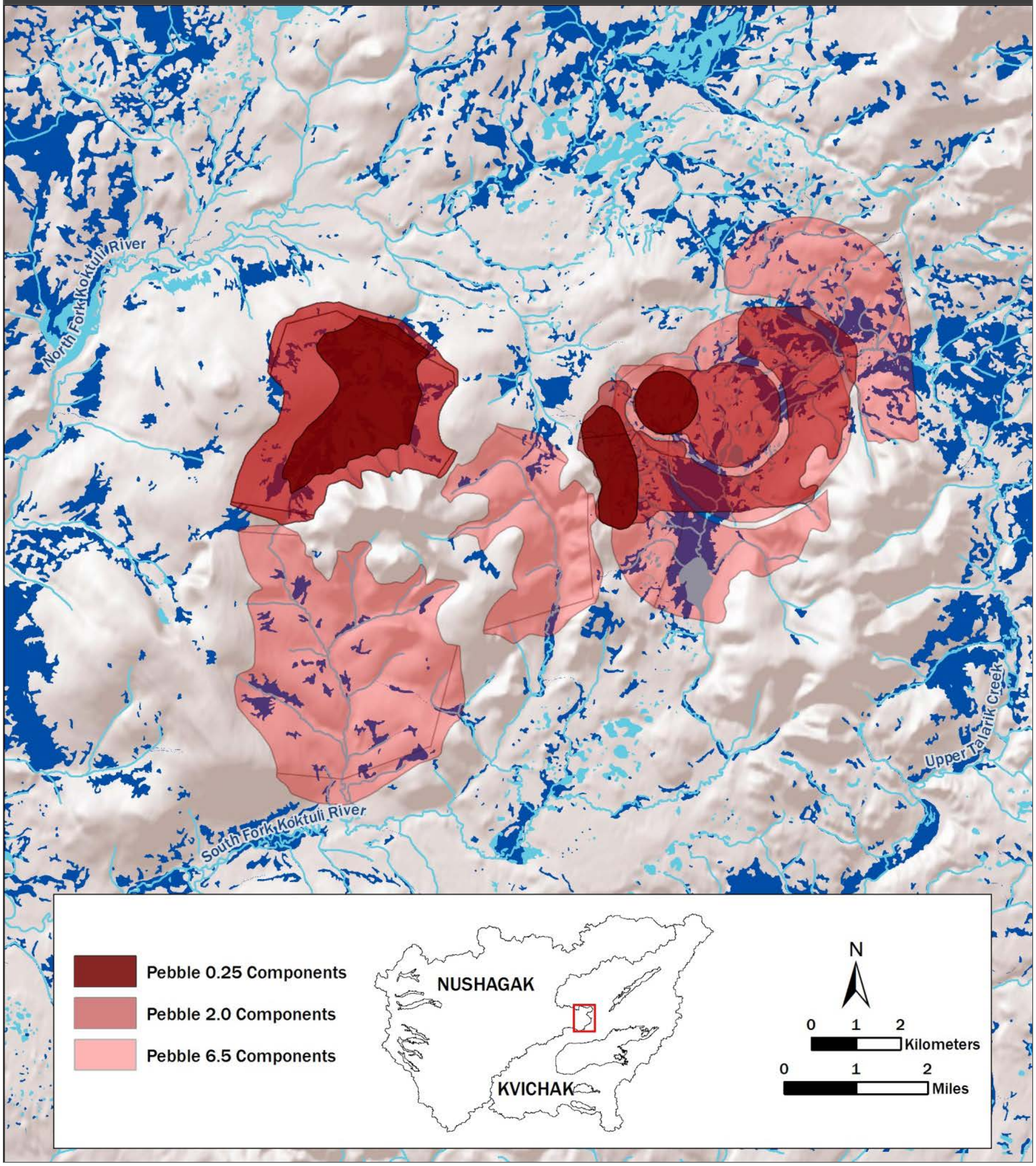
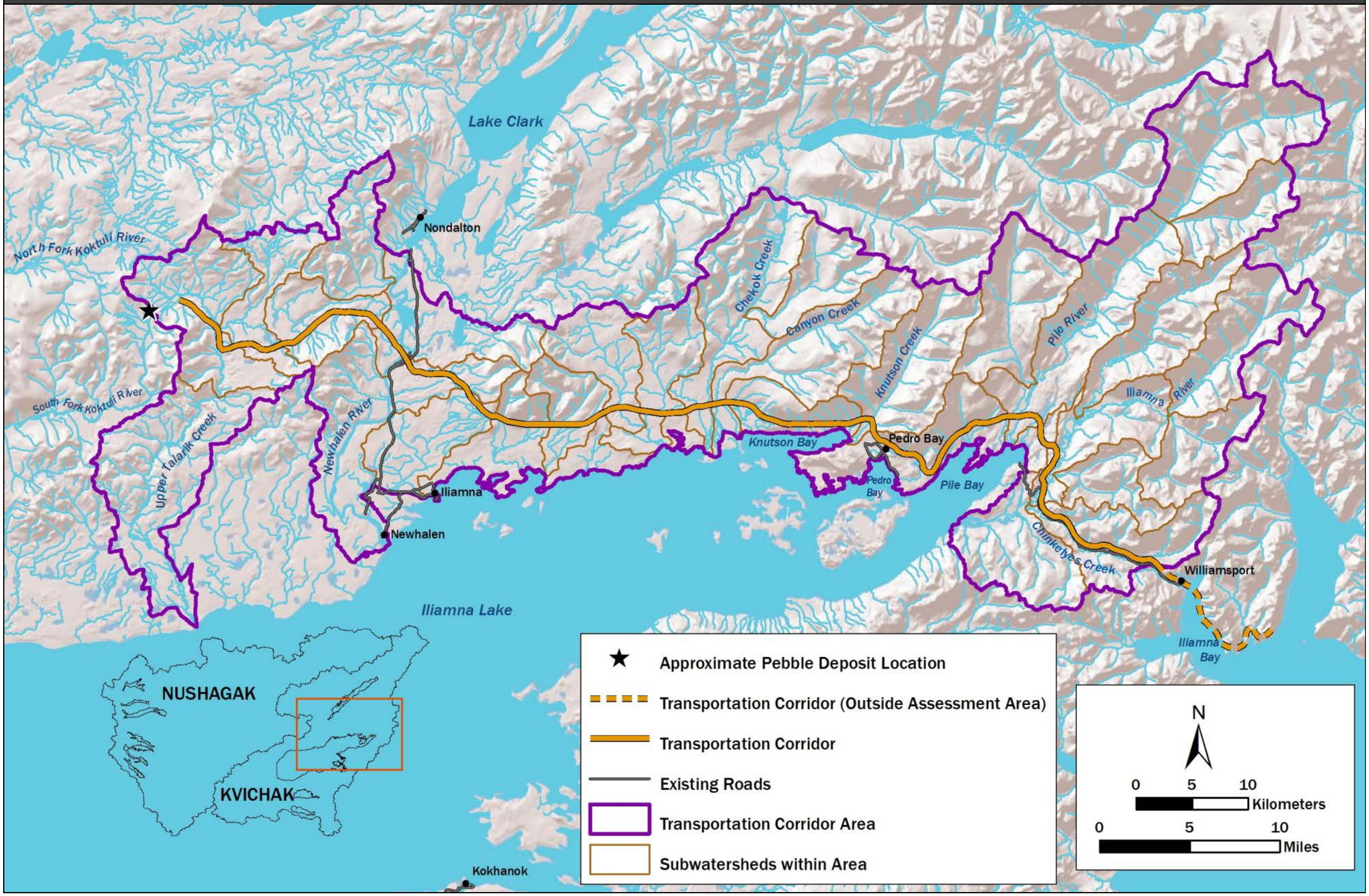


Figure ES-5. The transportation corridor area, comprising 32 subwatersheds in the Kvichak River watershed that drain to Iliamna Lake. Subwatersheds are defined by 12-digit hydrologic unit codes according to the National Hydrography Dataset (USGS 2012).



Risks to Salmon and Other Fishes

Based on the mine scenarios, the assessment defines mining-related stressors that would affect the Bristol Bay watershed's fish and consequently affect wildlife and human welfare. The scenarios include both routine operations (Tables ES-2 and ES-3) and several potential failure scenarios (Table ES-4).

Mine Footprint

Effects on fish resulting from habitat loss and modification would occur directly in the area of mine activity and indirectly downstream because of habitat destruction. These habitat loss estimates are believed to be low due to incomplete delineation of streams, wetlands, and salmon distribution across the region. However, it is possible that careful siting of mine facilities could reduce habitat losses to some degree.

- Due to the mine footprint (the area covered by the mine pit, waste rock piles, TSFs, groundwater drawdown zone, and plant and ancillary facilities), **38, 89, and 151 km (24, 55, and 94 miles) of streams would be lost**—that is, eliminated, blocked, or dewatered—in the Pebble 0.25, 2.0, and 6.5 scenarios, respectively (Table ES-2). This translates to losses of 8, 22, and 36 km (5, 14, and 22 miles) of streams known to provide spawning or rearing habitats for coho salmon, sockeye salmon, Chinook salmon, and Dolly Varden (Table ES-2, Figure ES-6).
- Altered streamflow due to retention and discharge of water used in mine operations, ore processing and transport, and other mine activities would reduce the amount and quality of fish habitat. **Streamflow alterations exceeding 20% would adversely affect habitat in an additional 15, 27, and 53 km (9.3, 17, and 33 miles) of streams** in the Pebble 0.25, 2.0, and 6.5 scenarios, respectively (Table ES-2), reducing production of sockeye salmon, coho salmon, Chinook salmon, rainbow trout, and Dolly Varden. Reduced streamflows would also result in the loss or alteration of an unquantifiable area of riparian floodplain wetland habitat due to loss of hydrologic connectivity with streams.
- Off-channel habitats for salmon and other fishes would be reduced due to **losses of 4.5, 12, and 18 km^2 (1,200, 3,000 and 4,900 acres) of wetlands and 0.41, 0.93, and 1.8 km^2 (100, 230, and 450 acres) of ponds and lakes** to the mine footprints in the Pebble 0.25, 2.0, and 6.5 scenarios, respectively (Figure ES-6). These losses would reduce availability of and access to hydraulically and thermally diverse habitats that provide enhanced foraging opportunities and important rearing habitats for juvenile salmon.
- **Indirect effects of stream and wetland losses** would include reductions in the quality of downstream habitat for coho salmon, sockeye salmon, Chinook salmon, rainbow trout, and Dolly Varden. Although these indirect effects cannot be quantified, such effects would be expected to diminish fish production downstream of the mine site because fish depend on these habitats. Indirect effects would be caused by the following alterations.

- Reduced food resources would result from the loss of organic material and drifting invertebrates from streams and streamside wetlands lost to the mine footprint.
- The balance of surface water and groundwater inputs to downstream reaches would shift, potentially reducing winter fish habitat and making streams less suitable for spawning and rearing.
- Seasonal temperatures could be altered by water treatment and reduced groundwater flowpaths, making streams less suitable for salmonids.

Water Quality

Leakage during Routine Operations

Water from the mine site would enter streams through wastewater treatment plant discharges and in uncollected runoff and leakage of leachates from the waste rock piles and TSFs. Wastewater treatment is assumed to meet all state standards and national criteria, or equivalent benchmarks for chemicals that have no criteria. However, water quality would be diminished by uncollected leakage of tailings and waste rock leachates from the containment system, which would occur during routine operations. Test leachates from the tailings and non-acid-generating waste rocks are mildly toxic. They would require an approximately two-fold dilution to achieve water quality criteria for copper, but are not estimated to be toxic to salmonids. Waste rocks associated with the ore body are acid-forming with high copper concentrations in test leachates, and would require 2,900- to 52,000-fold dilution to achieve water quality criteria. Several metals could be sufficiently elevated to contribute to toxicity, but copper is the dominant toxicant.

Uncollected leachates from waste rock piles and TSFs would elevate instream copper levels and cause direct effects on salmonids ranging from aversion and avoidance of the contaminated habitat to rapidly induced death of many or all fish (Table ES-2). Avoidance of streams by salmonids would occur in 24 and 34 to 57 km (15 and 21 to 35 miles) of streams in the Pebble 2.0 and Pebble 6.5 scenarios, respectively. Rapidly induced death of many or all fish would occur in 12 km (7.4 miles) of streams in the Pebble 6.5 scenario. Copper would cause death or reduced reproduction of aquatic invertebrates in 21, 40 to 62, and 60 to 82 km (13, 25 to 38, and 37 to 51 miles) of streams in the Pebble 0.25, 2.0, and 6.5 scenarios, respectively. These invertebrates are the primary food source for juvenile salmon and all life stages of other salmonids, so reduced invertebrate productivity would be expected to reduce fish productivity. These results are sensitive to the assumed efficiency of the leachate capture system, and a more efficient system could be devised. However, greater than 99% capture efficiency would be required to prevent exceedance of the copper criteria for the South Fork Koktuli River in the Pebble 6.5 scenario, which would require technologies beyond those specified in our scenarios or identified in the most recent preliminary mine plan.

Wastewater Treatment Plant Failure

Based on a review of historical and currently operating mines, some failure of water collection and treatment systems would be expected to occur during operation or post-closure periods. A variety of water collection and treatment failures are possible, ranging from operational failures that result in short-term releases of untreated or partially treated leachates to long-term failures to operate water collection and treatment systems in perpetuity. A reasonable but severe failure scenario would involve a complete loss of water treatment and release of average untreated wastewater flows into average dilution flows. In that failure scenario, copper concentrations would be sufficient to cause direct effects on salmonids in 27, 64 to 87, and 74 to 97 km (17, 40 to 54, and 46 to 60 miles) of streams in the Pebble 0.25, 2.0, and 6.5 scenarios, respectively. Aquatic invertebrates would be killed or their reproduction reduced in 78 to 100 km (48 to 62 miles) of streams in all three scenarios. In the Pebble 2.0 and 6.5 scenarios, a fish kill would occur rapidly in 3.8 and 31 km (2.4 and 19 miles) of streams, respectively, following treatment failure.

Spillway Release

In the event of TSF overfilling, supernatant water would be released via a spillway. If the water was equivalent to the test tailings supernatant, 2.6 km (1.6 miles) of streams would be avoided by fish and 3.4 to 23 km (2.1 to 14 miles) of streams would be toxic to invertebrates, independent of other sources.

Transportation Corridor

Construction and Routine Operation

In the Kvichak River watershed, the transportation corridor would cross approximately 64 streams and rivers. Of those, 55 are known or likely to support migrating and resident salmonids, including 20 streams designated as anadromous waters at the location of the crossing (Figure ES-7). The corridor would run near Iliamna Lake and cross multiple tributary streams near their confluences with the lake. These habitats are important spawning areas for sockeye salmon, putting sockeye particularly at risk from the road. Diminished habitat quality in streams and wetlands below road crossings would result primarily from altered streamflow, runoff of road salts, and siltation of habitat for salmon spawning and rearing and invertebrate prey production (Tables ES-2 and ES-3).

Culvert Failure

Culverts commonly fail to allow free passage of fish. They can become blocked by debris or ice that may not stop water flow but that create a barrier to fish movement. Fish passage also may be blocked or inhibited by erosion below a culvert that "perches" the culvert and creates a waterfall, by shallow water caused by a wide culvert and periodic low streamflows, or by excessively high gradients. If blockages occurred during adult salmon immigration or juvenile salmon emigration and were not cleared for several days, production of a year-class (i.e., fish spawned in the same year) would be lost from or diminished in the stream above the culvert.

Culverts can also fail to convey water due to landslides or, more commonly, floods that wash out undersized or improperly installed culverts. In such failures, the stream would be temporarily impassible to fish until the culvert is repaired or until erosion re-establishes the channel. If the failure occurs during a critical period in salmon migration, effects would be the same as with a debris blockage (i.e., a lost or diminished year-class).

Culvert failures also would result in the downstream transport and deposition of silt, which could cause returning salmon to avoid a stream if they arrived during or immediately following the failure. Deposition of silt would smother salmon eggs and alevins if they were present, and would degrade downstream habitat for salmonids and the invertebrates that they eat.

Blockages of culverts could persist for as long as the intervals between culvert inspections. We assume that the transportation corridor would be inspected daily and maintained during mine operation. The level of surveillance along the corridor can be expected to affect the frequency of culvert failure detection. Driving inspections would likely identify a single erosional failure of a culvert that damaged the road, or a debris blockage sufficient to cause water to pool above the road. However, long-term fixes may not be possible until conditions are suitable for culvert replacement, and these fixes may not fully address fish passage, which may be reduced or blocked for longer periods. Extended blockage of migration would be less likely if daily road inspections included stops to inspect each end of each culvert.

After mine operations cease, the road would likely be maintained less carefully by the operator or may be transferred to a government entity that would be expected to employ a more conventional inspection and maintenance schedule. In either case, the proportion of impassable culverts at any one time would be expected to revert to levels found in published surveys of public roads (mean of 48% [range of 30 to 61%] of culverts that had failed and not been repaired when surveyed). Of the approximately 45 culverts that would be required, 36 would be on streams that are believed to support salmonids. Hence, 11 to 22 streams would be expected to have impeded passage of salmon, rainbow trout, or Dolly Varden for an indefinite period of time, and some proportion of those streams would have degraded downstream habitat resulting from sedimentation following washout of the road.

Truck Accidents

Trucks would carry ore processing chemicals to the mine site and molybdenum product concentrate to the port. Truck accident records indicate that truck accidents near streams are likely over the long period of mine operation. These accidents could release sodium ethyl xanthate, cyanide, other process chemicals, or molybdenum product concentrate to streams or wetlands, resulting in toxic effects on invertebrates and fish. However, the risk of spills could be mitigated by using impact-resistant containers.

Tailings Dam Failure

Tailings are the waste materials produced during ore processing. In our scenarios, these wastes would be stored in TSFs consisting of tailings dams and impoundments. The probability of a tailings dam failure increases with the number of dams. The Pebble 0.25 scenario would include one TSF with a single dam, the Pebble 2.0 scenario would include one TSF with three dams, and the Pebble 6.5 scenario would include three TSFs with a total of eight dams. Because their removal is not feasible, the TSFs and their component dams would be in place for hundreds to thousands of years, long beyond the life of the mine. Available reports from the Pebble Limited Partnership suggest a tailings dam as high as 209 m (685 feet) at TSF 1 (Figure ES-8). We evaluated two potential dam failures at TSF 1 in this assessment: one at a volume approximating the complete Pebble 0.25 scenario (92-m dam height) and one at a volume approximating the complete Pebble 2.0 scenario (209-m dam height). In both cases we assumed 20% of the tailings would be released, a conservative estimate that is well within the range of historical tailings dam failures. Failures of the TSF 2 and TSF 3 tailings dams were not analyzed but would be expected to be similar in terms of types of effects.

Table ES-2. Summary of estimated stream lengths potentially affected in the three mine size scenarios, assuming routine operations.

Effect	Stream Length Affected (km)		
	Pebble 0.25	Pebble 2.0	Pebble 6.5
Eliminated, blocked, or dewatered	38	89	151
Eliminated, blocked, or dewatered—anadromous	8	22	36
>20% streamflow alteration[a]	15	27	53
Direct toxicity to fish[a]	0	24	34–57
Direct toxicity to invertebrates[a]	21	40–62	60–82
Downstream of transportation corridor	272		

Notes:
[a] Stream reaches with streamflow alterations partially overlap those with toxicity.

Table ES-3. Summary of estimated wetland, pond, and lake area potentially affected in the three mine size scenarios, assuming routine operations.

Effect	Wetland, Pond, and Lake Area Affected (km^2)		
	Pebble 0.25	Pebble 2.0	Pebble 6.5
Lost to the mine footprint	4.9	13	20
Lost to reduced streamflow below mine footprint	Unquantified		
Filled by roadbed	0.11		
Influenced by the road (within 200 m)	4.7		

Table ES-4. Probabilities and consequences of potential failures in the mine scenarios.		
Failure Type	**Probability[a]**	**Consequences**
Tailings dam	4×10^{-4} to 4×10^{-6} per dam-year = recurrence frequency of 2,500 to 250,000 years[b]	More than 29 km of salmonid stream would be destroyed or degraded for decades.
Product concentrate pipeline	10^{-3} per km-year = 95% chance per pipeline in 25 years	Most failures would occur between stream or wetland crossings and might have little effect on fish.
Concentrate spill into a stream	1.5×10^{-2} per year = 1 stream-contaminating spill in 78 years	Fish and invertebrates would experience acute exposure to toxic water and chronic exposure to toxic sediment in a stream and potentially extending to Iliamna Lake.
Concentrate spill into a wetland	2.6×10^{-2} per year = 2 wetland-contaminating spills in 78 years	Invertebrates and potentially fish would experience acute exposure to toxic water and chronic exposure to toxic sediment in a pond or other wetland.
Return water pipeline spill	Same as product concentrate pipeline	Fish and invertebrates would experience acute exposure to toxic water if return water spilled to a stream or wetland.
Diesel pipeline spill	Same as product concentrate pipeline	Acute toxicity would reduce the abundance and diversity of invertebrates and possibly cause a fish kill if diesel spilled to a stream or wetland.
Culvert, operation	Low	Frequent inspections and regular maintenance would result in few impassable culverts, but for those few, blockage of migration could persist for a migration period, particularly for juvenile fish.
Culvert, post-operation	3×10^{-1} to ~6×10^{-1} per culvert; instantaneous = 11 to 22 culverts	In surveys of road culverts, 30 to 61% are impassable to fish at any one time. This would result in 11 to 22 salmonid streams blocked at any one time. In 10 to 19 of the 32 culverted streams with restricted upstream habitat, salmon spawning may fail or be reduced and the streams would likely not be able to support long-term populations of resident species.
Truck accidents	1.9×10^{-7} spills per mile of travel = 4 accidents in 25 years and 2 near-stream spills in 78 years	Accidents that spill processing chemicals into a stream or wetland could cause a fish kill. A spill of molybdenum concentrate may also be toxic.
Water collection and treatment, operation	0.93 = proportion of recent U.S. porphyry copper mines with reportable water collection and treatment failures	Water collection and treatment failures could result in exceedance of standards potentially including death of fish and invertebrates. However, these failures would not necessarily be as severe or extensive as estimated in the failure scenario, which would result in toxic effects from copper in more than 60 km of stream habitat.
Tailings storage facility spillway release	No data, but spills are known to occur and are sufficiently frequent to justify routine spillway construction	Spilled supernatant from the tailings storage facility could result in toxicity to invertebrates and fish avoidance for the duration of the event.
Water collection and treatment, managed post-closure	Somewhat higher than operation	Post-closure collection and treatment failures are very likely to result in release of untreated or incompletely treated leachates for days to months, but the water would be less toxic due to elimination of potentially acid-generating waste rock.
Water collection and treatment, after site abandonment	Certain, by definition	When water is no longer managed, untreated leachates would flow to the streams. However, the water may be less toxic.

[a] Because of differences in derivation, the probabilities are not directly comparable.

[b] Based on expected state safety requirements. Observed failure rates for earthen dams are higher (about 5×10^{-4} per year or a recurrence frequency of 2,000 years).

Figure ES-6. Streams and wetlands lost (eliminated, blocked, or dewatered) in the Pebble 6.5 scenario. Light blue areas indicate streams and rivers from the National Hydrography Dataset (USGS 2012) and lakes and ponds from the National Wetlands Inventory (USFWS 2012); dark blue areas indicate wetlands from the National Wetlands Inventory (USFWS 2012).

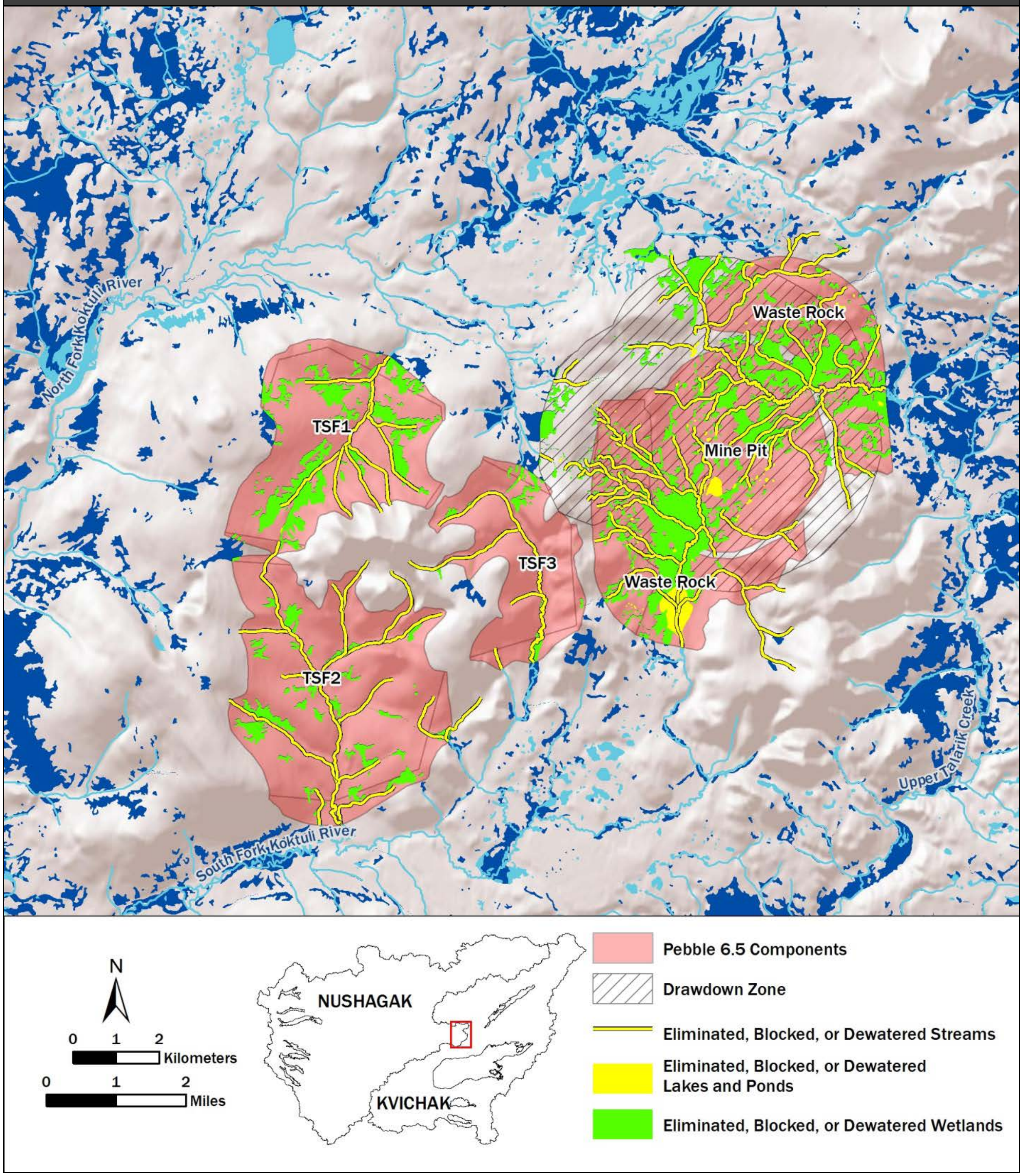


Figure ES-7. Reported salmon, Dolly Varden, and rainbow trout distribution along the transportation corridor. Salmon presence data are from the Anadromous Waters Catalog (Johnson and Blanche 2012); Dolly Varden and rainbow trout presence data are from the Alaska Freshwater Fish Inventory (ADF&G 2012). Note that rainbow trout have also been documented in the Iliamna River and Chinkelyes Creek, although these points are not indicated on this map.

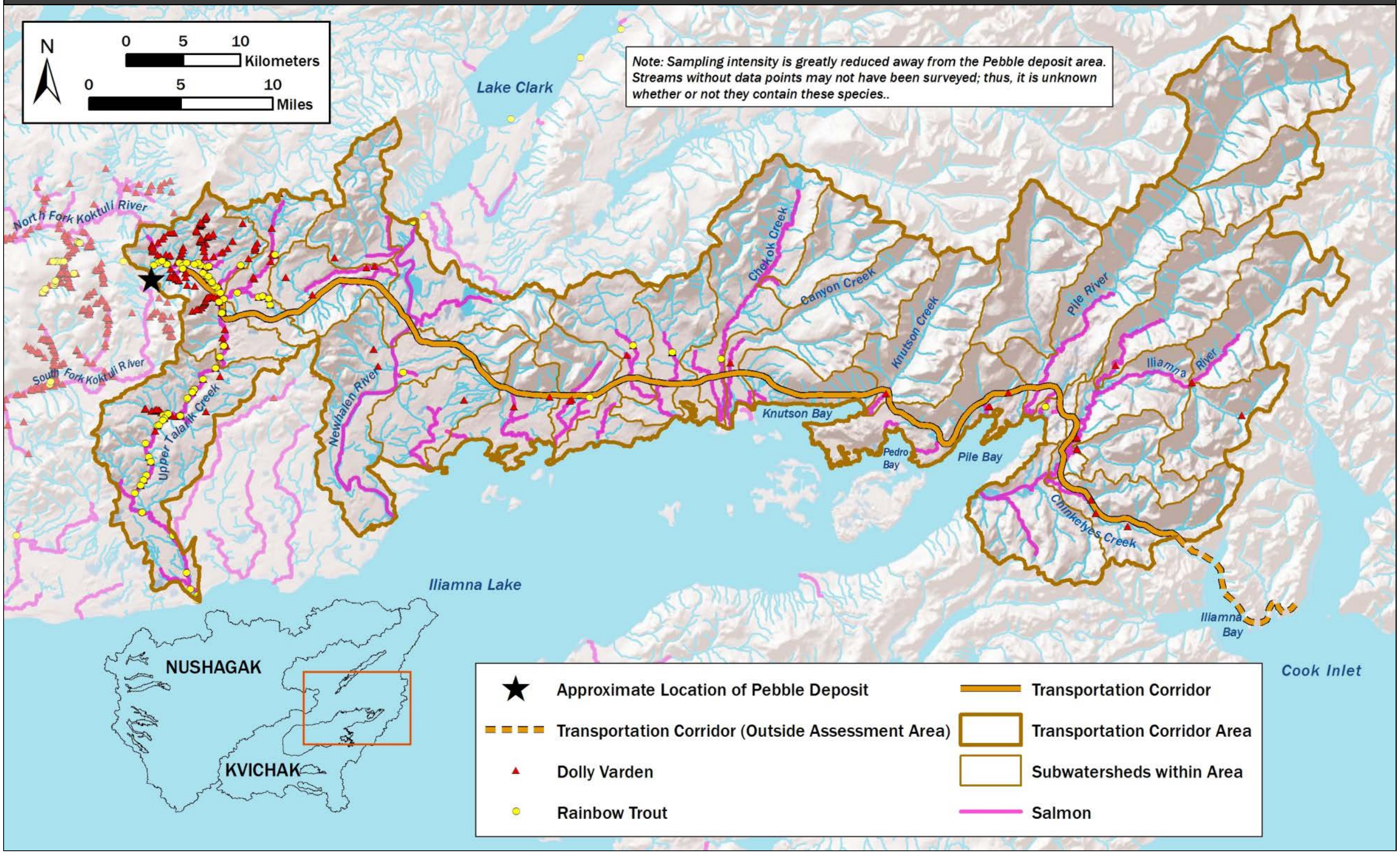
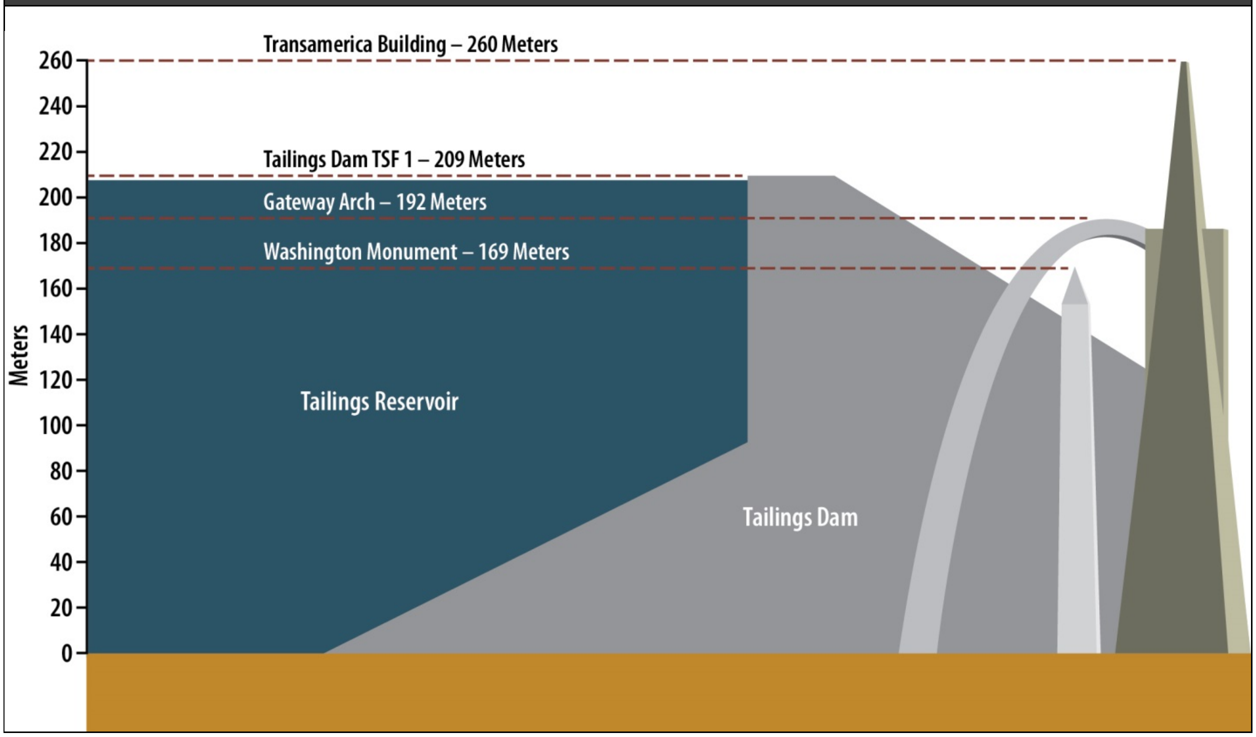


Figure ES-8. Height of the dam at tailings storage facility (TSF) 1 in the Pebble 2.0 and Pebble 6.5 scenarios, relative to U.S. landmarks.



The range of estimated dam failure probabilities is wide, reflecting the great uncertainty concerning such failures. The most straightforward method of estimating the annual probability of a tailings dam failure is to use the historical failure rate of similar dams. Three reviews of tailings dam failures produced an average rate of approximately 1 failure per 2,000 dam-years, or 5 x 10^{-4} failures per dam-year. Strictly speaking, these frequencies are properties that apply to a group of dams. However, by extension, if there is one dam and it is typical of the population, it would be expected to fail, on average, within a 2,000-year period. This does not mean it is expected to fail 2,000 years after it is built. Rather, it indicates that, after 2,000 years have passed, it is more likely than not that the dam would have failed and that expected failure could occur any year in that 2,000-year window with an average annual probability of 0.0005.

The argument against this method is that the record of past failures does not fully reflect current engineering practice. Some studies suggest that improved design, construction, and monitoring practices can reduce the failure rate by an order of magnitude or more, resulting in an estimated failure probability within the range assumed here (Table ES-4). The State of Alaska's guidelines suggest that an applicant follow accepted industry design practices such as those provided by the U.S. Army Corps of Engineers (USACE), the Federal Energy Regulatory Commission (FERC), and other agencies. Based on safety factors in USACE and FERC guidance, we estimate that the probability of failure for all causes requires a minimum factor of safety of 1.5 against slope instability for the loading condition corresponding to steady seepage from the filled storage facility. An assessment of the correlation of dam failure probabilities with slope instability safety factors suggests an annual probability of failure of 1 in 250,000 per year for facilities designed, built, and operated with state-of-the-practice engineering (Category I facilities) and 1 in 2,500 per year for facilities designed, built, and operated using standard engineering practice (Category II facilities). The advantage of this approach is that it addresses current regulatory guidelines and engineering practices. The disadvantage is that we do not know whether standard practice or state-of-the practice dams will perform as expected, particularly given the potential dam heights and subarctic conditions in these scenarios.

Failure of the dam at TSF 1 (the TSF included in all three mine scenarios) would result in the release of a flood of tailings slurry into the North Fork Koktuli River. This flood would scour the valley and deposit many meters of tailings fines in a sediment wedge across the entire valley near the TSF dam, with lesser quantities of fines deposited as far as the North Fork's confluence with the South Fork Koktuli River. The North Fork Koktuli River currently supports spawning and rearing populations of sockeye, coho, and Chinook salmon; spawning populations of chum salmon; and rearing populations of Dolly Varden and rainbow trout. The tailings slurry flood would continue down the mainstem Koktuli River with similar effects, the extent of which cannot be estimated at this time due to model and data limitations.

The tailings dam failures evaluated in the assessment would be expected to have the following severe direct and indirect effects on aquatic resources, particularly salmonids.

- **It is expected that the North Fork Koktuli River below the TSF 1 dam and much of the mainstem Koktuli River would not support salmonids in the short term (less than 10 years).**
    - In the tailings dam failure scenarios, spilled tailings would bury salmon habitat under meters of fines along nearly the entire length of the North Fork Koktuli River valley downstream of the dam (over 29 km or 18 miles in the Pebble 0.25 dam failure scenario), and beyond (in the Pebble 2.0 dam failure scenario).
    - Deposited tailings would degrade habitat quality for both fish and the invertebrates they eat. Based largely on their copper content, deposited tailings would be toxic to benthic macroinvertebrates, but existing data concerning toxicity to fish are less clear.
    - Deposited tailings would continue to erode from the North Fork Koktuli River and mainstem Koktuli River valleys.
    - Suspension and redeposition of tailings would be expected to cause serious habitat degradation in the mainstem Koktuli River and downstream into the Mulchatna River; however, the extent of these effects cannot be estimated at this time due to model and data limitations.
- **The affected streams would provide low-quality spawning and rearing habitat for a period of decades.**
    - Recovery of suitable substrates via mobilization and transport of tailings would take years to decades, and would affect much of the watershed downstream of the failed dam.

- Ultimately, spring floods and stormflows would carry some of the tailings into the Nushagak River.
- For some years, periods of high flow would be expected to suspend sufficient concentrations of tailings to cause avoidance, reduced growth and fecundity, and even death of fish.

- **Near-complete loss of North Fork Koktuli River fish populations downstream of the TSF and additional fish population losses in the mainstem Koktuli, Nushagak, and Mulchatna Rivers would be expected to result from these habitat losses.**
  - The Koktuli River watershed is an important producer of Chinook salmon. The Nushagak River watershed, of which the Koktuli River watershed is a part, is the largest producer of Chinook salmon in the Bristol Bay region, with annual runs averaging over 190,000 fish.
  - A tailings spill could eliminate 29% or more of the Chinook salmon run in the Nushagak River due to loss of the Koktuli River watershed population. An additional 10 to 20% could be lost due to tailings deposited in the Mulchatna River and its tributaries.
  - Sockeye are the most abundant salmon returning to the Nushagak River watershed, with annual runs averaging more than 1.9 million fish. The proportion of sockeye and other salmon species of Koktuli-Mulchatna origin is unknown.
  - Similarly, the North Fork Koktuli River populations of rainbow trout and Dolly Varden would be lost for years to decades if they could not successfully be maintained entirely in headwater networks upstream of the affected zone. Quantitative estimates of these losses are not possible given available information.

Effects would be qualitatively similar for both the Pebble 0.25 and Pebble 2.0 dam failures, although effects from the Pebble 2.0 dam failure would extend farther and last longer. Failure of dams at the two additional TSFs in the Pebble 6.5 scenario (TSF 2 and TSF 3) were not modeled, but would have similar types of effects in the South Fork Koktuli River and downstream rivers.

Pipeline Failure

In the mine scenarios, the primary mine product would be a sand-like copper concentrate with traces of other metals, which would be pumped via pipeline to a port on Cook Inlet. Water that carried the concentrate would be returned to the mine site in a second pipeline. Based on the general record of pipelines and further supported by the record of metal concentrate pipelines at existing mines, one near-stream failure and two near-wetland failures of each of these pipelines would be expected to occur over the life of the Pebble 6.5 scenario (approximately 78 years).

Failure of either the product or the return water pipeline would release water that is expected to be highly toxic due to dissolved copper and possibly processing chemicals. Invertebrates and potentially early fish life stages would be killed in the affected stream over a relatively brief period. If concentrate spilled into a stream, it would settle and form highly toxic bed sediment based on its high copper content and acid generation. The mean velocities of many streams crossed by the pipelines are sufficient to carry the concentrate downstream to Iliamna Lake, but some would collect in low-velocity areas of the receiving stream. If the spill occurred during low streamflows, dredging could recover some concentrate but would cause physical damage to the stream. Concentrations in Iliamna Lake could not be predicted, but near the pipeline route Iliamna Lake contains important sockeye salmon beach spawning areas that would be exposed to a spill. Sockeye also spawn in the lower reaches of streams that could be directly contaminated by a spill.

Based on petroleum pipeline failure rates, the diesel fuel pipeline also would be expected to spill near a stream over the life of the Pebble 6.5 mine. Evidence from modeling the dissolved and dispersed oil concentrations in streams, laboratory tests of diesel toxicity, and studies of actual spills in streams indicates that a diesel spill at a stream crossing would be expected to immediately kill invertebrates and likely fish as well. Remediation would be difficult but recovery would be expected to occur within 3 years. Failure of the natural gas pipeline would also be expected, but significant effects on fish would not be expected.

Spills into wetlands that support fish would be expected to have greater toxic effects because contaminants would be washed out slowly, if at all. However, retention of contaminants within the wetland would make remediation by removal more practical.

Common Mode Failures

Multiple, simultaneous failures could occur due to a common event, such as a severe storm with heavy precipitation (particularly precipitation that fell on spring snow cover) or a major earthquake. Over the long period that tailings impoundments, a mine pit, and waste rock piles would be in place, the likelihood of multiple extreme precipitation events, earthquakes, or combinations of these events becomes much greater. Multiple events further increase the chances that facilities remaining in place will weaken and eventually fail.

Such an event could cause multiple tailings dam failures that would spill tailings slurry into both the South and North Fork Koktuli Rivers; road culvert washouts that would send sediments downstream and potentially block fish passage; and pipeline failures that would release product slurry, return water, or diesel fuel. The effects of each of these accidents individually would be the same as discussed previously, but their co-occurrence would cause cumulative effects on salmonid populations and make any remedial responses more difficult.

Fish-Mediated Risks to Wildlife

Although the effects of salmonid reductions on wildlife—that is, fish-mediated risks to wildlife—cannot be quantified given available data, some reduction in wildlife would be expected in the mine scenarios. Changes in the occurrence and abundance of salmon have the potential to change animal behavior and reduce wildlife population abundances. The mine footprints would be expected to have local effects on brown bears, wolves, bald eagles, and other wildlife that consume salmon, due to reduced salmon abundance from habitat loss and degradation in or immediately downstream of the mine footprint. Any of the accidents or failures evaluated would increase effects on salmon, which would further reduce the abundance of their predators.

The abundance and production of wildlife also is enhanced by the marine-derived nutrients that salmon carry upstream on their spawning migration. These nutrients are released into streams when the salmon die, enhancing the production of other aquatic species that feed wildlife. Salmon predators deposit these nutrients on the landscape, thereby fertilizing terrestrial vegetation that, in turn, provides food for moose, caribou, and other wildlife. The loss of these nutrients due to a reduction in salmon would be expected to reduce the production of riparian and upland species.

Fish-Mediated Risks to Alaska Native Cultures

Under routine operations with no major accidents or failures, the predicted loss and degradation of salmonid habitat in the South and North Fork Koktuli Rivers and Upper Talarik Creek would be expected to have some impact on Alaska Native cultures of the Nushagak and Kvichak River watersheds. Fishing and hunting practices would be expected to change in direct response to the stream, wetland, and terrestrial habitats lost to the mine footprints and the transportation corridor. It is also possible that subsistence use of salmon resources would decline based on perceptions of reduced fish or water quality resulting from mining.

The potential for significant effects on Alaska Native cultures is much greater from mine failures that reduced or eliminated fish populations in affected areas, including areas significant distances downstream from the mine. In the case of the tailings dam failures described in the assessment, the significant loss of Chinook salmon populations would have severe consequences, especially for villages in the Nushagak River watershed.

Any loss of fish production from these failures would reduce the availability of these subsistence resources to local Alaska Native villages, and the reduction of this highly nutritious food supply could have negative consequences on human health. Because salmon-based subsistence is integral to Alaska Native cultures, the effects of salmon losses go beyond the loss of food resources. If salmon quality or quantity was (or was perceived to be) adversely affected, the nutritional, social, and spiritual health of Alaska Natives would decline.

Cumulative Risks of Multiple Mines

This assessment has focused on the effects that a single large mine at the Pebble deposit would have on salmon and other resources in the Nushagak and Kvichak River watersheds, including the cumulative effects of multiple stressors associated with that mine. However, multiple mines and their associated infrastructure may be developed in these watersheds. Each mine would pose risks similar to those identified in the mine scenarios. Estimates of the stream and wetland habitats lost would differ across different deposits, based on the size and location of mine operations within the watersheds. Individually, each mine footprint would eliminate some amount of fish-supporting habitat and, should operator or engineering failures occur, affect fish habitats well beyond the mine footprint.

We considered development of mines at the Pebble South/PEB, Big Chunk South, Big Chunk North, Groundhog, AUDN/Iliamna, and Humble claims in the Nushagak and Kvichak River watersheds. These sites were chosen because all contain copper deposits that have generated exploratory interest. If all six mine sites were developed, the cumulative area covered by these six mine footprints could be 37 to 57 km^2 (9,100 to 14,000 acres). Stream habitats eliminated or blocked could be 43 to 70 km (27 to 43 miles). Cumulative wetland losses could be 7.9 to 27 km^2 (2,000 to 6,700 acres).

These are conservative estimates of habitat loss, because we did not estimate the hydrologic drawdown zones around each mine pit as was done for the Pebble scenarios. Inclusion of the drawdown area in the Pebble 0.25 scenario increased the area of stream and wetlands losses by roughly 50%. A similar increase might be expected at the other mine sites, depending on local geology. These mines also would be expected to modify streamflows and diminish water quality to approximately the same extent as the Pebble 0.25 scenario. Waters on these claim blocks include the Chulitna River and Rock, Jensen, Yellow, Napotoli, Klutuk, and Kenakuchuk Creeks, as well as over 250 unnamed tributaries and over 50 unnamed lakes and ponds. Although not all support salmon, many do. Loss of substantial habitat across the watersheds could contribute to diminishing the genetic diversity of salmon stocks and thereby increasing annual variability in salmon returns.

Mitigation and Remediation

The mine scenarios assessed here include modern conventional mitigation practices as reflected in Northern Dynasty Mineral's published plan for the Pebble deposit, plus practices suggested in the mining literature and consultations with experts. These practices include, but are not limited to, processing all potentially acid-generating waste rock before closure, managing effluent water temperatures, inspecting and maintaining roads daily, and providing automatic monitoring and remote shut-off for the pipelines. However, we recognize that risks could be further reduced by unconventional or even novel mitigation measures, such as dry stack tailings disposal or the use of armored containers on the trucks carrying process chemicals to the site. These practices may be unconventional because they are expensive, unproven, or impractical. However, these obstacles to implementation might be overcome and justified by the large mineral resource and the highly valued natural and cultural resources of the Bristol Bay watershed.

Although remediation would be considered if spills contaminated streams, features of the Pebble deposit area would make remediation difficult. Spilled tailings from a dam failure would flow into streams, rivers, and floodplains that are in roadless areas and that are not large enough to float a barge-mounted dredge. Recovery, transport, and disposal of hundreds of millions of metric tons of tailings under those conditions would be extremely difficult and would result in additional environmental damage. Compensatory mitigation measures could offset some of the stream and wetland losses, although there are substantial challenges regarding the efficacy of these measures to offset adverse impacts. Pipeline crossings of streams would be near Iliamna Lake, so the time available to block or collect spilled material before it reached the lake would be short. Spilled return water and the aqueous phase of the product concentrate slurry would be unrecoverable. The product concentrate itself would resemble fine sand, and mean velocities in many receiving streams would be sufficient to suspend and transport it. Hence, concentrate spilled or washed into streams could be recovered only where it collected in low-velocity locations. Diesel spills would dissolve, vaporize, and flow as a slick to Iliamna Lake. Booms and absorbents are not very effective in moderate- to high-velocity streams.

Summary of Uncertainties in Mine Design and Operation

This assessment considers realistic mine scenarios that are based on specific characteristics of the Pebble deposit and preliminary plans proposed by Northern Dynasty Minerals. These scenarios are generally applicable to copper deposits in the Bristol Bay watershed. If the Pebble deposit is mined, actual events will undoubtedly deviate from these scenarios. This is not a source of uncertainty, but rather an inherent aspect of a predictive assessment. Even an environmental assessment of a specific plan proposed for permitting by a mining company would be an assessment of a scenario that undoubtedly would differ from actual mine development.

Multiple uncertainties are inherent in planning, designing, constructing, operating, and closing a mine. These uncertainties, summarized below, are inherent in any complex enterprise, particularly when that enterprise involves an incompletely characterized natural system. However, the large spatial scales and long durations required to mine the Pebble deposit make these inherent uncertainties more prominent.

- Mines are complex systems requiring skilled engineering, design, and operation. The uncertainties facing mining and geotechnical engineers include unknown geological features, uncertain values of geological properties, limited knowledge of mechanisms and processes, and human error in design and construction. Models used to predict the behavior of engineered systems represent idealized processes and by necessity contain simplifications and approximations that potentially introduce errors.
- Accidents are unplanned and inherently unpredictable. Although systems can be put into place to protect against system failures, seemingly logical decisions about how to respond to a given situation can have unexpected consequences due to human error (e.g., the January 2012 overflow of the tailings dam at the Nixon Fork Mine near McGrath, Alaska). Further, unforeseen events or events that are more extreme than anticipated can negate apparently reasonable operation and mitigation plans. Climate change will likely exacerbate this uncertainty. In the Bristol Bay region, climate change is expected to lead to changes in snowpack and the timing of snowmelt, an increased chance of rain-on-snow precipitation, and increased flooding. All of these changes are likely to affect multiple aspects of any large-scale mining in the area, including mine infrastructure, the transportation corridor, water treatment and discharge, and post-closure management, in unknown and potentially unpredictable ways.

- The ore deposit would be mined for decades and wastes would require management for centuries or even in perpetuity. Engineered mine waste storage systems have been in existence for only about 50 years, and their long-term behavior is not known. The response of current technology in tailings dam construction is untested and unknown in the face of centuries of unpredictable events such as extreme weather and earthquakes.
- Over the long time span (centuries) of mining and post-mining care, generations of mine operators must exercise due diligence. Priorities could change in the face of financial circumstances, changing markets for metals, new information about the resource, political priorities, or any number of currently unforeseeable changes in circumstance.

Summary of Uncertainties and Limitations in the Assessment

The most important uncertainties concerning estimated effects of the mine scenarios, as judged by the assessment authors, are identified below.

- Consequences of habitat loss and degradation for fish populations could not be quantified because of the lack of quantitative information concerning salmonid populations in freshwater habitats. The occurrence of salmonid species in rivers and major streams is known, but detailed and comprehensive information on abundances, productivities, and limiting factors in each of the watersheds is not available. Estimating fish population changes would require population modeling, which requires knowledge of life-stage-specific survival and production and limiting factors and processes. Further, it requires knowledge of how temperature, habitat structure, prey availability, density dependence, and sublethal toxicity influence life-stage-specific survival and production. Obtaining this information would require more detailed monitoring and experimentation. Salmon populations naturally vary in size due to many factors that vary among locations and years. At present, data are insufficient to establish reliable salmon population estimates, and obtaining such data would take many years. Estimated effects of mining on fish habitat thus become the best available surrogate for estimated effects on fish populations.
- Standard leaching test data are available for test tailings and waste rocks from the Pebble deposit, but these results are uncertain predictors of the actual composition of leachates from waste rock piles, tailings impoundments, or tailings deposited in streams and on their floodplains.
- Leachate capture efficiencies are uncertain. We assume 50% capture for waste rock leachates outside of the mine pit drawdown zone. In the Pebble 2.0 scenario, for example, this would result in capture of 84% of the leachate by the pit drawdown zone and the wells combined. To avoid exceeding water quality criteria for copper, more than 99% capture would be required.
- The quantitative effects of tailings and product concentrate deposited in spawning and rearing habitat are uncertain. It is clear that they would have harmful physical and toxicological effects on salmonid larvae or sheltering juveniles, but the concentration in spawning gravels required to reduce salmonid reproductive success is unknown.

- The estimated annual probability of tailings dam failure is uncertain because it is based on design goals. Historical experience is presumed to provide an upper bound of failure probability. Features that should reduce failure frequencies have not been tested for the thousands of years that they must function properly. Hence, actual failure rates could be higher or lower than the estimated probability.
- The proportion of tailings that would spill in the event of a dam failure could be larger than the largest value modeled (20%).
- The long-term fate of spilled tailings in the event of a dam failure could not be quantified. It is expected that tailings would erode from areas of initial deposition and move downstream over more than a decade. However, the data needed to model that process and the resources needed to develop that model are not available.
- The actual response of Alaska Native cultures to any impacts of the mine scenarios is uncertain. Interviews with village Elders and culture bearers and other evidence suggest that responses would involve more than the need to compensate for lost food, and would be expected to include some degree of cultural disruption. It is not possible to predict specific changes in demographics, cultural practices, or physical and mental health.
- Because we mention but do not evaluate potential direct effects of mining on wildlife or on Alaska Natives, this assessment represents a conservative estimate of how these endpoints would be affected by mine development and operation.

Uses of the Assessment

This assessment is a scientific investigation. It does not reflect any conclusions or judgments about the need for or scope of potential government action, nor does it offer or analyze options for future decisions. Rather, it is intended to provide a characterization of the biological and mineral resources of the Bristol Bay watershed, increase understanding of the risks from large-scale mining to the region's fish resources, and inform future government decisions. The assessment will also better inform dialogues among interested stakeholders concerning the resources in the Bristol Bay watershed and the potential impacts of large-scale mining on those resources.