An Assessment of Potential Mining Impacts on Salmon Ecosystems of Bristol Bay, Alaska

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Appendix G: Foreseeable Environmental Impact of Potential Road and Pipeline Development on Water Quality and Freshwater Fishery Resources of Bristol Bay, Alaska

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ABSTRACT

While Pacific salmon fishery resources have diminished around the Pacific Rim for more than a century, the Bristol Bay region of Alaska supports a globally unique, robust, productive, and sustainable salmon fishery associated with extremely high quality waters and high integrity freshwater ecosystems. The Bristol Bay watershed has seen a bare minimum of road development to date. However, State of Alaska long range plans envision a future of extensive inter-community transportation routes, including both highways and pipelines. Other developments being considered for the area would also require an infrastructure of roads and pipelines that would traverse previously roadless areas of the Kvichak and Nushagak river drainages. As a plausible example of such potential infrastructure, this report uses the 138-km-long access road and four pipelines likely to be part of Northern Dynasty Minerals' Pebble Mine, should the company elect to pursue development of that prospect. It reviews the known physical and biological effects of road and pipeline development on streams, rivers, lakes, and wetlands. The report identifies two key conditions in the Bristol Bay ecosystem that particularly contribute to its water quality and biological productivity and resilience: 1) a geologic and geomorphic template that provides abundant shallow groundwater resources and strong vertical linkage between surface waters and groundwater, across all stream sizes and wetland types; and 2) the lack of past industrial disturbance, including road development across most of the Bristol Bay watershed. The example Pebble Mine transportation corridor would bisect this landscape with the potential to shape the hydrology, water quality and fish habitat integrity of many of the Kvichak and Nushagak river drainages. Drawing from the literature that conceptualizes how to spatially project risk-impact footprints from road designs and landscape and stream network data, the report maps the spatial extent of potential harm from construction, operation, accidents and accidents response on the Pebble transportation corridor. More than 30 large streams and rivers known to support spawning salmon would intersect with the proposed transportation corridor, potentially affecting between twenty and thirty percent of known spawning populations of sockeye salmon in the Iliamna Lake system. The eastern half of Iliamna Lake supports the highest concentrations of rearing sockeye salmon and would also be very close to the road and pipeline corridor. The corridor would also bisect or closely approach more than 70 streams known to support resident fishes such as Dolly Varden, arctic grayling, and others. The report also assesses potential mitigation measures and identifies practices that could potentially reduce the risk of impact to water quality, freshwater ecosystem function, and Bristol Bay fishery resources should the corridor be developed.

I. INTRODUCTION AND SCOPE OF THIS REPORT

While Pacific salmon fishery resources have diminished around the Pacific Rim to the point that many populations are managed as endangered or threatened species, the Bristol Bay region of Alaska supports a globally unique, robust and productive salmon fishery (Burgner 1991, Schindler et al. 2010). Commercial fishers harvest five Pacific salmon species in Bristol Bay, including a sockeye salmon landing of over 29 million fish in 2010 (ADFG 2010). Bristol Bay’s wild rivers support sport fisheries likely exceeding 90,000 angler days and millions of dollars in related expenditures (Duffield et al. 2007).

Hilborn et al. (2003) identified key factors sustaining the productivity and resilience of Bristol Bay, specifically, 1) a highly accountable system of fishery regulation, 2) favorable ocean conditions in recent years, and 3) a stock complex sustained by variable production from an abundance and high diversity of freshwater and estuarine habitats., Salmon production in different Bristol Bay rivers and lakes, in their current, largely natural and undeveloped condition, varies independently over time spans of decades. Despite the local variability, the system sustains a high overall fishery production because at any given time, a collection of extremely high-quality habitats contributes extraordinarily high abundance and production of fishes. These same factors (i.e., diversity and high quality of interconnected habitats) likely confer to Bristol Bay a degree of resilience in the face of future climate and environmental change (Hilborn et al. 2003, Woody and O’Neal 2010, Schindler et al. 2010).

Although some planners have projected extensive highways and industrial development in the Bristol Bay region (BBAP 2005), the Pebble Mine is the most likely large-scale development to be proposed in the near future. Development of the Pebble project would include a major 138-km-long access road, pipeline, and electric utility corridor between the mine site, north of Lake Iliamna, and a deepwater port on Cook Inlet, to the east (Ghaffari et al. 2011) (Figure 1). This corridor would cross many tributaries of the of the Kvichak and Nushagak Rivers, including tributaries of Iliamna lake, as well as bisecting numerous wetlands and groundwater-rich areas that connect to and sustain the water quantity and quality in those fish habitats.

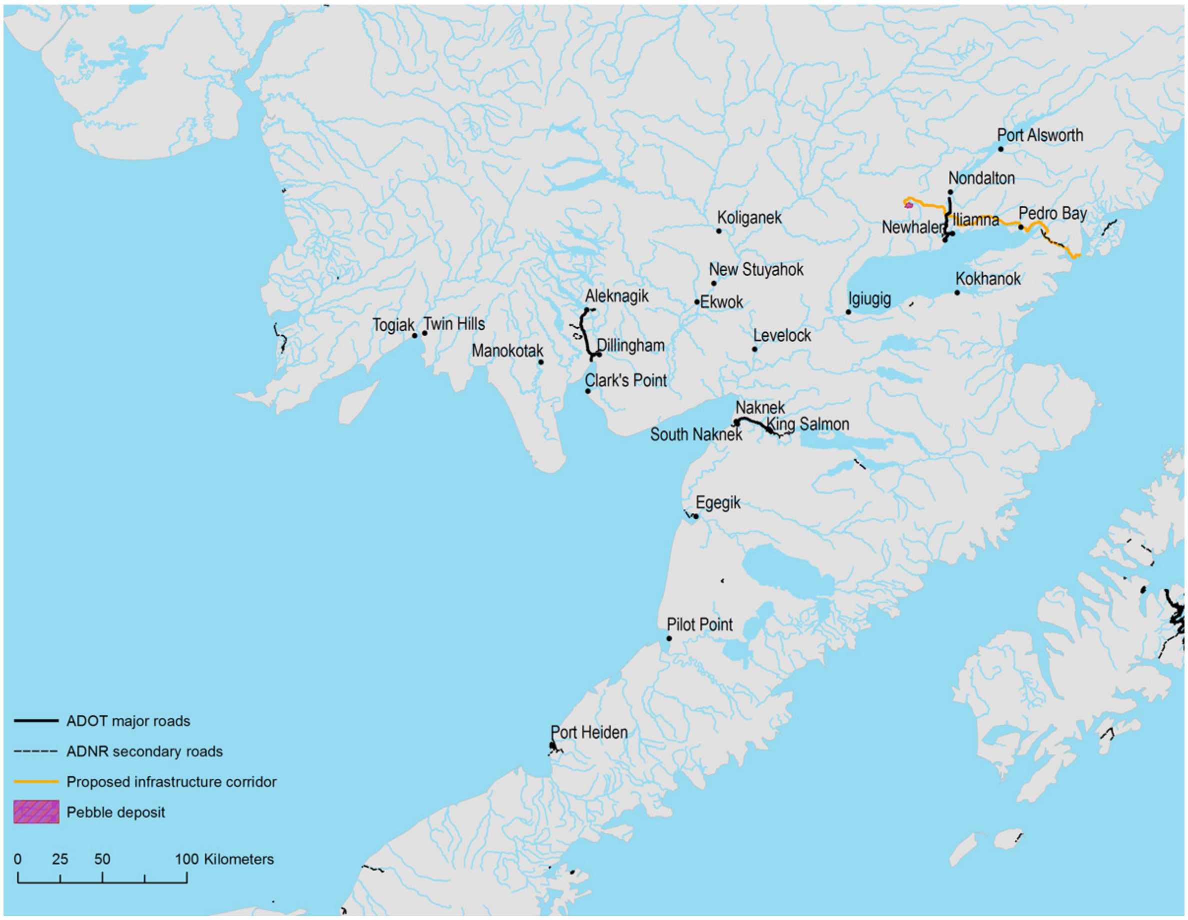

Figure 1. Existing roads in the Bristol Bay region, and the proposed route of the Pebble Mine transportation corridor. Mapped by Rebecca Shaftel (Alaska Natural Heritage Program, Anchorage) based on data from Alaska Department of Transportation and Alaska Department of Natural Resources (Anchorage).

Through its contractor for this report, NatureServe, U.S. Environmental Protection Agency charged the author with providing a review of: 1) relevant literature and expert input on the risks, threats, and stressors to Bristol Bay area water quality and salmon resources associated with the construction, operation, and maintenance of reasonably foreseeable roads in the region; and 2) mitigation practices used to abate such impacts, including both commonly used and available, but uncommonly used practices.

Accordingly, after a brief review of known consequences of road and pipeline development on streams, rivers, and lakes, this report will assess the scope of likely and possible environmental impacts on the water quality and fishery resources of the Bristol Bay region from development of the potential Pebble Mine Transportation Corridor.

II. THE BRISTOL BAY ECOSYSTEM

Bristol Bay is one of the world's few remaining, large virtually roadless near-coastal regions. There are but a few short segments of state highway and road, and no railroads, pipelines, or other major industrial transportation infrastructure. Roadways presently link Iliamna Lake (Pile Bay) to Cook Inlet (tidewater at Williamsport); the Iliamna area (including Iliamna airport) north to a proposed bridge over the Nondalton River and then to the village of Nondalton; and two other short road segments from Dillingham to Aleknagik and Naknek to King (Figure 1). A short road system also connects the village of Pedro Bay with its nearby airstrip. Improvements have been proposed by the state of Alaska for the road between Iliamna and Nondalton, in part to alleviate erosion and sedimentation.

Glacial landforms dominate much of Bristol Bay's surface geology and geomorphology and include extensive glacial outwash glacial till mantles on hillslopes, expansive, interbedded glacial lake deposits, and glacial and periglacial stream deposits (Hamilton 2007). These landforms, and more specifically, the extensive, interconnected surface and near-surface groundwater systems resulting from them, are one of the two factors that principally account for Bristol Bay's high productivity for salmon. (The other key factor is the dearth of industrial and commercial development in the basin.)

Most available information on fish distribution and abundance in the Bristol Bay region focuses on large rivers (in part because they can be surveyed from the air, at least for sockeye salmon). However, a myriad of smaller streams and wetlands also provide high-quality habitat for coho salmon, Dolly Varden, rainbow trout, and arctic grayling, as well as other species including round whitefish, pond smelt, lamprey, slimy sculpin, northern pike, sticklebacks and burbot (Rinella 2011, personal communication, and Shaftel 2011, personal communication). In the most comprehensive published field inventory, Woody and O'Neal (2010) reported detection of one or more of these species from 96 percent of the 108 small waters they sampled in the vicinity of the projected site of Pebble prospect in the Nushagak and Kvichak River drainages. They summarize:

> Small headwater streams are often assumed not to be important salmon producing habitats in Alaska, although collectively they produce millions of salmon and determine water flow and chemistry of larger rivers. As illustrated by this and numerous other studies, headwaters comprise a significant proportion of essential spawning and rearing habitat for salmon and non-salmon species all of which are important to subsistence users in the region.

III. ROADS AND PIPELINES PROPOSED OR FORESEEABLE IN BRISTOL BAY

In evaluating the environmental impact of any road, it is important to recognize that the development of a new road is often only the first step toward industrial or commercial development of the landscape in general, including the proliferation of additional roads (Trombulak and Frissell 2000, Angermeier et al. 2004). Additional large-scale landscape development, facilitated by the initial road, is a reasonably foreseeable impact of road construction in a roadless area. Essentially, finance and construction of the initial road subsidizes future developments that rely on that road to route traffic, particularly when that initial road connects to a possible trade hub, such as a deepwater port. The environmental impact of the ensuing development can dwarf by orders of magnitude the direct, local effects of constructing the initial road segment (Angermeier at al. 2004).

That there is some interest in industrialization of Bristol Bay beyond the Pebble Mine is evident in various State of Alaska sources. The ADNR's Bristol Bay Area Plan from the (BBAP 2005, citing the ADOT's Southwest Alaska Transportation Plan, November 2002), lays out an ambitious long-range vision for future development of a network of roads and highways in the Bristol Bay region. The roads, highways, and related infrastructure envisioned by the BBAP include "regional transportation corridors" that would connect Cook Inlet to the area of the Pebble prospect, as well as Aleknagik (already connected by road to Dillingham), King Salmon, Naknek, Egegik, and Port Heiden, and finally, to Chignik and Perryville, on the southern Alaska Peninsula. The State also foresees other "community transportation projects" that involve extensions, improvements, or new roads within or adjacent to Bristol Bay watershed (Chignik Road Intertie, King Cove-Cold Bay Connection, Newhalen River Bridge, Iliamna-Nondalton Road Intertie, and Naknek-South Naknek Bridge and Intertie). The plans also identify three potential "Trans-Peninsula transportation corridors" (Wide Bay/Ugashik Bay, Kuiulik Bay/Port Heiden, and Balboa Bay/Herendeen Bay,) routes that could serve for roads, oil and gas pipelines or other utilities as needed (BBAP 2005, Figure 2.5).

Several other large ore bodies and at least seven different complexes of mineral claims lie within a roughly concentric 24-km radius around the existing Pebble Prospect, encompassing a vast swath of the Bristol Bay watershed north of Iliamna Lake (Ghaffari et al. 2011, The Nature Conservancy 2010). The area spans the headwaters of the Koktuli, Stuyahok, and Newhalen Rivers, as well as Kaskanak, and both Lower and Upper Talarik Creeks. There are other large mineral leases farther afield within Bristol Bay, including tracts north and west of the Nushagak and Mulchatna Rivers. Although they are at various stages of exploration, these prospects could yield future mine proposals, particularly if road and other transportation improvements completed for Pebble Mine provided a transportation stepping stone to them.

IV. EFFECTS OF ROADS AND PIPELINES ON WATER AND FISH HABITAT

Roads have persistent multifaceted impacts on ecosystems and can strongly affect water quality and fish habitat. Several authors have reviewed the suite and scope of environmental impacts from roads (e.g., Forman and Alexander 1998, Trombulak and Frissell 2000, Gucinski et al. 2001) with particular focus on water quality and fish habitat impacts found in sources such as Furniss et al. (1991), Jones et al. (2000), and Angermeier et al. (2004). The increasing presence of roads in the developed and developing world has been identified as a threat to native freshwater species and water quality alike. Czech et al. (2000), for example, identified roads as a likely contributing factor in the local extinction and endangerment of 94 taxa across the U.S.

Road construction causes mortality and injury of stationary and slow-moving organisms both within and adjacent to the construction footprint and alters the physical conditions in the area, as well (Trombulak and Frissell 2000), often including direct conversion of habitat to non-habitat within and adjacent to the footprint (Forman 2004). Behavior modification depends on species and road size/type. Voluntary modification ranges from use of the road corridor to avoidance; involuntary modification may result when a road completely blocks the movement of organisms, resulting in fragmentation or isolation of populations, often with negative demographic and genetic effects and with potential consequences as grave as local population or species extinction and loss of biodiversity (Forman 2004, Gucinski et al. 2001, Trombulak and Frissell 2000). Truncation of fish migrations due to passage barriers created by roads is one example of involuntary behavioral alterations that compromise survival and productivity. Other behavior modifications include changes in home range, reproductive success, escape response, and/or physiological state (Forman and Alexander 1998, Trombulak and Frissell 2000).

Roads can create long-term, local changes in soil density, temperature, and water content, light, dust, and/or surface water levels, and flow, runoff, erosion, and/or sedimentation patterns, as well as adding heavy metals, deicing salts, organic molecules, ozone, and nutrients to roadside environments (Forman 2004, Gucinski et al. 2001, Trombulak and Frissell 2000, Forman and Deblinger 2000). When delivered to streams, road-derived pollutants directly and indirectly impact water quality. The extension of natural stream networks to integrate eroding road surfaces can cause sustained delivery of fine sediments that alter bed texture and reduce the permeability of streambed gravels (Furniss et al. 1995, Wemple et al. 1996, Jones et al. 2000, Angermier et al. 2004). Increased loading of fine sediments has been linked to adverse impacts on fish though several, often co-occurring biological mechanisms, including decreased fry emergence, decreased juvenile densities, loss of winter carrying capacity, increased predation on fish, and reduced benthic organism populations and algal production (Newcombe and MacDonald 1991, Newcombe and Jensen 1996, Gucinski et al. 2001, Angermier et al. 2004, Suttle et al. 2004, and many others). In steeper terrain, roads greatly increase the frequency of slope failure and debris flow, with the resulting episodic sediment delivery to streams and rivers (Montgomery 1994, Jones et al. 2000, Gucinski et al. 2001). Roads often promote the dispersal of exotic species and pathogens by altering habitats, stressing native species, and providing corridors and vehicle transport for seed/organism dispersal (Forman 2004, Trombulak and Frissell 2000, Gucinski et al. 2001). So long as they remain accessible and passable enough to facilitate human use, roads also lead to increased hunting, fishing, poaching, fish and wildlife harassment, use conflicts, lost soil productivity, fires, landscape modifications, and decreased opportunities for solitude (Forman 2004, Gucinski et al. 2001, Trombulak and Frissell 2000, Angermeier et al. 2004). Although impacts to water and fish are the primary focus of this report, the direct and indirect impacts of roads on other resources and their use should also be recognized.

While the only certainly effective mitigation to avoid the impacts of roads and pipelines is to find alternatives that do not require building and using them, it does not appear geographically or operationally feasible to develop the Pebble mine without a road and pipeline corridor.

Immediate Effects of Construction versus Long-term Impact of Use and Maintenance

Following Angermeier et al. (2004), the effects of roads are distributed across scales of space and time in three discernible quanta. The first is the immediate and site-specific effect from the construction of a new road. Many of these impacts are either transient or are acute only during and shortly after initial construction. An example is the delivery of large pulses of sediment to streams during runoff events after placement of fill or major ground disturbance by heavy equipment. The second quantum is the suite of effects caused by sustained operation, maintenance, and/or mere existence of the roadway. Examples include seasonal runoff of pollutants such as deicing salts into nearby streams, transport of wind-eroded dust from road surfaces to adjacent areas, chronic delivery of sediment from erosion of road surfaces, ditches, and cut slopes, and the alteration or sustained displacement of natural vegetation in the footprint and influence zone of the road. Finally, often the greatest impact of road development is the ancillary development of the landscape, or change in the pattern of human habitation, resource extraction, and land and water use of a region, that the road in some way facilitates. The remainder of this report focuses on the first two quanta, while acknowledging that the third class of impacts is likely the most significant for Bristol Bay.

The hydrologic and biological effects of roads are generally similar in nature for wetlands, streams, rivers, and lakes. Darnell et al. (1976, see especially pp. 129-136) identified basic construction activities typically associated with industrial projects, including roads and pipelines:

1) Clearing and grubbing;
2) Disposition of materials;
3) Excavation;
4) Sub-grade and slope/cut stabilization, including riprap;
5) Placement of fill;
6) Aggregate production;
7) Paving;
8) Equipment staging;
9) Borrow pits;
10) Landfills (disposal sites of excess excavated material).

The authors summarized the categories of possible or likely impact from such projects and activities on adjoining aquatic areas as follows:

1) Loss of natural vegetation;
2) Loss of topsoil;
3) Change of water table elevation;
4) Increased erosion;
5) Leaching of soil minerals from exposed and eroding soil surfaces;
6) Fluctuations in streamflow;
7) Fluctuations in surface water levels;
8) Increased downstream and upstream flooding;
9) Increased sediment load;
10) Increased sedimentation;
11) Increased turbidity;
12) Changes in water temperature;
13) Changes in pH;
14) Changes in chemical composition of soils and waters;
15) Leaching of pollutants from pavement;
16) Introduction of hydrocarbons to soils and waters;
17) Addition of heavy metals;
18) Addition of asbestos fibers (dispersed from industrial or natural sources); and
19) Increased oxygen demand (caused by organic matter export to and accumulation in waterways).

These various alterations interact in complex cause-and-effect chains. Although recognizing that long-term consequences of these alterations are to a significant degree dependent on local circumstances, Darnell et al. (1976) nevertheless identified common, general long-term outcomes that include 1) permanent loss of natural habitat; 2) increased surface runoff and reduced groundwater flow; 3) channelization or structural simplification of streams and hydrologic connectivity; and 4) persistent changes in the chemical composition of water and soil.

Three other categories of impact common to roads have been identified in more recent literature (Trombulak and Frissell 2000, Forman 2004): 1) disruption of movements of animals, including fishes and other freshwater species; 2) aerial transport of pollutants via road dust; and 3) disruption of near-surface groundwater processes, including interception or re-routing of hyporheic flows, and conversion of subsurface slope groundwater to surface flows. Because of their potential importance in the Bristol Bay region, these are further described in the following section.

<u>Connectivity and Barriers to Fish Movement</u>

Because roads alter surface drainage, and their stream crossing structures can either by design or by subsequent alteration by erosion or plugging with debris, roads can form barriers to the movement of freshwater organisms (Roeloffs et al. 1991, Trombulak and Frissell 2000, Gucinski et al. 2001.) Barriers to upstream passage into headwater streams are most common.   Pipelines may or may not have similar effects, depending on their crossing design and association with access and maintenance roads.

Small headwater streams are the lifeblood of rivers and lakes; they sustain processes and natural communities that are critically and inextricably linked to water quality, habitat and ecosystem processes that sustain downstream resources (Lowe and Likens 2005). The direct dependence of some fish on headwater streams for habitat is just one example of these linkages. When road crossings block fish passage—as they often do (Harper and Quigley 2000, Gucinski et al. 2001, FSSSWP 2008), the isolated population(s) immediately lose migratory (anadromous or freshwater migrant) species and life history types. Resident species that remain are also at risk of permanent extirpation because barriers can hinder their dispersal and natural recolonization after floods, drought, or other disturbances.

Bryant et al. (2009) found in southeast Alaska that Dolly Varden char moved upstream into very small streams primarily in fall, and coastal cutthroat trout primarily in spring. Both species moved upstream just prior to their spawning season, but during low water intervals, not during high-runoff events. Wigington et al. (2006) developed clear quantitative evidence that free access to spawning and early rearing habitat in small headwater streams is critical for sustaining coho salmon in an Oregon river.   Culverts and other road crossing structures not designed, constructed, and maintained to provide free passage of such species can curtail migration, isolate these species from their spawning and nursery habitats, and fragment populations into small demographic isolates that are vulnerable to extinction (Hilderbrand and Kirshner 2000, Young et al. 2004). Drawing inference from natural long-term isolates of coastal cutthroat trout and Dolly Varden in Southeast Alaska, Hastings (2005) found that About 5.5 km length of perennial flow headwater stream habitat supporting a census population size of greater than 2000 adults is required for a high likelihood of long-term population persistence.   Beyond diminishing potential survival and reproduction, barriers to movement can truncate life history and genetic diversity of populations, reducing resilience and increasing their vulnerability to environmental variability and change (Hilborn et al. 2003, Bottom et al. 2009).

The loss of some fish species due to road blockages and other barriers can bring cascading ecological effects by altering key biological interactions. For example, the blockage of anadromous salmon from headwater streams could trigger declines in food web productivity caused by loss of marine-derived nutrients that originate from carcasses and gametes of spawning salmon (Bilby et al. 1996, Wipfli and Baxter 2010).

Dust and Its Impact

Previous syntheses of the impacts of roads have not sufficiently addressed the effects of road dust. Dust results from traffic operating on unpaved roads in dry weather, grinding and breaking down road materials into fine particles (Reid and Dunne 1984). The resulting fines either transport aerially in the dry season or are mobilized by water in the wet season. The dust particles may also include trace contaminants including deicing salts, hydrocarbons, and a variety of industrial substances used in construction or maintenance, or that are dispersed intentionally or unintentionally by vehicles on the road (e.g., heavy metals or cyanide from transported mining waste, or asbestos fibers in some mine and treatment projects). Especially after initial suspension by vehicle traffic, aerial transport by wind spreads dust over varying terrain and long distances, meaning that it can reach surface waters that are otherwise buffered from sediment delivery via aqueous overland flow. Walker and Everett (1987) evaluated the impacts of road dust generated in particular from traffic on the Dalton Highway and Prudhoe Bay Spine Road in northern Alaska. Dust deposition altered the albedo of snow cover, causing earlier (and presumably more rapid) snowmelt up to 100 meters from the road margin, as well as increased depth of thaw in roadside soils. The authors also associated dust with loss of lichens, sphagnum and other mosses, and a reduction of plant cover (Walker and Everett 1987). Loss of near-roadway vegetation has important implications for water quality, as that vegetation is a major contributor to filtration of sediment from road runoff. Hence, dust deposition not only contributes to stored sediment that will mobilize to surface waters in wet weather, but can also reduce the capacity of roadside landscapes to filter that sediment.

Near-Surface Groundwater and Hyporheic Flows

The potential Pebble Mine transportation corridor would have a high frequency of crossings of streams, wetlands, and areas of shallow groundwater. These groundwater systems include extensive hyporheic flow networks that connect surface waters through shallow, subsurface flow paths. In the Bristol Bay watershed, they appear to be especially associated with alluvial, glacio-fluvial and glacio-lacustrine deposits, but also locally with slope-mantling till and other locally porous deposits. Existing research sheds relatively little light on the crucial subject of the impacts of road development on shallow groundwater and the connectivity to surface water habitats important to fish. Due to the apparent large extent and hydrologic importance of subsurface-to-surface hydrologic connectivity to streams, lakes and wetlands in Bristol Bay (e.g., Woody and Higman 2011, Woody and O'Neal 2010), and to the recognized importance of groundwater-fed habitats for northern latitude fishes (e.g., Cunjak 1996, Power et al. 1999, Malcom et al. 2004), this review pays particular attention to those linkages and how they can be impacted by roads.

Rudimentary groundwater studies at roads traversing moderate slopes of conifer forest and muskeg in southeast Alaska (Kahklen and Moll 1999) revealed there could be either a bulge or a drawdown in groundwater level near the upslope ditch, while immediately downslope of the road the water table was most often depressed. These effects appeared for distances between 5 and 10 meters on each side of the road prism. The effect of observed water table deformation on the downslope flux of groundwater remains unknown.

The distance to which a road influences subsurface flow paths may be considerably greater in gently sloping alluvial and glaciolacustrine terrain, typically characterized by shallower, porous zones of subsurface hyporheic or channeled subsurface flow that roads can unearth or compact (Jones et al. 2000). It is well-recognized that management of roads in such terrain types can be unpredictable and challenging, in part because it is very difficult to anticipate the extent and nature of disruption to subsurface flow paths, large volumes of water may be involved, and with low gradients, the effects of water table deformation can project hundreds of meters from the road itself (Darnell et al. 1976).

The field observations reported by Hamilton (2007) and Woody and O'Neal (2010) in the Pebble mine area indicate terrain with an abundance of near-surface groundwater and a high incidence of seeps and springs associated with complex glaciolacustrine, alluvial, and slope till deposits. The abundance of mapped wetlands (see main report) further testifies to the pervasiveness of shallow subsurface flow processes and high connectivity between groundwater and surface water systems in the areas traversed by the transportation corridor. The construction and operation of roadways and pipelines can fundamentally alter the intricate connections between shallow aquifers and surface channels and ponds, leading to further impacts on surface water hydrology, water quality, and fish habitat (Darnell et al. 1976, Stanford and Ward 1993, Forman and Alexander 1998, Hancock 2002). In wetlands, for example, hydrologic disruptions from roads, by altering hydrology, mobilizing minerals and stored organic carbon, and exposing soils to new wetting and drying and leaching regimes, can lead to changes in vegetation, nutrient and salt concentrations, and reduced water quality (e.g., Ehrenfeld and Schneider 1991). Hyporheic exchange processes may be further altered by changes in sediment supply, both positive and negative, which alter infiltration, porosity, and exfiltration of subsurface flow paths, as well as affecting mixing of upwelled and surface water (Hancock 2002, Kondolf et al. 2002). Roads can either reduce sediment supply by blocking downslope or downstream sediment transport or increase sediment supply by creating a new source of eroded material (e.g., road fills, cuts, landslides), often exacerbated by stream diversions that result in more erosive flows (Montgomery 1994).

Ground disturbance and catchment alteration by roads and other land use practices generally increases erosion and sediment delivery to streams. In the Bristol Bay region, many streams and rivers connect, directly or indirectly, to lakes. Of particular regard to Pebble project is Lake Iliamna, which supports abundant and diverse sockeye salmon and other species (Schindler et al. 2010). Accelerated sedimentation and accompanying phosphorus deposition in lakes, as well as mobilization of dissolved and particulate carbon and nitrogen result from shoreline and catchment disturbance (Birch et al. 1980, Stendera and Johnson 2006), and these inputs can, in turn, trigger profound changes in lake trophic status and food webs that could result in harmful effects on production of sockeye salmon and other lake-dwelling species (Schindler and Scheurell 2002). Nutrient delivery from road runoff and other road-related hydrologic alterations differs in seasonal timing, quantity, and chemical makeup from nutrients delivered to streams and lakes by anadromous fishes that die after spawning, hence it may have different ecosystem–level effects. For example, road-associated runoff commonly combines inputs of carbon, phosphorus, and nitrogen with suspended sediments, and the physical and light-reducing properties of the sediments can profoundly impact the processing of those nutrients by microbial films, plants, and filter feeders (Newcombe and Jensen 1996, Donohue and Molinos 2009). While the most profound and detectable physical and biological effects occur in littoral zones and deltas, where sediments and nutrients are directly delivered (and where sockeye spawning is often concentrated, [Woody 2007]), suspended sediment and accelerated nutrient delivery can produce lake-wide effects (Schindler and Scheurell 2002, Stendera and Johnson 2006, Donohue and Molinos 2009, Ask et al. 2009). Ultraoligotrophic lakes (nutrient concentrations in both the water column and lake sediments are extremely low) such as Iliamna can be among the most vulnerable to major changes in lake status and function in response to increases in nutrient or sediment inputs (e.g., Ramstack et al. 2004, Bradshaw et al. 2005).

Relationship of Road Density and Roadless Condition to Salmon

Across many studies in North America, higher abundances and more robust populations of native salmonids typically correlate to areas of relatively low road density or large roadless blocks (e.g., Baxter et al. 1999, Trombulak and Frissell 2000, Gucinski et al. 2001). One study from Alberta documented that bull trout occur at substantially reduced abundance when even limited road development (road density of less than one mile per square mile) occurs in the local catchment, compared to their typical abundance in roadless areas (Ripley et al. 2005). In Montana, Hitt et al. (2003) found the incidence of hybridization that threatens the westslope cutthroat trout within its native range increased with increasing catchment road density. However consistent the correlations, the specific causal links between roads and harm to fish are complex and manifold, and seldom laid clear in existing research.

Nevertheless, in light of the already dramatic and widespread influence of roads in North America (Forman 2000), protection of remaining roadless areas has been identified as a potentially crucial and fiscally sound step for effective regional conservation of fish and wildlife (Trombulak and Frissell 2000, Gucinski et al. 2001).

Pipeline Spills

Pipelines have similar environmental effects as roads, with the primary difference being that pipelines constantly or semi-continuously transport potentially toxic or harmful materials that are only intermittently transported on roadways. In contrast to vehicle transport, pipeline transport is often remote from direct oversight by human operators, putting heavy reliance on remote leak detection. As a consequence, accidents with pipelines can lead to dramatically larger spills than roadway accidents. Beyond pipeline design, effective leak detection systems and inspection protocols are crucial for reducing risk of leaks and spills, particularly in a relatively active seismic zone such as the Pebble Mine area. However, in a review of recent pipeline spills in North America, Levy (2009) finds that existing technology and contemporary practice does not provide firm assurance against catastrophic spills.

Pipeline crossings of streams are an obvious source of direct channel disturbance and sediment entry, and as a result they have received considerable study (e.g., Lawrence and Campbell 1980, Lévesque and Dubé 2007, Levy 2009). Pipeline installation can avoid or reduce direct disturbance to channels by building full-span pipeline bridges over waterways (at less expense than road bridges), or by boring underneath the streambed.

In addition to the access road, Ghaffari et al. (2011) describes a transportation corridor (Figure 3) with four pipelines:

1) An 8-inch diameter steel pipeline to transport a slurry of copper-molybdenum concentrate from the mine site to the port site, with one pump station at the mine end of the line and a choke station at the port terminal;
2) A 7-inch diameter steel line returning reclaimed filtrate water (remaining after extraction of the concentrate) to the mine site, fed from a pump station at the port site;
3) A 5-inch diameter steel pipeline for pumping diesel fuel from the port site to the mine site;
4) An 8-inch diameter pipeline for delivering natural gas from the port site to the mine site (specifics of design not yet released).

All four lines would be contained in close proximity, for an unspecific portion of the distance buried about five feet below the ground surface in a common trench, either adjacent to or—in steeper terrain—beneath the road surface. The combined lines would cross streams via either subsurface borings or suspended bridges, apparently with all pipes encased in a secondary containment pipe, although the specific circumstances that would receive secondary containment and what the containment design would be are not available. In the design presented in Ghaffari et al. (2011, p. 336), there would be no secondary encasement of the pipelines away from stream crossings

Available documents do not discuss the composition or potential toxicity of the mineral slurry concentrate. However, it is likely that such a slurry would be toxic to some organisms and that, due to its concentrated, aqueous form, it would readily transport downstream or downslope of a spill site, and deposited materials on terrestrial surfaces could generate leachate that enters groundwater systems. Projected chemical composition of the returned slurry filtrate is also not available, but it is likely that this water would have toxic levels of acidity and/or metals. As for the third line, diesel fuel has known toxicity, with both acute and chronic effects on fish and other organisms (Levy 2009 and elsewhere).

Liquefied natural gas, the product that the fourth line would carry, consists primarily of methane, which dissipates rapidly when released into water or the air, and is considered non-toxic in those circumstances (Levy 2009). Large-scale explosions of natural gas pipelines have occurred as a result of the accumulation of gas from slow leaks. Such an explosion could pose a major risk of damaging or destroying the other pipelines in the

Pebble Mine corridor, disabling electronic leak detection and severing road access necessary for emergency shut-offs or repairs. Containing all four pipelines, the primary access road, and the utility lines in a single narrow corridor, while reducing spatial footprint impacts like erosion and sedimentation, would also bring the consequence, albeit a low-probability one, of compounding the risk and potential scope of environmental impact from a catastrophic event such as a methane explosion.

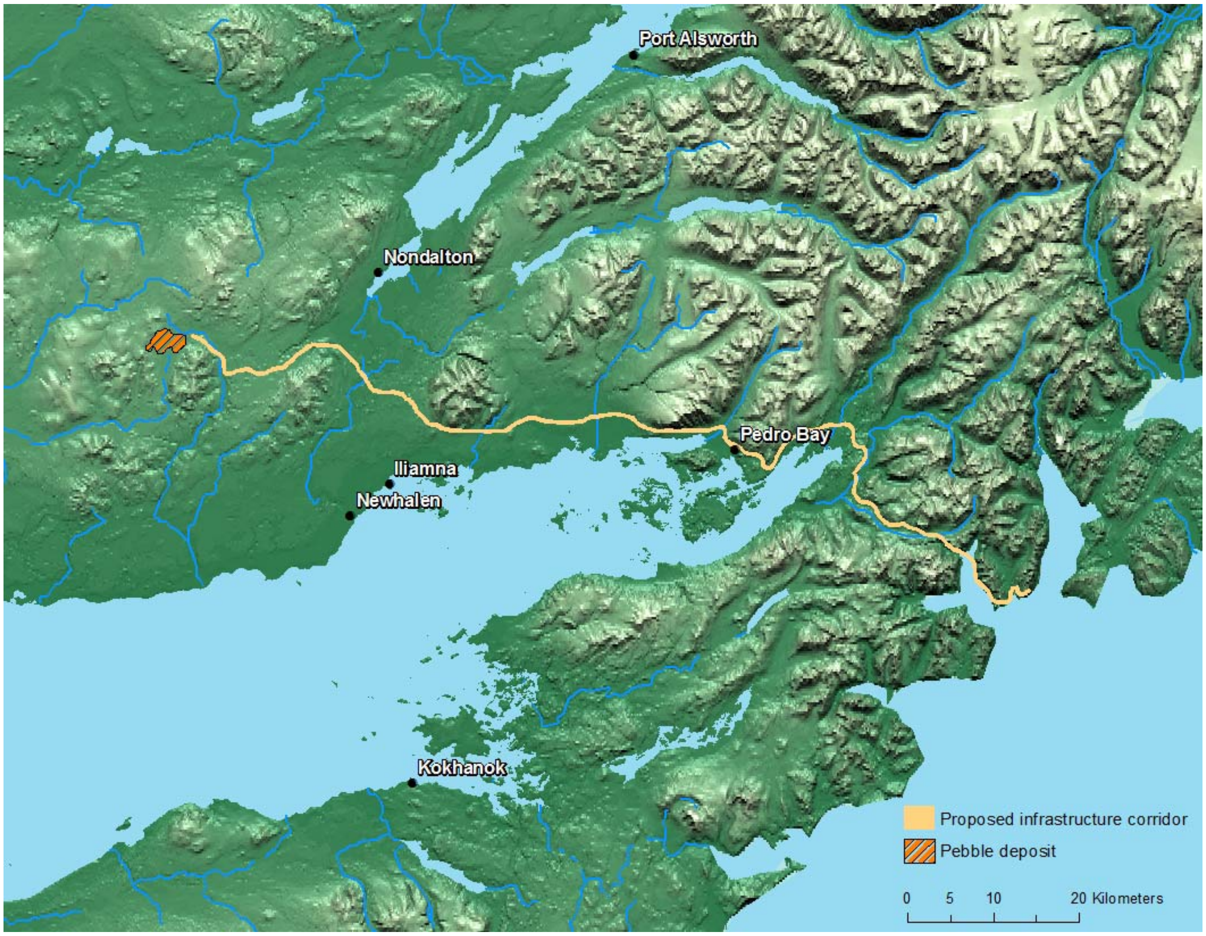

Figure 2. Anticipated location of the road, pipeline, and utility transmission corridor for Pebble Mine (Ghaffari et al. 2011, p. 326). The new road and pipeline corridor would connect the Pebble Mine operations with a new seaport on Cook Inlet. Not shown is an existing north-south connecting tie road from near Nondalton to the Iliamna area (see Figure 1). The Pebble segment from Cook Inlet west to near Lake Iliamna would be reconstructed over an existing lower-standard roadway.

V. IMPACT FOOTPRINT OF THE PROPOSED PEBBLE MINE TRANSPORTATION CORRIDOR ON WATER AND FISH

The Preliminary Assessment of the Pebble Project produced for Northern Dynasty Minerals, Ltd. (Ghaffari et al. 2011) included a map and moderately detailed description of the route of the potential Pebble Mine transportation corridor (see Fig. 2). The following summary relies on that source for road location, while noting the caveat cited in the document that the project ultimately proposed may be different.

According to Ghaffari et al. (2011), the proposed access road and pipelines would provide for the basic infrastructural and transportation needs of the mine and its products and have a fifty-year design life, consistent with the anticipated operating life of the mine. The 86-mile corridor would contain an all-weather road with a two-lane, 30-foot wide gravel driving surface. The road would link with the Iliamna airfield, as well as a new deepwater port on Cook Inlet, from which ships would transport ore elsewhere for processing. Northern Dynasty anticipates that the route would require twenty bridges, ranging from 40 to 600 feet in total span, as well as 1,880 feet of causeway passing over the upper end of Iliamna Bay and five miles of fill embankment along the shorelines of Iliamna and Iniskin Bays.

The route of the transportation corridor stays south of the Lake Clark National Park boundary. About eighty percent of the potential alignment is on private land held by Alaska Native Village Corporations and other corporate landowners, with the rest owned by the State of Alaska (Ghaffari et al. 2011). The route was reportedly selected with regard to transportation and environmental concern in mind, but also with regard to avoiding parcels of private land held by individuals (Ghaffari et al. 2011).

The Preliminary Assessment (Pp. 326-328) characterizes the proposed route as amenable to road and pipeline construction with

> . …terrain favourable for road development. In general, soils are good to excellent; where rock is encountered, it is fairly competent, useable for construction material and amenable to reasonable slope development. The numerous stream crossings appear to have favourable conditions for abutment foundations. There are no significant occurrences of permafrost or areas of extensive wetlands. Where the terrain is challenging, the rock or soil conditions are generally favourable. In intertidal areas, subsurface conditions appear favourable for placement of rock to create the required road embankment

A comparison of the route to National Wetlands Inventory (NWI) data available for the middle portions indicates that while the proposed route might avoid areas of particularly extensive wetlands, nevertheless the route intersects or closely approaches a large number of mapped wetlands (see main report). The route also crosses a great number of mapped (and likely many more unmapped) tributary streams to Iliamna Lake on its 86-mile traverse. The Preliminary Assessment does not identify alternative routes that would avoid or reduce impacts to wetlands, streams or shorelines. Identifying alternative routes to accomplish this would be very difficult given the high density of such hydrologic features.

Summarizing the account of Ghaffari et al. (2011, pp. 327-329), traveling eastward from the Pebble Mine site, north of Iliamna Lake, the proposed transportation corridor passes through diverse terrain and climatic zones. From the mine site, at an elevation of 1,100 feet above mean sea level, the road traverses variably sloping upland terrain over glacial drift before descending to the Newhalen River valley, 11 kilometers north of Iliamna Lake. From there, the route crosses variable terrain of dry, open tundra until approaching Roadhouse Mountain, about 8 kilometers east of the river. The terrain and climatic conditions of this western portion of the route are typical of western interior Alaska, with relatively light precipitation, mild summers and winters with windblown snow. East of Roadhouse Mountain, the route parallels the shoreline of Iliamna Lake apparently at a distance of about five to eight kilometers from the shoreline, spanning a transitional landscape of increasing snowpack and extensive spruce-hardwood forest cover. Roughly 20 kilometers west of Pedro Bay, the route approaches and occupies the shoreline of Iliamna Lake, traversing the steep escarpment of Knutson Mountain, an area vulnerable to avalanches, debris flows, and other high-energy montane processes. After skirting the face of Knutson Mountain above the lakeshore, the route traverses an extensive outwash plain northeast of Iliamna Lake, then ascends rugged terrain to cross Iliamna Pass and wends its way some 32 kilometers through rugged terrain and increasingly warmer and wetter Maritime climatic conditions until descending to the Iniskin Bay port site on Cook Inlet.

This report, together with material referenced on wetlands, provides a quantitative conceptualization of the potential impact footprint of the Pebble Mine transportation corridor on the following known resources:

1) Wetlands (see main report);
2) Anadromous fish-bearing streams (Figures 3a and 3b);
3) Sockeye salmon spawning (Figure 4) and rearing (Figure 5) areas in the Iliamna Lake system; and
4) Resident fish (Dolly Varden, arctic grayling, rainbow trout, three-spine stickleback, nine-spine stickleback, northern pike, and slimy sculpin; Figures 6a, 6b, and 6c).

Figure 3a. Anadromous fish-bearing streams (documented to support at least one species of salmon) crossed by the *eastern half* of the potential Pebble Mine transportation corridor (Chekok Creek east to Y Valley Creek).[1] Map compiled from Alaska Department of Fish and Game catalog sources (ADFG 2012, Johnson and Blanche 2011a, 2011b)[2], supplemented with additional spawner count data (Morstad 2003).

[1] Median alignment of the corridor was defined by scanning and geo-referencing the Pebble transportation corridor route map from Ghaffari et al. (2011. Figure 1.9.2, p.57).

[2] Field surveys indicate that ADFG Catalog (Johnson and Blanche 2011a, 2011b) under-represents the actual extent of salmon spawning (Woody and O'Neal 2010, and Daniel Rinella, University of Alaska, Anchorage, AK, unpublished data), although these figures do reflect updates based on recent surveys.

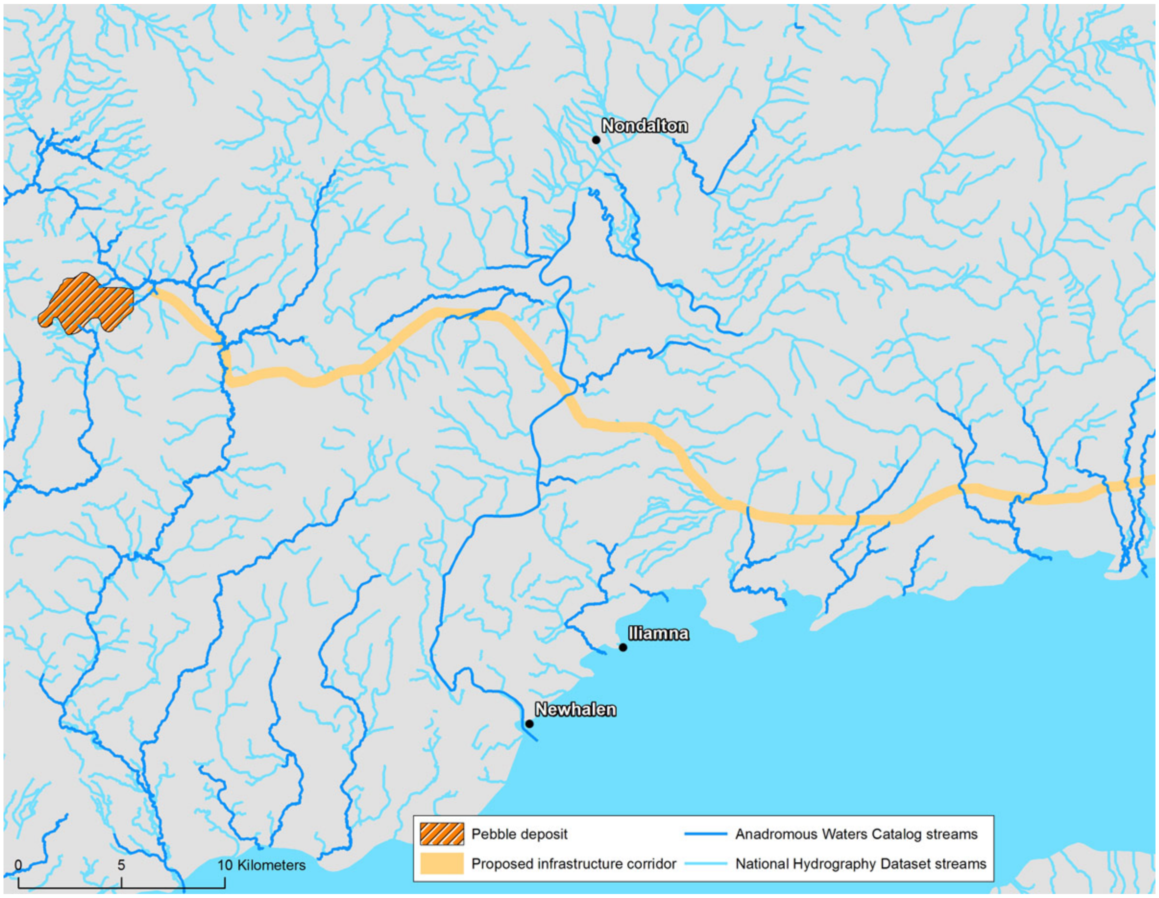

Figure 3b. Anadromous fish-bearing streams (documented to support at least one species of salmon) crossed by the *western half* of the potential Pebble Mine transportation corridor (Upper Talarik Creek east to Canyon Creek).[3] Map compiled from Alaska Department of Fish and Game catalog sources (ADFG 2012, Johnson and Blanche 2011a, 2011b)[4], supplemented with additional spawner count data (Morstad 2003).

[3] Median alignment of the corridor was defined by scanning and geo-referencing the Pebble transportation corridor route map from Ghaffari et al. (2011. Figure 1.9.2, p.57).

[4] Field surveys indicate that ADFG Catalog (Johnson and Blanche 2011a, 2011b) under-represents the actual extent of salmon spawning (Woody and O'Neal 2010, and Daniel Rinella, University of Alaska, Anchorage, AK, unpublished data), although these figures do reflect updates based on recent surveys.

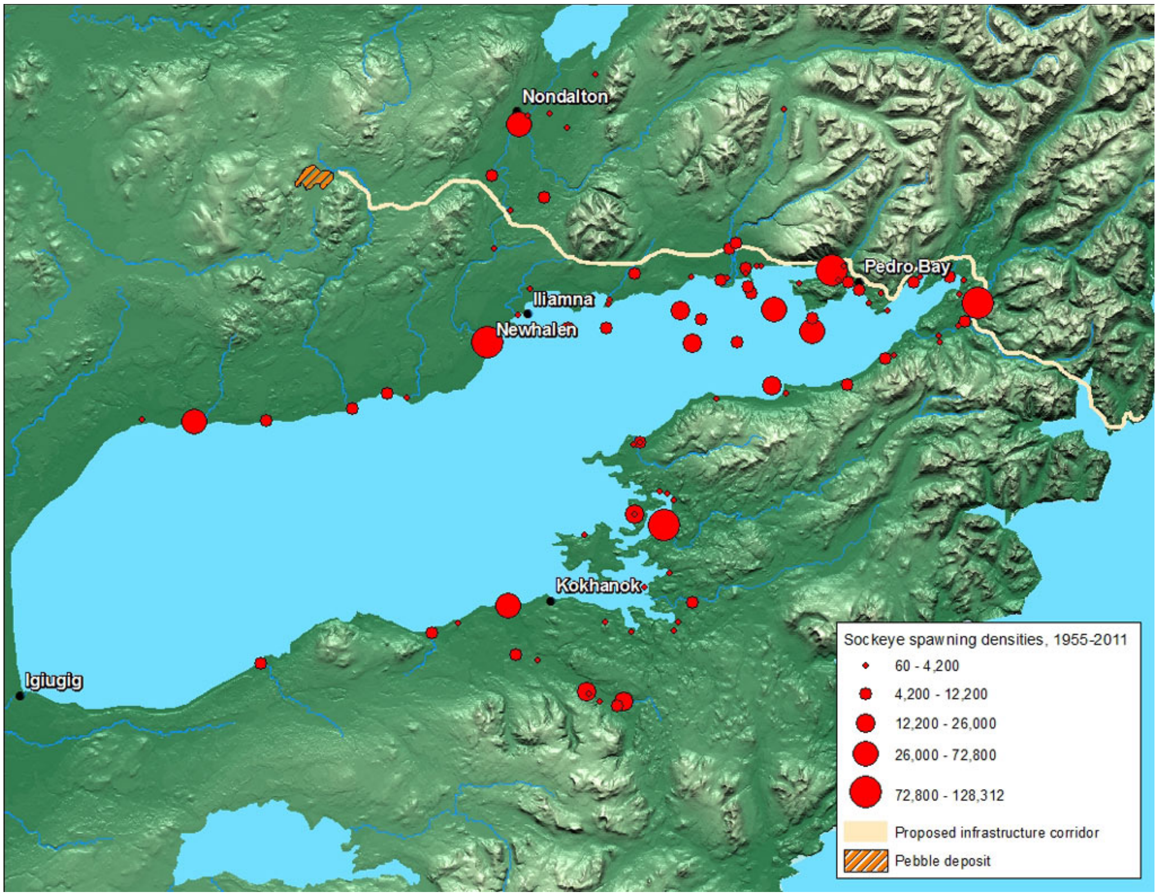

Figure 4. Pattern in abundance of spawning sockeye salmon in Iliamna Lake and tributary streams relative to the potential Pebble Mine transportation corridor. A general concentration of sockeye spawning is apparent in the northeast portion of Iliamna Lake. Spawner density data compiled from Johnson and Blanche (2011a, 2011b, as average counts collected with varying regularity between 1955-2011).[5]

[5] Morstad (2003) with additional information on sampling locations from Harry Rich (2011, and University of Washington, Seattle, WA, unpublished data)

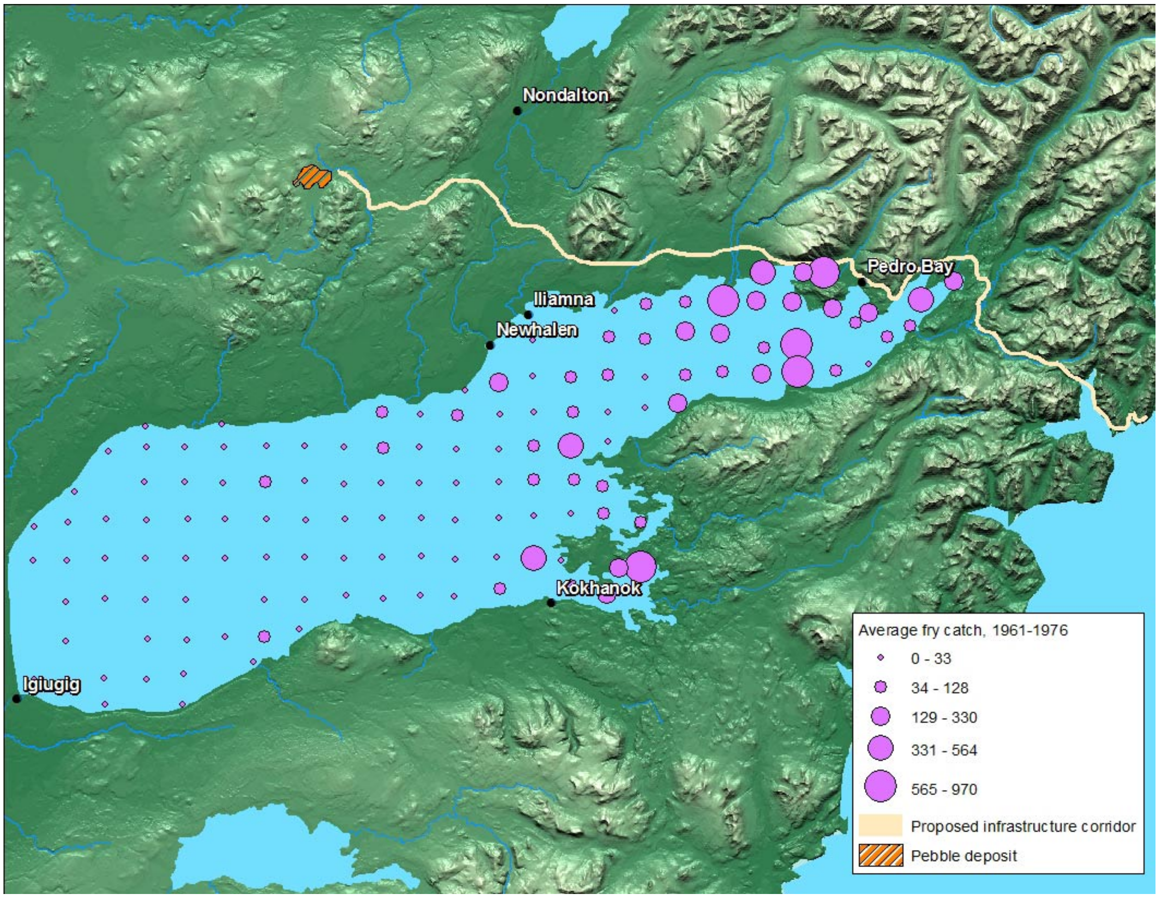

Figure 5. Iliamna Lake juvenile sockeye catches in tow-net sampling, 1961-1976, relative to the potential Pebble Mine transportation corridor. High-density rearing sites are concentrated in the eastern half of the lake, where the transportation corridor comes closest to the lakeshore and intersects with numerous tributaries. Compiled from data provided by Harry Rich (2011, and University of Washington, Seattle, WA, unpublished data).[6]

[6] Sampling methods for these data are described in Rich (2006).

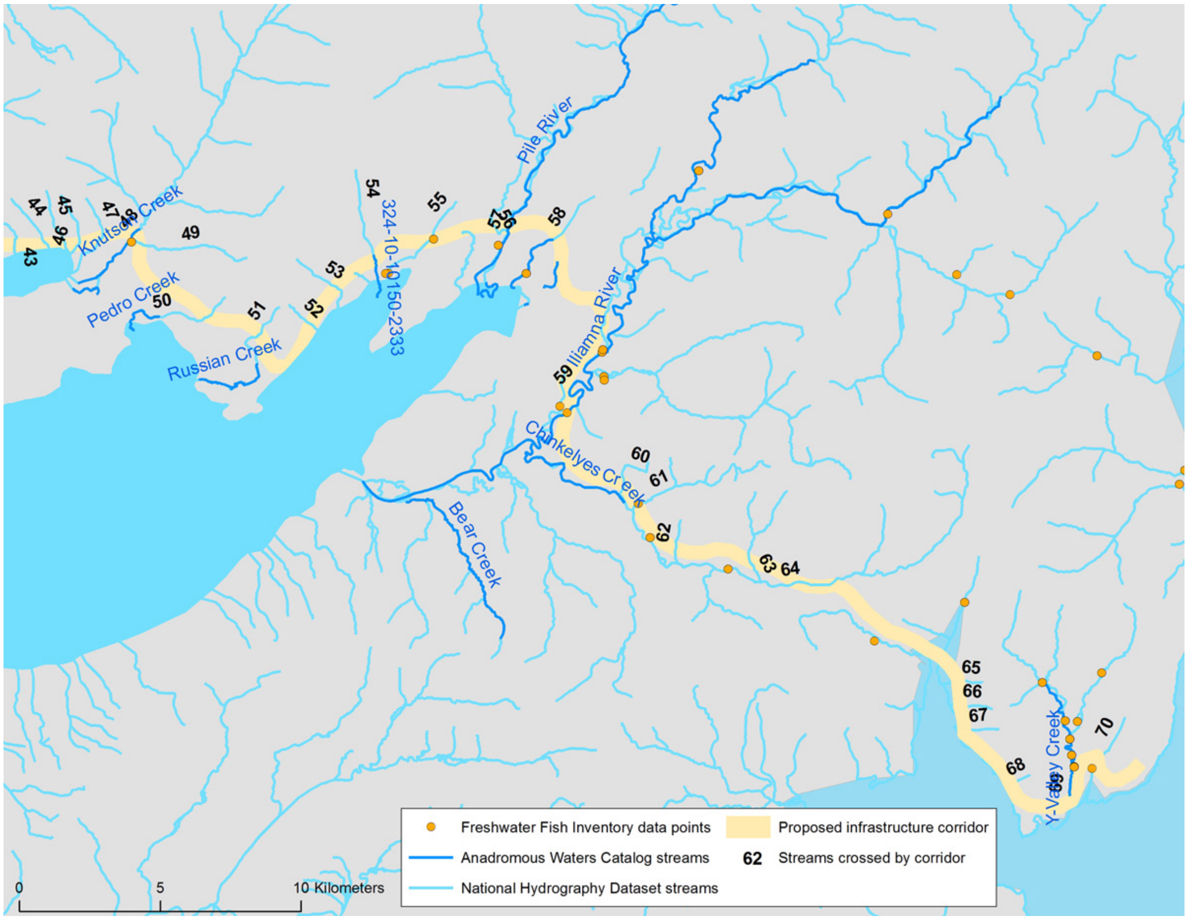

Figure 6a. Resident or nonanadromous fish streams crossed or potentially affected by[7] the *eastern one-third* of the potential Pebble Mine transportation corridor.[8] Compiled from the Alaska Freshwater Fish Inventory (AFFI) Database (ADFG 2012, Johnson and Blanche 2011a and 2011b, additional information provided by Joe Buckwalter, ADFG, Anchorage, AK, Unpublished data). Stream names and fish species known present are summarized in Attachment A.

[7] Secondary tributaries entering trunk streams downstream of the transportation corridor are indicated because they could be isolated and freshwater migrant life histories harmed by spills affecting the trunk stream.

[8] Median alignment of the corridor was defined by scanning and geo-referencing the Pebble transportation corridor route map from Ghaffari et al. (2011).

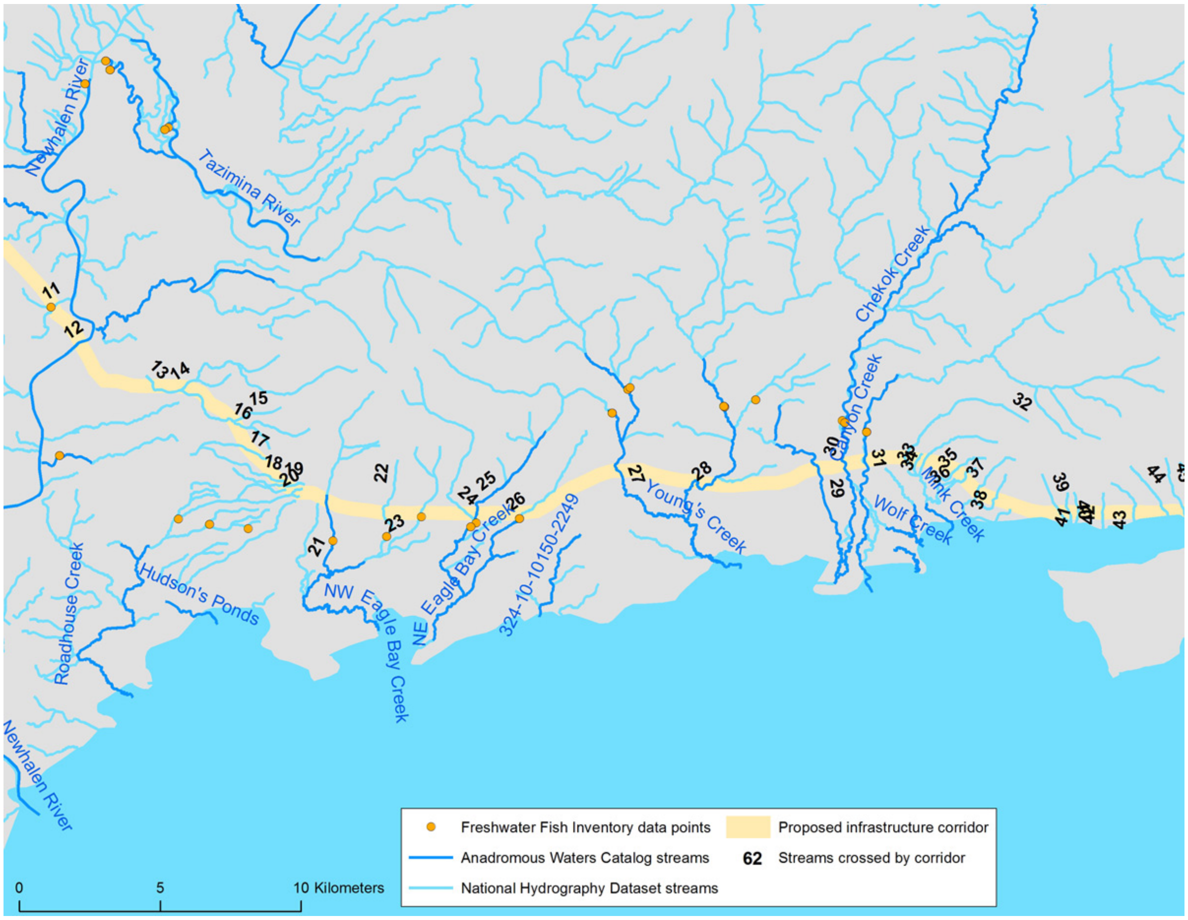

Figure 6b. Resident or non-anadromous fish streams crossed or potentially affected by[9] the *central one-third* of the potential Pebble Mine transportation corridor.[10] Compiled from the Alaska Freshwater Fish Inventory (AFFI) Database (ADFG 2012, Johnson and Blanche 2011a and 2011b, additional information provided by Joe Buckwalter, ADFG, Anchorage, AK, Unpublished data). Stream names and fish species known present are summarized in Attachment A.

[9] Secondary tributaries entering trunk streams downstream of the transportation corridor are indicated because they could be isolated and freshwater migrant life histories harmed by spills affecting the trunk stream.

[10] Median alignment of the corridor was defined by scanning and geo-referencing the Pebble transportation corridor route map from Ghaffari et al. (2011).

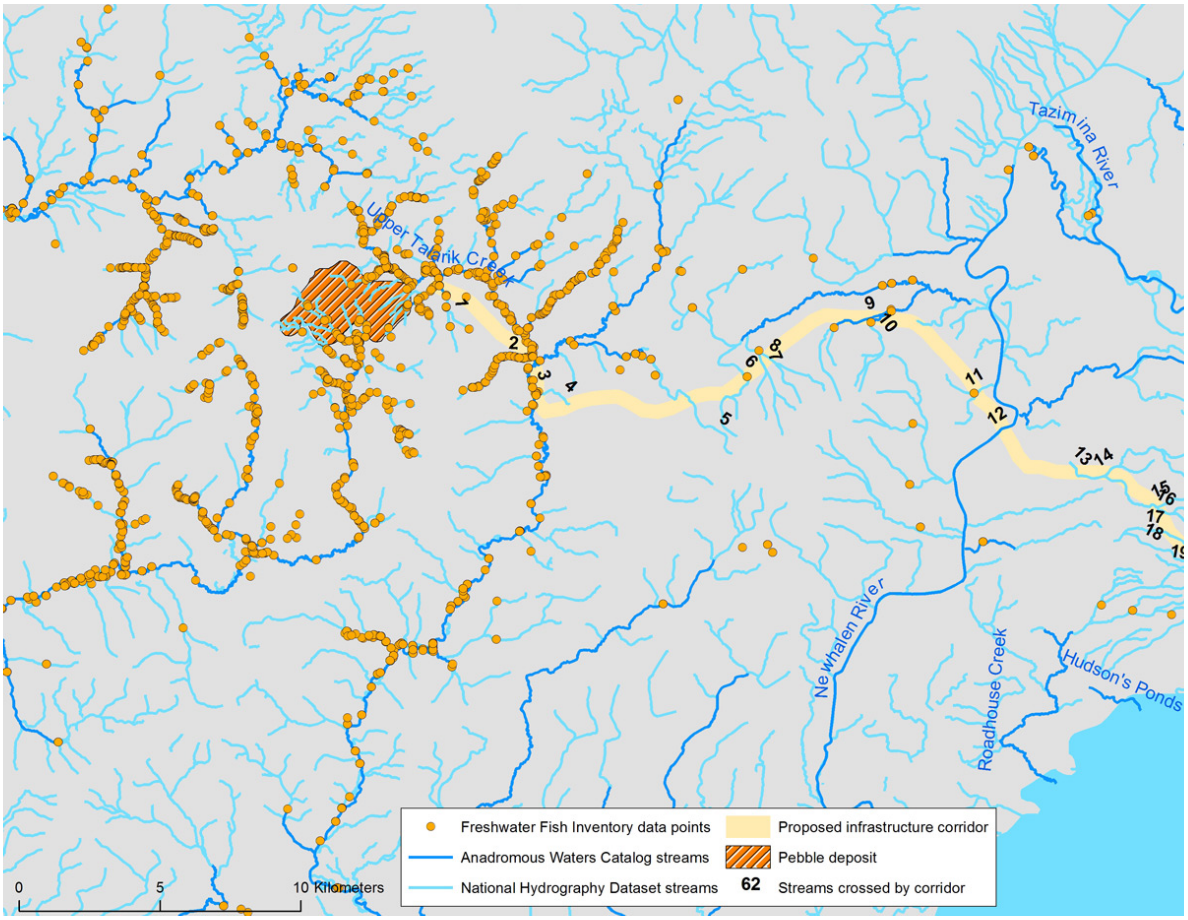

Figure 6c. Resident or non-anadromous streams crossed or potentially affected by[11] the *western one-third* of the potential Pebble Mine transportation corridor.[12] Compiled from the Alaska Freshwater Fish Inventory (AFFI) Database (ADFG 2012, Johnson and Blanche 2011a and 2011b, additional information provided by Joe Buckwalter, ADFG, Anchorage, AK, Unpublished data). Stream names and fish species known present are summarized in Attachment A.

[11] Secondary tributaries entering trunks downstream of the transportation corridor are indicated because they could be isolated and freshwater migrant life histories harmed by spills affecting the trunk stream.

[12] Median alignment of the corridor was defined by scanning and geo-referencing the Pebble transportation corridor route map from Ghaffari et al. (2011).

Drawing on published conceptualizations that plot the extent of environmental and ecological influences of roads as a spatial footprint (Forman 2000, Forman and Deblinger 2000, Trombulak and Frissell 2000, Jones et al. 2000), Figures 3a through 6c illustrate that the potential Pebble transportation corridor could have widespread regional effect on the aquatic ecosystems that feed Iliamna Lake. Figures 6a, 6b, and 6c identify both upstream and downstream habitat that is susceptible to loss or degradation due to structural failures, spills, sedimentation, or other impacts originating in the transportation corridor. Through hydrological dispersion of sediment or toxicants, the maps illustrate that a large proportion of Iliamna Lake salmon habitat would be vulnerable to indirect impact, or direct impact at a point removed from the origin of a spill, either through potential exposure to pollutants downstream of the transportation corridor or blockage of migration to spawning and nursery habitats upstream.

A significant fraction of Iliamna Lake's sockeye salmon resource would be vulnerable to impacts from the Pebble transportation corridor. Migration and spawning in these streams could be compromised below the corridor crossing by sedimentation or contamination from spills, and habitat upstream from the crossings could be cut off from access by spills or structural failures. To roughly estimate the proportion at risk, we adjusted the stream length potentially affected by the transportation corridor in each system by the average surveyed spawner density for that system (Figure 4). This analysis suggests that about twenty percent of known stream spawning populations of Iliamna system sockeye reproduces in streams and rivers intersected by the Pebble corridor. Moreover, many principal sockeye fluvial spawning areas lie in close proximity to road and pipeline crossing sites. In addition, a major sockeye salmon beach spawning site is located at the mouth of Knutsen Creek (Rich 2006, and unpublished data), a stream that the Pebble transportation corridor would cross, making its delta vulnerable to impacts from upstream. If the Knutsen Creek delta spawning population is included in the tally of potentially affected waters, roughly thirty percent of known Iliamna Lake sockeye spawners could be at risk. A similar analysis from the University of Washington Fisheries Research Institute came to a similar conclusion (Rich 2011, and unpublished data).

Available data show that rearing sockeye salmon are most concentrated in the eastern half of the lake (Figure 5), where the Pebble transportation corridor would intersect with numerous direct tributaries to the lake and for some distance would occupy the lakeshore itself, posing a high risk, if not a certainty of affecting Iliamna Lake habitats.

VI. MITIGATION MEASURES AND THEIR LIKELY EFFICACY

It is commonly recognized that the environmental impact of a major construction project like a road or major pipeline corridor can never be fully mitigated (Trombulak and Frissell 2000). Indeed, inherent to the underlying purpose of road projects (i.e., to alter natural conditions so that vehicle transportation is possible where it was physically impossible before) are changes to landscape structure that not only irretrievably alter ecosystem and biological conditions within the construction footprint, but also interrupt or modify the natural flux of water, sediment, nutrients, and biota across the ecosystem, usually permanently (Darnell et al. 1976, Rhodes et al. 1994, Forman and Alexander 1998, Forman 2000, Forman and Deblinger 2000, Trombulak and Frissell 2000). Moreover, engineering or implementation failures, unanticipated field conditions, and/or unforeseen environmental events inevitably test and compromise the effectiveness of mitigation measures applied in large projects (e.g., Espinosa et al. 1997, Levy 2009). The only sure way to avoid impacts to a freshwater ecosystem from a large road or pipeline project is to refrain from building such a project in that ecosystem (Frissell and Bean 2009).

Unfortunately the scientific and professional literature on the subject of the effectiveness of environmental mitigation measures for water and fish is sparse and poorly synthesized. There are lists of standard practices and there are a scattering of short-term, site-specific studies of efficacy of mitigation measures for roads and pipelines (e.g., assessment of mitigation of the delivery of sediment and its local impact on biota). Some report showing adverse impact, or ineffectiveness of mitigation measures, and others report not detecting adverse effects, which is often taken as circumstantial evidence that mitigation measures were effective. Exceedingly few of these studies extend to medium- or long-term evaluation of mitigation effectiveness, and fewer still have been published in accessible peer-reviewed forums. Therefore, evaluating the effectiveness of proposed mitigation measures remains a process of best professional judgment and logical evaluation of premises, specific environmental context, and likely operational circumstances. The release of the Preliminary Assessment for the Pebble project (Ghaffari et al. 2011) allows some specific analysis of the potential transportation corridor.

A few synthesis documents also provide some guidance (e.g., Rhodes et al. 1994), but the over-arching theme is that implementation of site-specific mitigation measures is fraught with uncertainty and risk and that, overall, mitigation has proven to be ineffective in fully protecting water quality and conserving freshwater fishery resources (Esiponsa et al. 1997).

Mitigation Measures for Pebble Road and Pipelines

In the following section I cite mitigation measures identified in Ghaffari et al. (2011) for the Bristol Bay transportation corridor and briefly assess 1) their likely effectiveness to avoid or prevent harm to Bristol Bay water quality and fishery values, 2) possible adverse side effects of applying the mitigation measure, and 3) alternative mitigation measures that could be more effective, given the project is assumed to proceed.

As far as practicable, minimize areas of disturbances (Ghaffari et al. 2011, p.329). This means restricting the footprint of construction activities and the final footprint of the project to the minimum practical surface area (for example, by stacking the road and pipelines in a single corridor). The effectiveness of this measure depends on the location of disturbance relative to resources at risk. Even a small footprint that involves permanent alteration of soils, vegetation, and hydrology can have significant adverse effects that propagate across the landscape by hydrologic and other vectors. This measure must be practiced in the context of measures to avoid sensitive locations to be effective. Secondly, the effectiveness of this measure depends on how other project parameters, including capital cost, delimit what is "practicable." Limiting the area disturbed can often involve expensive practices such as long-distance hauling of waste material in preference to onsite storage. Finally, it is important to reiterate there are potential risks associated with minimizing the footprint of the transportation corridor by "stacking" the road and pipelines closely together. A pipeline failure or gas explosion could sever the sole available route for ground transportation of equipment and personnel to take emergency remedial measures.

As far as practicable, minimize stream crossings and avoid anadromous streams (Ghaffari et al. 2011, p.329). This mitigation measure can be effective if three conditions are met: 1) the landscape structure supports a route that avoids and is buffered from strong interaction with streams, wetlands, and areas of near-surface groundwater; 2) implementation does not result in a route so long and tortuous that it encumbers additional environmental risk (e.g., to upland vegetation and wildlife), 3) resources are sufficient to ensure that costly but environmentally sounder locations and possibly longer routes are "practicable." Ghaffari et al. (2011, pp. 329-330) lists several other criteria that constrain choice of road location, such as:

1) Avoiding certain "unfavorable" land ownerships;
2) Avoiding potential (albeit unspecified) geologic hazards;
3) Keeping road gradients under 8 percent;
4) Maintaining minimum curvature and design speeds;
5) Facilitating high axle loads for transporting assembled mine equipment;
6) Optimizing crossings of soils suitable to maintaining roadway structure and stability;
7) Optimizing access to sources of construction and surfacing rock;
8) Incorporating minimum 2.5–foot (76 centimeter) ditches (possibly necessary for maintaining subgrade stability in many wet or seasonally wet areas); and
9) Minimizing area of disturbance.

These competing objectives for the roadway, coupled with the large number of streams in the landscape between the Pebble Mine site and Cook Inlet serve to limit the effectiveness of this measure. To be most effective, minimizing stream crossings must take primacy above other objectives of economic or operational convenience in project siting and route location. However, even then, one potential side effect of basing route selection on minimization of stream crossings in a stream-rich landscape would likely be a route that is tortuous, countervailing the preceding mitigation measure of minimizing area of disturbance. Hence the two most potentially effective mitigation measures can stand in opposition to each other, especially in landscapes of relatively high stream density.

Appropriate Best Management Practices (BMPs) will be utilized for the maintenance of the road during operations and construction. Ghaffari et al. (2011, p. 370). The Preliminary Assessment does not identify the appropriate practices for road maintenance and construction, so it is not possible to specifically address their likely effectiveness at reducing water quality and fisheries impacts. Specifically with regard to maintenance, BMPs should include a strict prohibition on the disposal of material generated from grading and snow removal into surface waters, and should specify grading practices that retain a local road contour necessary to disperse road surface drainage away from streams, rivers, Iliamna Lake and areas that drain to those waterways (Weaver and Hagans 1994, Wemple et al. 1999, Furniss et al. 1991, Moll 1999). Construction specifications should also designate sites for waste rock disposal and temporary materials storage and stipulate that they be in locations with minimum risk of subsequent transport of material to streams, rivers, or Iliamna Lake, whether by water, wind, or mass failure (Weaver and Hagans 1994). These practices pose minimal risk of environmental side effects, though they may increase annual operational costs. However, because these practices are also effective at reducing roadway harm from erosion, over years they may reduce maintenance and repair costs of the roadway.

Road dust abatement measures. Ghaffari et al. (2011, p. 458) mentions dust suppression as a generic need, but the only allusion to specific mitigation regards procurement of a water spreading truck (Ghaffari et al. 2011, p. 313). The Preliminary Assessment mentions developing a dust dispersion model as part of the permitting process for air emissions (Ghaffari et al. 2011, p. 458), but it does not address dust impacts to surface waters. Depending on mineralogy, water application can be effective at reducing dust transport, if application is frequent and of appropriately limited volume (USDA Forest Service 1999). There are, however, offsetting factors: moderate or heavy application of water that exceeds the very low infiltration capacity of the road surface mobilizes dust in fluid runoff instead of aerial deposition. Wherever a road is in close proximity to surface waters, such runoff can deliver suspended sediments, perhaps quite frequently, to locations where, or at seasons when, they are otherwise virtually nonexistent. Loss of fines from the road rock matrix can contribute to breakdown and accelerated erosion of the road surface (USDA Forest Service 1999). On the other hand under-application of water fails to fully abate dust generation.

Dust abatement measures can bring unintended side effects. Even when dust abatement is effective in retaining fines within the road rock matrix during the dry season, these fines are simply mobilized by water and transported to the surrounding landscape in wet season runoff (Reid and Dunne 1984). The fine sediments are not eliminated—merely reallocated. Other dust controls, including chloride salts, clays, lignosulfanate or other organic compounds, and petroleum distillates (Hoover 1981) bring risk of toxic effects when they run off and enter surface waters, though little research is available to assess their environmental risks or safe conditions of application (USDA Forest Service 1999). In the case of chloride salts, one recommendation is to avoid application within 8 meters of surface waters or anywhere groundwater is near the surface (USDA Forest Service 1999). Adverse biological effects are likely to be particularly discernible in naturally low-conductivity waters like those of Bristol Bay, although research is needed to substantiate this speculation. The best practice to minimize dust pollution is to avoid road construction; the next most effective mitigation is surfacing all roadways with high-grade asphalt pavement, with diligent maintenance of the paved road surfaces.

Paving can measurably reduce (though not eliminate) the chronic generation and delivery of both wet-weather surface-erosion and dust (Furniss et al. 1991, Weaver and Hagans 1994). However, asphalt production, deposition, and weathering generates hydrocarbons that may, in some circumstances, be harmful to aquatic life (Spellerberg 1998, Trombulak and Frissell 2000). In addition, off-site transfer of heavy metals and other contaminants from road treatments such as deicing salts could be more rapid and direct from paved road surfaces. Moreover, in the case of the potential Pebble transportation corridor, pavement could complicate excavation needed to access pipelines buried under the road for visual inspection or repairs of leaks.

River and stream crossing structures have been designed to minimize the impact of the project on areas of sensitive habitat (Ghaffari et al. 2011, p. 370). The Preliminary Assessment further specifies that structural elements, including foundation elements, will be designed to comply with a Memorandum of Agreement between ADOT and ADFG regarding the design of culverts for fish passage and habitat protection. Wherever culverts are not "suitable," Ghaffari et al. state the road would incorporate single- or multiple-span bridges, with specifications based on "hydrological considerations, local topography and fish passage requirements." Although criteria for determining crossing structure type are not provided, the Preliminary Assessment identifies thirteen possible multi-span bridge crossings, at "major" rivers, including 600-foot spans both at the Newhalen River and across tidal flats at Iliamna Bay (Ghaffarri et al. 2011, p. 332).

Road crossing designs are much improved over historic practice, but where rivers are wide and river or stream channels shift location frequently, any crossing structure short of fully spanning the channel migration or flood-prone valley width can prove problematic. Because of the nature of design structures and geomorphic setting, crossings of small streams (under about 3 meters in width) pose greater risk of causing barriers to animal migration and movement of sediment and natural debris, whereas crossings of larger streams pose risk of erosion, sedimentation, channel and floodplain alteration, and delivery of pollutants from spills. The importance of small streams in Bristol Bay for Dolly Varden and other fish species (Woody and O'Neal 2010) underscores the need for culverts to provide fish passage and maintain fish habitat, even where salmon are absent. Numerous studies also document that connectivity between small headwater streams (including streams with intermittent or seasonal flow) and downstream habitats is important and, in some cases, critical for productivity and survival of salmonids (e.g., Hilderbrand and Kirshner 2000, Young et al. 2004, Fausch et al. 2002, Hastings 2005, Wigington et al. 2006, Bryant et al. 2009).

In general, culvert crossings of small streams remain problematic, even under contemporary standards and practices as applied by state highway departments and land management agencies. Gibson et al. (2005) surveyed a 210-kilometer segment of the Trans-Labrador highway, newly constructed under prevailing Canadian government and provincial regulations for fish protection, and found that more than half of the culverts posed fish passage problems due to inadequate design or poor installation. Chestnut (2002), in a survey of stream crossings in Kamloops, British Columbia, found that out of 31 culverts assessed, all but one failed to meet Department of Fisheries and Oceans objectives for juvenile fish passage and maintenance of fish habitat. In an audit of two other Provincial Forest Districts in British Columbia, Harper and Quigley (2000) concluded about a third of road culverts blocked fish passage to upstream habitat.

In small streams without significant near-surface groundwater associations, the effectiveness of different stream crossing structures depends on the geomorphic setting, including stream gradient and channel stability, road slope and angle of interception, flashiness of water and sediment flows, potential for ice rafting and plugging, and abundance and size range of wood and other waterborne debris. In small prairie streams, for example, Bouska et al. (2010) found that large box culverts were less disruptive of stream morphology and hydrodynamics than were low water crossings and corrugated metal culverts. Large-width, bottomless arch or "squashed design" culverts that preserve or restore a natural channel bed material train through the length of the culvert are the current standard norm for stream crossings to maintain both physical and biological connectivity (Weaver and Hagans 1994, FSSSWG 2008). In recent years, the US Forest Service has worked to reduce risk of failure and improve passage of fish and other biota at road at road crossings using a new so-called "Stream Simulation" design protocol for culvert crossings of small streams that emphasizes dramatically wider, open-bottom arch stream crossing designs that strive to maintain both geomorphic and biological continuity through the crossing (FSSSWG 2008). Greater expense of initial design and installation may be compensated by longer life spans (round corrugated steel culverts commonly have a functional life span of 20 years, if properly functioning) and fewer emergency maintenance and repair costs (Weaver and Hagans 1994).

Effective mitigation of adverse roadway impacts to streams must account explicitly not just for the passage of fish and surface waters; in ecosystems like Bristol Bay that are rich in shallow groundwater, roadways must also avoid disrupting or obstructing hyporheic flow paths and shallow aquifers. Short of not building new roads altogether, the most effective practice to avoid alteration of hydrology and hydrologic connectivity is to locate the route well away from streams, wetlands, springs, seeps, areas of near-surface groundwater, pond and lake shorelines, and alluvial fans and glacio-alluvial valley trains where frequently shifting stream courses are present. Due to the number and density of streams, zones of near-surface groundwater, and associated wetlands in the area of the potential transportation corridor (Hamilton 2007), complete avoidance of "sensitive habitat" would be exceedingly difficult. If avoidance of these sensitive hydrologic features is impossible, the next best mitigation is bridge the roadway across them, completely spanning the area of both surface water and near-surface groundwater, thereby reducing direct physical intersection of the roadway and water features. At streams, crossings should occur only where channels are stable, not migrating and not branching. Where long suspensions are necessary to bridge multiple or coextensive hydrologic features, special engineering is required to manage stormwater drainage that accrues on the extensive suspended roadway and route and disperse this discharge to areas well away from surface waters.

Where spanning extensive areas of shallow groundwater is impracticable (e.g., due to expense), the next most effective mitigation would be to "lift" the road surface over them by use of porous fills. Porous fills (commonly large, angular open-framework rock capped by a surface of mixed material) can provide a stable road prism and support heavy vehicle loads, while passing overland or sheet flow with limited concentration and maximum dispersion of water, thereby reducing erosive forces and impacts to local hydrology (Moll 1999). Nevertheless, porous fills do partly obstruct surface drainage, blocking the movement of sediment, debris, and aquatic organisms and despite some filtering capacity, they do not fully control delivery of sediment and other pollutants from the road surface into surface waters. Under heavy tire loads, porous fill road beds may, over time, subside into subsurface soils and alluvial deposits, allowing native fines to enter and clog the porous matrix, eventually making it a barrier to subsurface flow.

Burial in a common trench. (Ghaffari et al. 2011, p. 336). Burial aids in insulation of the pipeline. It also can reduce pipeline impact on wildlife movements, and in steep, mountainous terrain, it can partially protect pipelines from damage and potential spills caused by surface processes like avalanches, landslides and debris flows (Levy 2010). Equally important, clustering of pipelines reduces the direct spatial footprint of disturbance to habitat by concentrating construction and maintenance activity. The smaller footprint, in turn, minimizes the area destabilized by excavation and backfill, thus reducing impacts to water quality from construction site runoff. The downsides of pipeline burial are that: 1) it prevents visual inspection of the lines for leakage and visual monitoring of spilled materials; 2) it typically does not incorporate secondary containment measures for spills and leaks; and 3) it can disrupt subsurface hydrology by severing, damming, or capturing buried flow paths. Visual inspection is a vital backup to electronic leak detection systems and may be the only sure way to detect some chronic, slow leaks. Finally, buried pipelines are still vulnerable to stress and rupture from subsurface processes, such as earthflows, slumps, and seismic shocks.

Secondary containment of buried lines, using an impermeable lining for the trench, could help limit the discharge of material in the event of leaks or spills, but would have the opposing effect of causing greater distortion of natural subsurface flow paths. By acting as a subsurface dam, a lined trench could not only disrupt natural hydrology patterns, but by obstructing subsurface water flow, belowground containment structures could complicate the management of drainage that is necessary to maintain the road surface and the trench itself. From the standpoint of the protection of water quality and fish resources, ideal mitigation measures could include: 1) keeping the pipelines above ground and visible (except where landslide and avalanche risks are moderate to high); 2) incorporating some means of secondary containment for spills and leaks; 3) installing manual shutoff valves at either side of all surface water crossings and all locations vulnerable to damaging landslides or avalanches; and 4) implementing robust plans for both very frequent or full-time visual inspection for leaks, and rapid response for containment, shutdown, repair, and disposal of contaminated material when leaks do occur. Note that these measures may have adverse side effects; for example, elevated pipelines may be more disruptive of wildlife movements, such as caribou migrations.

There is another drawback of clustering that the above mitigation measures would not resolve. With common proximity of the lines, there might be some risk that natural gas leakage and subsequent explosion could both damage the other lines and hinder rapid response to repair damage and contain spills (due to damage to the road). This risk bears close examination by appropriate experts.

Boring pipelines under stream (Ghaffari et al. 2011, p.337). Horizontal boring of a pipeline under stream crossings can reduce much of the channel disruption, erosion and sedimentation associated with trenching and exposed line surface crossings. However, the method suffers from the same drawbacks identified above under *Burial in a common trench*. In particular, leakage of the lines under the stream course could result in undetected contamination of hyporheic, thence surface waters. To reduce impacts to fish and water quality, the most effective mitigation measure likely would include suspending pipelines (along with road crossings) on full-span bridges that minimize disturbance to surface water, as well as containing the pipelines in a secondary pipe designed for and operated under a plan that includes frequent visual inspection and robust spill response procedures. Burial—with secondary containment—could be appropriate for unavoidable crossings of areas with unstable slopes prone to landslides and avalanches. Note that these measures may have adverse side effects; for example, elevated pipelines may be more disruptive of wildlife movements.

Secondary containment pipe ("encased in a protective layer") for overhead stream crossings on bridges (Ghaffari et al. 2011, p. 337). Secondary containment is a particularly important measure for isolating and managing leaks or spills wherever the pipeline is directly above surface water. Ideally, some form of secondary containment should extend to other locations where leaks or spills could reach and contaminate surface or subsurface waters. There also should be specific procedures and requirements for response and materials handling in the event of leaks or spills into the containment system, to prevent secondary pollution from leaching or spill of contaminated materials. Advance designation and preparation of an array of well-distributed storage pads for contaminated soils at dry, stable sites far removed from surface waters or shallow groundwater would be among the needs to implement this measure effectively. These precautionary structural measures are likely to be costly.

Manual isolation valves on either side of major river crossings (Ghaffari et al. 2011, p. 376). The Preliminary Assessment does not define "major" river crossings, but they would presumably include multi-span crossings such as that of the Newhalen River. The effectiveness of manual closure correlates directly to the effectiveness of leak detection and rapid response. Coupled with full-time, fully redundant electronic and visual leak detection systems and valve locations as suggested above, manual valves could considerably improve the odds of successful stream protection from leaks and spills. Again, the surveillance and logistical measures needed to support a rapid response to accidents can be costly.

Electronic Leak Detection Systems (Ghaffari et al. 2011, p. 376). The Preliminary Assessment discusses implementing an electronic leak detection system for the pipelines, using pressure transmitters located along the length of the lines. It also specifies a SCADA (Supervisory Control and Data Acquisition) system for monitoring and control of the pumping stations, with fiber optic communications between the concentrator and the port site tying the detection systems together. The most effective approach to leak detection includes redundant systems for each separate pipeline. However, the proposed approach appears to tie leak detection for all four systems to a single fiber optic line. Coupled with the close proximity of the four pipelines, a single communications line increases the chance that leak detection could be disrupted by the same event that triggered a leak (e.g., a seismic dislocation, lake seiche wave, or large landslide). As suggested above, providing for rigorous visual inspection would further increase the effectiveness of electronic leak detection and reduce the risk of undetected spills.

Likely Effectiveness of Mitigation Measures

Special circumstances prevail in Bristol Bay and specifically in the area proposed for the Pebble Mine road and pipeline corridor that render the effectiveness of standard or even "state of the art" mitigation measures highly uncertain. These include:

1) Subarctic extreme temperatures and frozen soil conditions could complicate planning for remediation, with outcomes uncertain as a result of variable conditions and spill material characteristics.
2) Subarctic climatic conditions limit the lushness and rapidity of vegetation growth or re-growth following ground disturbance, reducing the effectiveness of vegetated areas as sediment and nutrient filtration buffers.
3) Widespread and extensive areas of near-surface groundwater and seasonally or permanently saturated soils limit potential for absorption or trapping of road runoff, and increase likelihood of its delivery to surface waters.
4) Likelihood of ice flows and drives during thaws that can make water crossing structures problematic locations for jams and plugging.

5) Seismically active geology; even a small increment of ground deformation can easily disturb engineered structures and alter patterns of surface and subsurface drainage in ways that render engineered mitigations inoperative or harmful.
6) Remote locations that are not frequented by human users, hence mitigation failures and accidents may not be detected until substantial harm to waters has occurred.

While many possible mitigation measures can be identified and listed in a plan, they cannot all be ideally applied in every instance. Mitigation measures are commonly mutually limiting or offsetting in field application, as is common knowledge to practicing engineers. As a salient example for the potential Pebble Mine corridor, choosing a road location that minimizes crossings of streams, wetlands, and areas of shallow groundwater in a landscape that is rich in those hydrologic features can result in a tortuous alignment, or one that is substantially lengthened, and might involve substantially more vertical curvature to accommodate upland terrain. A tortuous alignment greatly increases the total ground area disturbed, and increased road curvature in either horizontal and vertical dimensions may increase risk of traffic accidents and consequent spills. Moreover in this case it would increase the length and structural complexity of the road-parallel pipelines. Avoidance of sensitive features therefore elevates other environmental risks. This underscores the fact that there is no “free lunch” when it comes to mitigating the environmental impacts of a new road in a previously roadless landscape.

VII. CONCLUSIONS

- Bristol Bay’s robust and resilient salmon fishery is in part associated with the watershed’s extremely high quality waters and high integrity freshwater ecosystems, minimally impacted by roads and industrial development.

- A second major contributor to the Bristol Bay watershed’s productivity for salmon is its abundant and extensive near-surface groundwater and strong vertical linkage between surface waters and groundwaters, across a wide range of stream sizes and landscape conditions.

- Any environmental analysis and planning of a road project such as the Pebble Mine road must consider the significance of initial road development as an economic and social stepping stone to future roads and developments.

- Roads, in particular can foster the incremental decline of salmon and other native fishes by their own direct environmental impact, but equally important is that roads facilitate a variety of human activities that bring their own suite of impacts including increased access to primitive lands, increasing legal and illegal hunting and fishing, use of off-highway vehicles, increased mineral prospecting, and others.

- For the Pebble road corridor, each stream or wetland crossing has the potential for impacts to not just salmon populations in the stream itself, but also downstream in Iliamna Lake, which is in close proximity.

- The Pebble transportation corridor poses risks of direct and acute impacts to salmonids, including possible loss of populations due to blocking of migration pathways from spills or from stream crossing dysfunctions. Like any such development, it will certainly cause chronic, pervasive "press disturbances" (Yount and Niemi 1990) all along its length and for its entire existence, contributing to deterioration of quality of spawning habitats, reduced habitat diversity, disrupted groundwater hydrology, alteration of roadside vegetation, and related impacts that stem from construction, operation and maintenance.

- Many environmental mitigation measures identified for the Pebble Project suffer from being mutually exclusive or offsetting, from being potentially superseded or limited by engineering, operational, maintenance, or fiscal concerns, or are likely to be ineffective given the hydrogeomorphology, subarctic climate and hydrogeologic conditions, seismicity, and pristine condition and inherent sensitivity of the environment in Bristol Bay watershed.

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Attachment A

Resident fish streams potentially affected, crossed or closely approached by the potential Pebble Mine transportation corridor.

Compiled from the Alaska Freshwater Fish Inventory (AFFI) Database (ADFG 2012, Johnson and Blanche 2011a and 2011b, additional information provided by Joe Buckwalter, ADFG, Anchorage, AK, Unpublished data).

Stream names from the Alaska Freshwater Fish Inventory Database.

"Yes (spp?)" entry in the Anadromous Fish column means the AFFI database classifies the stream as "Anadromous," but anadromous species present are not identified.

Stream No. (west to east)	Stream Name (if known)	NHD Reach Code	Stream Order (Map)	Resident Fish	Anadromous Fish
1		19030206007351	1	Dolly Varden, rainbow trout, slimy sculpin	Coho
2		19030206007354	1	Dolly Varden, slimy sculpin	Coho
3	Upper Talarik Cr.	19030206007015	4	Arctic grayling, Dolly Varden, ninespine stickleback, rainbow trout, slimy sculpin, threespine stickleback	Chinook, chum, coho, sockeye
4		19030206007159	1	[none reported]	Coho
5		19030206007175	1	Dolly Varden, ninespine stickleback, rainbow trout, slimy sculpin, threespine stickleback	
6		19030205007587	2	Ninespine stickleback, slimy sculpin	
7		19030205007593	2	Dolly Varden	

Stream No. (west to east)	Stream Name (if known)	NHD Reach Code	Stream Order (Map)	Resident Fish	Anadromous Fish
8		19030205007598	2	Dolly Varden	
9		19030205007606	2	Slimy sculpin	Yes (spp.?)
10		19030205007602	2	Slimy sculpin	Yes (spp.?)
11		19030205007615	2	Arctic grayling, longnose sucker	
12	Newhalen River	19030205000002	5+	Arctic grayling, jumpback whitefish, longnose sucker, rainbow trout, round whitefish, sculpin	Arctic char, chinook, coho, sockeye
13		19030205013069	3	[no data]	
14		19030205013055	2	[no data]	
15		19030205013057	1	[no data]	
16		19030205013041	2	[no data]	
17		19030205010623	1	[no data]	
18		19030205010628	1	[no data]	
19		19030205010629	1	[no data]	
20	Roadhouse Cr	19030206006712	1	Slimy sculpin	
21	NW Eagle Bay Cr	19030206006678	2	Dolly Varden	Arctic char, sockeye
22		19030206006677	1	Ninespine stickleback, slimy sculpin	
23		19030206006644	2	Dolly Varden	

Stream No. (west to east)	Stream Name (if known)	NHD Reach Code	Stream Order (Map)	Resident Fish	Anadromous Fish
24		19030206006671	2	Dolly Varden, ninespine stickleback	
25		19030206006663	2	Dolly Varden, ninespine stickleback	Arctic char, sockeye
26	NE Eagle Bay Cr	19030206006654	1	Ninespine stickleback, Rainbow trout, slimy sculpin	Sockeye
27	Young's Cr, mainstem	19030206006598	3	Dolly Varden, ninespine stickleback, rainbow trout, slimy sculpin	Arctic char, coho, sockeye
28	Young's Cr, east branch	19030206006553	3	Dolly Varden, rainbow trout, slimy sculpin	Arctic char, coho, sockeye
29	Chekok Cr, west branch	19030206006533	2	[no data]	Arctic char, coho, sockeye
30	Chekok Cr, mainstem	19030206032854	3	Rainbow trout, slimy sculpin	Arctic char, sockeye
31	Canyon Cr	19030206006359	3	Dolly Varden, slimy sculpin	Arctic char, sockeye
32		19030206006336	1	[no data]	
33		19030206006337	1	[no data]	
34		19030206006236	1	[no data]	

Stream No. (west to east)	Stream Name (if known)	NHD Reach Code	Stream Order (Map)	Resident Fish	Anadromous Fish
35		19030206006331	1	[no data]	
36		19030206006329	1	[no data]	
37		19030206006327	1	[no data]	
38		19030206006325	1	[no data]	
39		19030206006322	1	[no data]	
40		19030206006320	1	[no data]	
41		19030206006321	1	[no data]	
42		19030206006318	1	[no data]	
43		19030206006317	1	[no data]	
44		19030206006316	1	[no data]	
45		19030206006315	1	[no data]	
46		19030206006314	1	[no data]	
47		19030206006251	1	[no data]	
48	Knutson Cr	19030206006255	4	Dolly Varden, slimy sculpin	Arctic char, sockeye
49		19030206006280	1	Dolly Varden, slimy sculpin	
50	Pedro Cr	19030206006239	1	[no data]	
51	Russian Cr	19030206006248	1	[no data]	
52		19030206006231	1	[no data]	
53		19030206006230	1	[no data]	
54		19030206006228	1	[no data]	
55		19030206006227	1	Dolly Varden, slimy sculpin	
56		19030206006222	1	[no data]	
57	Pile River	19030206000474	3	Slimy sculpin, threespine stickleback	Arctic char, sockeye

Stream No. (west to east)	Stream Name (if known)	NHD Reach Code	Stream Order (Map)	Resident Fish	Anadromous Fish
58	(Long L. outlet)	19030206010632	1	Threespine stickleback, rainbow trout, slimy sculpin	Yes (spp?)
58a		19030206010632_2	1	[no data]	Yes (spp?)
59	Iliamna R	19030206000032	4	Dolly Varden, slimy sculpin	Chinook, chum, coho, pink, sockeye, Dolly Varden
60		19030206005773	1	[no data]	
61		19030206005761	2	Dolly Varden, slimy sculpin	
62		19030206005759	1	[no data]	
63		19030206005754	2	[no data]	
64	Chinkelyes Cr	19030206005737	2 (at crossing)	Slimy sculpin	
65		19020602004863	1	[no data]	
66		19020602004864	1	[no data]	
67		19020602004865	1	[no data]	
68		19020602004866	1	[no data]	
69	Y-Valley Cr	19020602004967	1	Dolly Varden	Arctic char, chinook, chum, coho, pink, sockeye
70		19020602004882		No fish recorded or observed	