TRUSTEES FOR ALASKA
PROTECT | DEFEND | REPRESENT

August 5, 2022

Steven Feldgus, Deputy Assistant Secretary
Land and Minerals Management
Bureau of Land Management
Division of Solid Minerals
1849 C Street NW, Room 5645
Washington, DC 20240

Submitted via regulations.gov

RE: Request for Information to Inform Interagency Working Group on Mining Regulations, Laws, and Permitting (Docket No. DOI-2022-0003; 223D0102DM, DS6CS00000, DLSN00000.00000, DX.6CS25)

Dear Mr. Feldgus:

Trustees for Alaska submits these comments in response to the Request for Information to Inform Interagency Working Group in Mining Regulations, Laws, and Permitting on behalf of Alaska Soles Broadband of the Great Old Broads for Wilderness, Alaska Wilderness League, Cook Inletkeeper, Native Movement, Natural Resources Defense Council, Northern Alaska Environmental Center, SalmonState, Salmon Beyond Borders, Southeast Alaska Conservation Council, and Winter Wildlands Alliance. Alaska's unique environment poses additional challenges to those facing all hardrock mining operations. The Interagency Working Group (IWG) should develop regulations that account for these challenges to ensure that hardrock mining operations in Alaska are conducted in a way that protects the environment and ensures that Alaskans are not saddled with cleanup costs from abandoned mines. Specifically, the IWG should look closely at ways to account for the impacts of a rapidly changing climate and for the technical infeasibility of reclaiming anadromous waters destroyed by industrial-scale mining.

I. CLIMATE CHANGE POSES SPECIFIC CHALLENGES FOR HARDROCK MINING IN ALASKA.

The IWG should look closely at developing regulations that ensure hardrock mining operations plan for a rapidly changing climate. This is especially important in the Arctic, which is warming four times faster than the rest of the world.[1] Alaska's roads and other infrastructure

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[1] Paul Voosen, *The Artic is warming four times faster than the rest of the world*, Science (Dec. 14, 2021), available at: https://www.science.org/content/article/arctic-warming-four-times-faster-rest-world.

are already seeing the impact of this warming climate, and any new development such as hardrock mining, which depends on vast amounts of infrastructure, must account for these challenges. Specifically, the IWG should require mine plans to account for climate change impacts, require mine operators to post bonds that anticipate the associated financial expenses, and require mine operators to source a significant percentage of their energy needs from renewable resources.

A. Mine planning should account for the effects of a changing climate, especially from melting permafrost.

The most recent Intergovernmental Panel on Climate Change report notes that climate change impacts are approaching the point of "irreversibility" including to "Arctic ecosystems driven by permafrost thaw."[2] Accordingly, hardrock mining regulations should require mine plans to include a climate change management plan that provides a comprehensive description for how the operator intends to address the effects of climate change in mine design, operations, management, reclamation, and closure. It should detail how the operation will adapt to a changing climate and related impacts, such as an altered hydrologic landscape, melting permafrost, or other effects of climate change. Mine plans should include baseline studies regarding permafrost, soil, and hydrology that are frequently updated to inform the mine operator of on-the-ground changes that may affect operations and/or the ability of the mine to continue to meet all applicable laws and regulations, including those that protect water quality and other environmental resources.[3] These studies are critically important: permafrost, for example, is widely variable, which requires large projects like the infrastructure associated with hardrock mining to be carefully planned.[4]

Existing infrastructure in Alaska faces widespread—and incredibly expensive—challenges from a warming climate. The Dalton Highway, which runs from north of Fairbanks to the Arctic Ocean, "faces three major categories of threats linked to a warming climate . . . loss of permafrost . . . floods of increasing frequency and intensity . . . [and] frozen debris lobes—large,

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[2] Intergovernmental Panel on Climate Change, *Climate Change 2022 Impacts, Adaptation, and Vulnerability, Summary for Policymakers* at 11, Working Group II Contribution to the Sixth Assessment Report of the IPCC (Feb. 2022), available at: https://report.ipcc.ch/ar6wg2/pdf/IPCC_AR6_WGII_SummaryForPolicymakers.pdf.

[3] *See*, *e.g.*, Sergeant, C.J., *et al.*, *Risks of mining to salmonid-bearing watersheds* at 11, Science Advances (July 1, 2022) (attached as Exhibit 4) ("To design infrastructure that accounts for the environmental variability brought about by climate change and the dynamic nature of watersheds, rigorous baseline data collection is critical for properly capturing system variability.").

[4] *See*, *e.g.*, Lois Parshley, *For some Alaskans, thawing permafrost brings instability, rising costs and a need to adapt*, Anchorage Daily News (May 3, 2022), available at: https://www.adn.com/alaska-news/2022/05/03/for-some-alaskans-thawing-permafrost-brings-instability-rising-costs-and-a-need-to-adapt/ ("Many variables influence permafrost's stability, like how cold it is, how deep it runs, and the quantity of soil moisture, or its 'ice richness.' In some parts of Alaska, ice extends nearly a half-mile below the surface, while in others, it has formed the landscape itself, sprouting tundra-covered ice hills called pingos.").

slow-moving underground landslides of rock, dirt, and trees."[5] When the permafrost underneath melts, the road collapses, resulting in sinkholes and heaves that can make it undriveable.[6] Unusual flooding events have closed the highway for long stretches at a time, and "DOT has now spent $70 million in state and federal funds to raise the highway over the new flood levels."[7] Frozen debris lobes "are like a landslide in slow motion, huge chunks of rock, soil, ice and trees that slowly slump down slopes" and—so far—have required shifting the road 400 feet to avoid being crushed, costing $2 million.[8] And that move is only temporary: in approximately 13–15 years, the frozen debris lobe will cross the rerouted portion of the road.[9]

Similarly, further south, thawing permafrost due to increased temperatures and rainfall is "speeding up several landslides in [Denali National Park]," including one large enough to shut down a major portion of the only road into the park.[10] The National Park Service is constructing a 400-foot bridge to span the Pretty Rocks Landslide, which had been moving only inches per year prior to 2014 but was moving up to .65 inches per hour in 2021.[11] The federal infrastructure law contains $25 million to pay for the first part of the project as well as address some other needed road work in the area.[12] More funding will be required to build the bridge, and how much depends on the final design.[13]

Melting permafrost causes not only physical changes to the surface, but also significant changes to surface water and groundwater chemistry.[14] These changes may affect the ability of mine operators to comply with water quality standards, which both regulators and operators should understand prior to permitting. The IWG should require mine plans to include both data and strategies for how a project will respond to and adapt with a rapidly changing environment.

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[5] Michelle Theriault Boots, *Curious Alaska: What is climate change doing to the haul road?*, Anchorage Daily News (Apr. 16, 2022), available at: https://www.adn.com/alaska-news/2022/04/16/curious-alaska-what-is-climate-change-doing-to-the-haul-road/.

[6] *Id.*

[7] *Id.*

[8] *Id.*

[9] *Id.*

[10] Morgan Krakow, *The Denali Park Road landslide made 'shocking' progress this winter, reinforcing the need for a fix*, Anchorage Daily News (Apr. 20, 2022), available at: https://www.adn.com/outdoors-adventure/2022/04/20/the-denali-park-road-landslide-made-shocking-progress-this-winter-reinforcing-the-need-for-a-fix/.

[11] *Id.*

[12] Dan Bross, *Bridge plan moves forward as Denali Park Road landslide speeds up*, Alaska Public Medis (Apr. 25, 2022), available at: https://www.alaskapublic.org/2022/04/25/bridge-plan-moves-forward-as-denali-park-road-landslide-speeds-up/.

[13] *Id.*

[14] United States Geological Survey, *Permafrost Loss Changes Yukon River Chemistry with Global Implications* (Nov. 30, 2016), available at: https://www.usgs.gov/news/featured-story/permafrost-loss-dramatically-changes-yukon-river-chemistry-and-hydrology.

B. Bonding should be set at a level that accounts for the significant financial resources required to respond to a changing climate.

The IWG should also consider requiring additional bonding to account for impacts and uncertainty from a changing climate. The fiscal impacts to Alaska's existing infrastructure have already been significant. In addition to the examples detailed above, a recent study predicted that the State of Alaska will need to spend billions more on maintaining and repairing public infrastructure because of a changing climate.[15]

C. Hardrock mining operations should source a significant portion of their energy needs from renewable resources.

Further, hardrock mining regulations should require any new or expanded mining operations to obtain a certain percentage of their energy needs from renewable sources. Because mining is one of the most energy-intensive industries, a shift to renewables could have significant impacts—and countries that impose more pressure to transition towards renewables will be ahead of that curve.[16] Notably, the industry itself has found in Alaska that renewable sources are less expensive and more reliable.[17]

II. RECLAIMING AND RESTORING DESTROYED ANADROMOUS WATERS AND THE HYDROLOGY THAT SUPPORTS THEM IS TECHNICALLY SUSPECT AND ECONOMICALLY INFEASIBLE.

The IWG should develop regulations that prohibit hardrock mining in anadromous waters, including the headwaters and wetlands that support them. As the Environmental Protection Agency (EPA) recently observed, "[r]eplacing destroyed salmon habitats with new constructed channels is . . . not a simple task" and "the ability to replicate ecosystem function is clearly limited."[18] Some scientists have been more blunt. For example, Dr. Margaret Palmer has noted that:

> Wetlands and headwaters cannot be restored to ecological function if the very

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[15] Melvin, April M., *et al. Climate change damages to Alaska public infrastructure and the economics of proactive adaptation*, Proceedings of the National Academy of Sciences (Dec. 27, 2016), available at: https://www.pnas.org/doi/abs/10.1073/pnas.1611056113.

[16] Maisch, Marija, *Mining Sector to rely increasingly on renewables, report finds* (Sept. 11, 2018), available at: https://www.pv-magazine.com/2018/09/11/mining-sector-to-rely-increasingly-on-renewables-report-finds/.

[17] *Id.*, *see also* Ellis, Tim, *GVEA changes course, OKs Healy 2 shutdown, Healy 1 upgrade* (June 28, 2022), available at: https://fm.kuac.org/2022-06-28/gvea-changes-course-oks-healy-2-shutdown-healy-1-upgrade.

[18] U.S. Environmental Protection Agency, *Proposed Determination of the U.S. Environmental Protection Agency Region 10 Pursuant to Section 404(c) of the Clean Water Act; Pebble Deposit Area, Southwest Alaska* at C-16 (2022), available at: https://www.epa.gov/system/files/documents/2022-05/Pebble-Deposit-Area-404c-Proposed-Determination-May2022.pdf.

> material that they rely on — deep sediment structure and long-entrained flow paths — are mined through, ground up, and replaced in the mining pit as a relatively homogenous pile of rubble and dirt. . . . While stream reconstruction has been done successfully by re-grading and re-vegetating banks, or adding or removing debris to create habitat, no one has simply created a new stream where none exists. A new ditch can be dug where the old stream used to be, and can have the same curves and shape. But it will not have the exchange of surface and groundwater at the streambed, upwelling areas for fish to lay their eggs in, biodiversity of insects that headwater streams provide as food for fish, the purity of water and nutrients wetlands provided.[19]

In other words, while it may be possible to create a post-mining landscape that appears similar to the pre-mining stream and riparian area, the ecological function and aquatic productivity of the area will be forever lost. This impacts the entire ecosystem, including salmon and the system dependent on them. As Lance Trasky, a fisheries biologist and former Regional Supervisor for the Habitat and Restoration Division in the Alaska Department of Fish and Game, observed when analyzing a large proposed mine project in Alaska:

> If these streams and the genetically unique salmon demes that use them are destroyed or blocked by strip-mining . . . it is unlikely that these local salmon stocks could be restored to their former level of productivity even if a new stream channel could be successfully constructed. . . .
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> It is probably not be possible to reconstruct a new stream with the same level of productivity . . . [The mining company] has not provided any examples of where a strip-mined salmon spawning and rearing drainage the size of [the stream at issue, 17.4 km] has been restored to premining productivity. An extensive search of the scientific literature and discussions with stream restoration experts in Alaska and elsewhere have not produced any examples. . . . .
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> Even if [the stream] could be successfully restored to full physical and ecological function, it may not be possible to restore it to its former level of biological productivity because of the loss of marine derived nutrients (MDN) from salmon carcasses and the permanent removal of all the wetlands in the mine area. Wetlands and MDN are the primary sources of stream nutrients and productivity in salmon streams.[20]

In comments to the State of Alaska regarding a petition to designate headwaters as unsuitable for

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[19] Palmer, Margaret A., *Report on Chuitna Coal Project of PacRim Coal, Executive Summary* (2009) (attached as Exhibit 1); *see also* Palmer, Margaret A., *Report on Chuitna Coal Project of PacRim Coal*, 3–5, 8–12 (2009), available at: https://inletkeeper.org/wp-content/uploads/2017/11/Palmer_Chuitna_Report_2009.pdf.

[20] Trasky, Lance, *Report on Chuitna Coal Project Aquatic Studies and Fish and Wildlife Protection Plan* 55–56 (2009), available at: https://inletkeeper.org/wp-content/uploads/2017/10/Trasky_Chuitna_Report_2009.pdf.

mining, Trasky noted that for stream restoration to be successful, the seasonal phreatic and hyporheic flows must be returned to pre-mining flow patterns.[21] After conducting a literature review, he concluded that "[m]ost experts do not believe that it is possible to reconstruct a functioning shallow aquifer for an anadromous streams system in a deep mined system with any degree of confidence that it would work."[22]

Dr. Mark Wipfli noted something similar in a scientific review of a baseline monitoring and restoration plan for a proposed coal mine in Alaska: "recreating the structural complexity and interconnectivity of the below-ground sediment layers in the back-filled mine pit will be impossible, permanently and negatively affecting the natural flowpaths and hyporheic function (including natural upwelling and downwelling) upon which existing biological productivity and biocomplexity depend."[23] These essential flowpaths are not only impossible to recreate, but "riverine systems also cannot 'repair' such damage."[24]

Setting aside the impossibility of recreating a functional and productive salmon stream, the interruption of flow alone can have catastrophic impacts on the health of wild salmon stocks. Even small streams and wetlands are essential for protecting the resiliency of salmon runs: individual streams and habitat mosaics can be thought of as a portfolio where the number and diversity of runs provide resiliency and buffer against loss in any one area.[25]

The science demonstrates that is not possible to truly reconstruct salmon-bearing streams, and that the loss of those streams weakens the resiliency of the entire watershed. Neither mitigation nor reclamation can ameliorate these impacts, and mining should therefore not be permitted in anadromous waters.

III. CONCLUSION

Large intact ecosystems, including a wealth of anadromous waters, still exist in Alaska—and those resources are of national and international importance. However, Alaska also faces unique threats, including the faster pace at which climate change is affecting the north. We ask the IWG to consider that context, and include regulations targeted at addressing Alaska's unique concerns. Specifically, we recommend that the IWG address the outsized impacts of climate change in Alaska by requiring (1) that mine plans address the impacts of climate change, (2)

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[21] Letter from Lance Trasky to Commissioner Sullivan, Alaska Dept. of Natural Resources at 3 (Jan. 17, 2011) (attached as Exhibit 2).

[22] *Id.*

[23] Wipfli, Mark S., *Chuitna Coal Mine baseline monitoring and restoration plan review* at 1 (2009), available at: https://inletkeeper.org/wp-content/uploads/2017/11/Wipfli_Chuitna_Baseline_2009.pdf.

[24] *Id*. at 7.

[25] Schindler, D.E., R. Hilborn, B. Chasco, C.P. Boatright, T.P. Quinn, L.A. Rogers, M.S. Webster. 2010. *Population diversity and the portfolio effect in an exploited species*. Nature 465: 609-612, available at: https://asset-pdf.scinapse.io/prod/2105620701/2105620701.pdf; *see also* Brennan, S.R., D.E. Schindler, T. J. Cline, T.E. Walsworth, G. Buck, and D.P. Fernandez. 2019. *Shifting habitat mosaics and fish production across river basins.* Science 364: 783-786 (attached as Exhibit 3).

increased bonding to account for uncertainty, and (3) requiring mining companies to utilize renewable energy sources. We suggest that the IWG address the importance of anadromous waters, and the impossibility of truly reclaiming them, by prohibiting mining in anadromous waters.

Thank you for considering these comments. If you have any questions, please do not hesitate to contact us.

Sincerely,

/s K.Strong_
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Report on Chuitna Coal Project of PacRim Coal

Margaret A. Palmer
Professor and Director
Chesapeake Biological Laboratory
University of Maryland

Impacts from mining coal from the wetlands and forests above the Chuitna River will cause destruction of over 4,000 acres of wetlands and is highly likely to permanently change the ecosystem of the area and the productivity of the Chuitna River.

The ecosystem is a woven fabric of wetlands, tundra, forests, and tiny headwater streams that gather to build larger streams, to eventually pour into the Chuitna River.   Forty-one percent of the watershed will be directly impacted from mining and backfilling of the mine. What occurs in these headwaters, wetlands, tundra, and forests is vital to the water quality and the fish downstream. It is in these areas that carbon is stored and nutrients are cycled from detritus to microbes, from microbes to insects. The wetlands in particular are vital to storing water that seeps down into flow paths beneath the earth, to surface at the bottom of streams, keeping them flowing when there is no rain or snow.   As water trickles through wetlands, microbes in the muck and peat remove heavy metals and purify the water. Wetlands are the source of both pure water and primary nutrients such as carbon, nitrogen, and phosphorous which make up the very base of the food chain.

Wetlands water seeps up to become headwater streams, disproportionately rich in biodiversity for their small size, and the source of much of the food that arrives downstream. Headwaters provide breeding and nursery grounds for insects that spend the rest of their lives in larger streams and rivers, and are an important food source for fish. Headwaters provide spawning grounds and help to regulate stream temperature. The rich biodiversity found here buffers the streams so they recover more rapidly from rapid changes such as climate swings, flooding, and human damage.

Tundra, wetlands, and headwater streams will all be destroyed during mining. And there is little chance they will be restored. Tundra is very sensitive and only revives when specific conditions are met, including maintaining corridors to more tundra throughout the mining process. Wetlands and headwaters cannot be restored to ecological function if the very material that they rely on – deep sediment structure and long-entrained flow paths – are mined through, ground up, and replaced in the mining pit as a relatively homogenous pile of rubble and dirt.

One stream, "Stream 2003" also called Middle Creek, will be completely destroyed. It will not be "impacted", but rather mining will go down hundreds of feet beneath it, completely removing the stream bed and any remnant of the stream for 11 miles. While stream reconstruction has been done successfully by re-grading and re-vegetating banks, or adding or removing debris to create habitat, no one has simply created a new stream where none exists. A new ditch can be dug where the old stream used to be, and can have the same curves and shape. But it will not

Exhibit 1

have the exchange of surface and groundwater at the streambed, upwelling areas for fish to lay their eggs in, biodiversity of insects that headwater streams provide as food for fish, the purity of water and nutrients wetlands provided.

Nor is PacRim attempting to assess the functions of the stream and its associated ecosystems as they are now. Without such an assessment – rates of nutrient cycling, flood control, sediment control, water purification, and more – PacRim has no end goal to attempt to reach.

In summary, there are three main areas of concern with the mitigation plan:

First, the applicants have not directly measured ecosystem functions and thus have not applied current science to the mitigation issues. Without these functional assessments, they do not know exactly what natural resource values are being lost and thus what they need to mitigate for. Second, the approach proposed for replacing the lost streams (especially Stream 2003) is outside the realm of stream restoration or rehabilitation practices. Their approach basically amounts to channel "creation" in an area in which the earth has been disturbed to depths of 300- 500 feet, the natural flow paths destroyed, and landscape topography reshaped. Indeed, there is ample evidence in the peer-reviewed literature that the approach they propose (Natural Channel Design) typically fail ecologically. Third, impacts to the watershed and the headwater streams from the mining activities will fundamentally alter the chemical, hydrologic and sediment regimes which are master variables controlling the water quality and productivity downstream.

In sum, based on the most current and rigorous science, the impacts of this project are very significant and there is no evidence that the restoration and mitigation plans that are proposed will compensate for the natural resource losses.

Lance Trasky
Lance Trasky and Associates
3941 Truro Drive
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Mr. Daniel S. Sullivan, Commissioner
Alaska Department of Natural Resources
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Subject: Petition to Designate the Streambeds of Anadromous Water Bodies and Riparian Areas within the Chuitna River Watershed, Alaska as Unsuitable for Surface Coal Mining Pursuant to AS. 27.21.260

Dear Commissioner Sullivan:

I am a fisheries habitat consultant with 37 years of experience as a fisheries and habitat biologist and as a Habitat and Restoration Division Regional Supervisor with the Alaska Department of Fish and Game. I am writing in support of the petition to designate the streambeds of anadromous water bodies and riparian areas within the Chuitna River watershed, Alaska, as unsuitable for surface coal mining pursuant to As. 27.21.260. I support the petition for the following reasons:

1. **The Chuitna River is an important salmon producing system**: Unlike current coal producing areas of Alaska the Chuitna River is located in a productive coastal ecosystem which supports a diversity of fish and wildlife species. Chuitna River supports all five species of pacific salmon as well as Dolly Varden, rainbow trout and whitefish. Chuitna River salmon are harvested by an in river sport fishery, the Northern district commercial fishery, and the Tyonek subsistence fishery. On the west side of Cook Inlet the Chuitna River sport fishery for Chinook salmon is the second only in importance to the Deshka River. Because of its importance the Chuitna River Chinook stock was listed as a stock of management concern by the Alaska Board of Fisheries in 2010 (Helsinger 2010).

2. **Strip mining for coal will destroy the shallow aquifers and interrupt the flow of ground water to anadromous streams in and adjacent to the mined area:** Over the past several years I have conducted an extensive search of the scientific literature but have not found any examples of strip mine reclamation projects where phreatic ground water flow in streams has been restored to premine conditions by replacing mining tailings. However there is a large body of information documenting long term disruption of both surface and ground water flow as the result of recently permitted strip mining and reclamation (Bonta, 2007, Wilson 1978 and Schwartz and Crowe 1985). Bonta et al 2007 studied the effect of surface mining and reclamation on physical watershed conditions and ground water hydrology in three watersheds. This study found that mining disturbances in watersheds affected ground water levels in adjacent undisturbed watersheds prior to mining. Monitoring and testing of groundwater in reclaimed strip coal mines indicate that groundwater is stored in and flows through large voids or conduits in spoil. However, these voids are not always

connected across a mine site (Hawkins 1998, Hawkins and Aljoe 1992). New subsurface flow paths with different characteristics formed during mining and reclamation. Ground water recovery in the mined upper saturated zone was slow and irregular both temporally and spatially after reclamation. Wilson 1978 found that the impact of a strip mine can extend far beyond its radius of influence at the water table, and mines near regional discharge areas have a more significant effect on the regional system.

The uninterrupted flow of shallow ground water to salmonid spawning and streams is essential for successful spawning and survival of eggs and fry. The flow of ground water to streams particularly during the winter is one of the most critical factors in salmonid egg incubation and juvenile overwintering survival (Baxter and McPhail 1999 and Douglas 2006). Mining coal to a depth of 300 feet would remove all the geological structure's which currently provides shallow ground water to stream 2003 and possibly streams 2002 and 2004.

Two types of ground water influence streams: Hyporheic groundwater, and phreatic ground water (Poole and Berman 2001). Hyporheic groundwater is from the alluvial material which underlies the streambed. It travels downstream along localized pathways before emerging further downstream. Phreatic ground water comes from the catchment's aquifer and feeds a stream by entering the bottom of the alluvial material and mixing with the hyporheic ground water (USGS 2006). Groundwater from the phreatic aquifer influences stream temperature when it enters the stream. The two way exchange between the alluvial aquifer and the stream channel is perhaps the most important stream temperature buffer (Douglas, 2006).

Figures 1-4 illustrate how ground water is supplied to salmon streams in an undisturbed watershed.

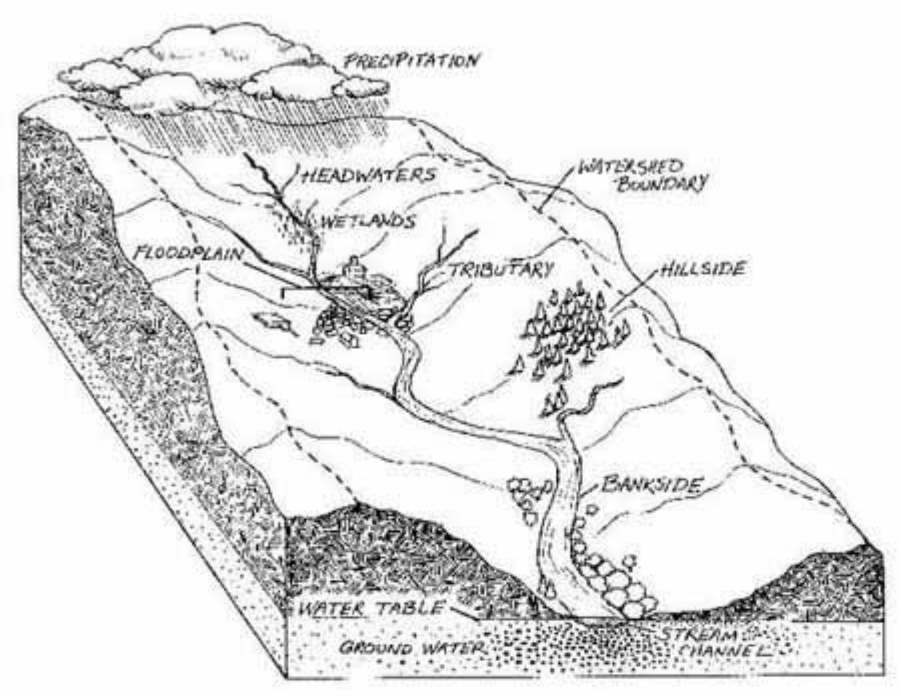

Figure 1: Cross Section of a Watershed (Source: USEPA)

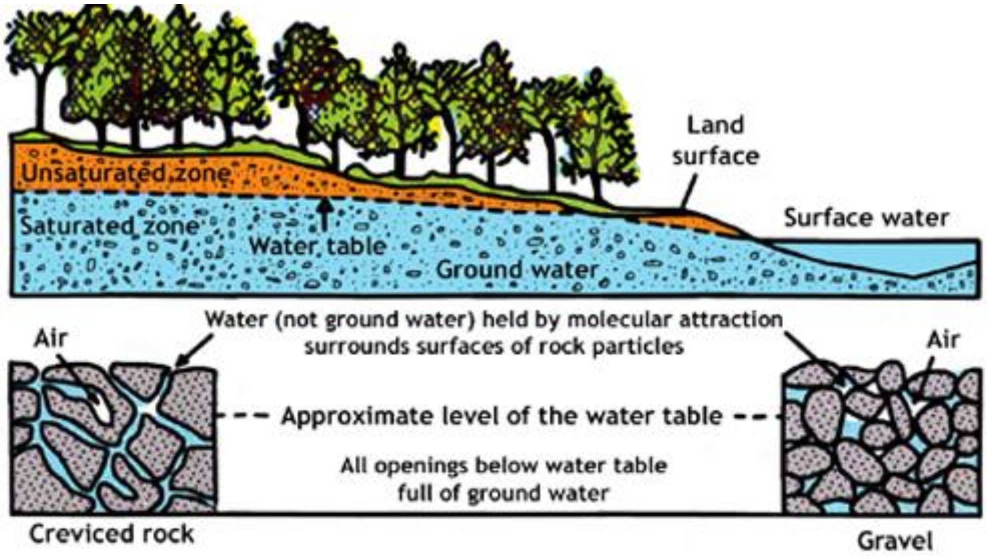

Figure 2: Cross Section of an Aquifer (Source: USGS)

Ground water is critical because it maintains stream base flow and moderates water level fluctuations, particularly in the winter when there is no precipitation. It provides stable temperatures and thermal refugia for fish. It provides water for riparian vegetation which controls bank strength and the rate of erosion (Douglas 2006). It also creates the hyporheic zone (Figure 3).

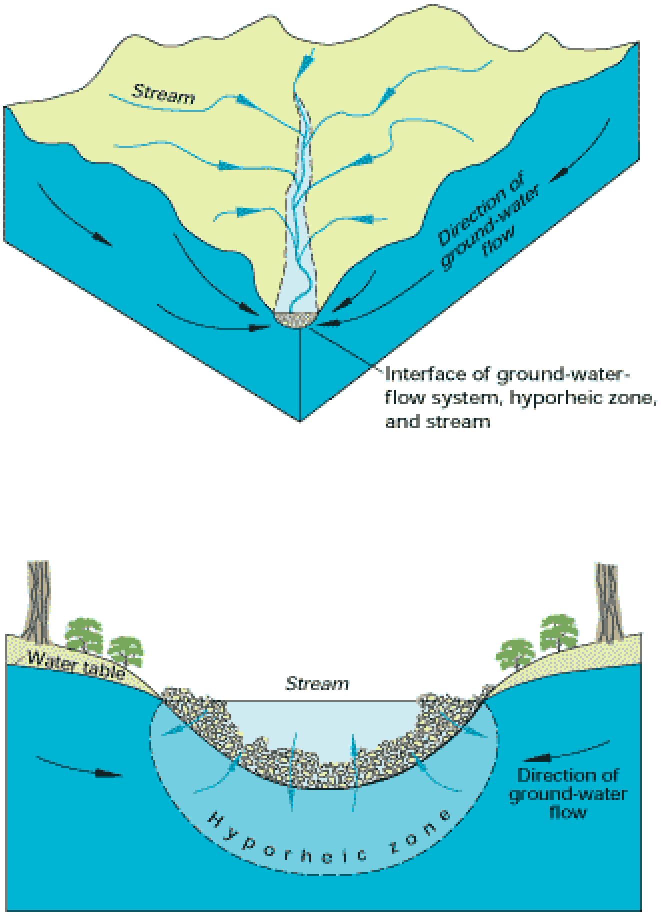

Figure 3: Hyporheic Zone (Source: USGS circular 1186)

The hyporheic zone is the region beneath and lateral to a stream bed where there is mixing of shallow ground and surface water. It is an active ecotone between the surface stream and ground water. Exchanges of water, nutrients, and organic matter occur in response to variations in discharge and bed topography and porosity. Upwelling subsurface water supplies stream organisms with nutrients and cool water in the summer and warm water in the winter. Down welling stream water provides dissolved oxygen and organic matter to microbes, and invertebrates, in the stream bottom (Boulton, et al 1998). Upwelling ground water is vital to protect salmonids and other cold water fishes from water temperatures which exceed their thermal tolerance in the summer (Hayes 2009). Ground water provides over-wintering habitat free of subsurface ice protect fish eggs, larvae, and juvenile fishes from freezing in the winter (Power et al 1999).

The hyporheic zone is an area of intense biochemical activity. Biogeochemical processes within the upper few centimeters of sediments have a profound effect on the chemistry of ground water and surface water which mix in that area. Biogeochemical process is the partitioning and cycling of chemical elements and compounds between the living and non living parts of a stream. The highly interactive nature of physical, chemical and biological processes in the hyporheic zone play a central role in the functioning of stream ecosystems (Malcolm et al 2003).

To restore fish habitat in these streams after mining it, it would be necessary to restore the same quality and quantity of ground water. To successfully reconstruct a new stream that is as productive as mined streams, it would be necessary to reconstruct a new shallow aquifer to provide the same amount of phreatic and hyporheic flow, the same seasonal flow patterns and same quality (temperature, pH, dissolved elements, dissolved solids etc.) of ground water present prior to mining. I conducted an extensive search of the scientific literature to find examples of restoration of salmon streams after the type of strip mining proposed for the Chuitna River drainage. I also consulted with experts who have been involved in salmon habitat and strip mine restoration in Alaska and the continental United States. The search found many examples of how strip mining has dramatically altered local and regional ground water flow during and after mining, but no references to any scientific studies of mines where the aquifer's supplying phreatic ground water to the hyporheic zone of a salmon spawning and rearing stream has been successfully restored to premining productivity after strip mining. Most experts do not believe that it is possible to reconstruct a functioning shallow aquifer for an anadromous streams system in a deep mined system with any degree of confidence that it would work. Attempts to restore ground water flow to mined stream would be further hampered by the fact that the very complex geology of the Chuitna River drainage and how these shallow aquifers function is poorly understood except that ground water from these aquifers up well's at certain points in these streams and currently supports salmon spawning, rearing and overwintering.

3. **Strip mining will result in the long loss of marine derived nutrients and organic carbon essential to stream productivity:** Even if mined anadromous stream channel's in the Chuitna River drainage could be successfully reconstructed to full physical function, it is unlikely these streams could be restored to their former level of biological productivity because of the loss of marine derived nutrients (MDN) from salmon carcasses in the mined areas and the loss of organic carbon from the removal of all of the wetlands in the mine area. Significant loss of stream productivity from premining conditions has been documented in studies of streams in reclaimed stripmines. Matter and Ney (1981) found that "benthic invertebrate and fish populations were significantly lower in abundance in the reclaimed mine streams than in the reference stream and showed less taxonomic richness and stability: they were similar in these respects to the biota of unreclaimed mine streams."

Wetlands and MDN from salmon carcasses are the primary sources of stream nutrients and productivity in salmon streams. There is a large body of scientific literature showing that Pacific salmon are the major vehicle transporting marine nutrients across ecosystem boundaries from marine to freshwater and terrestrial ecosystems. Nutrients from salmon eggs and carcasses play a major role in the productivity of both freshwater and riparian ecosystems and in perpetuating future salmon runs. Most fisheries scientists and progressive fisheries managers have concluded that stream ecosystem health benefits from having the largest number of spawners possible which in turn produces a large number of carcasses (WDFW 1997). The eggs and carcasses from these spawning salmon provide an essential source of food for rearing salmon and other fishes which concentrate in these areas. Nutrients from decaying carcasses also provide food and nutrients for insects such as chironomids which are the major food source for salmonids during the rest of the growing season. Bilby, et al 1996 and 1998 found that benthic algae, invertebrates and fish in salmon streams were significantly enriched with both marine carbon and nitrogen. The average contribution of marine nitrogen ranged from 11% for invertebrate predators to 31% for juvenile Coho. The highest percentage of marine nitrogen was 46% for adult cutthroat trout and 61% for age 1 plus steelhead. The same researchers also found that the growth rate of juvenile coho doubled after adults spawned in the stream, where as in a nearby stream without spawning salmon juvenile steelhead showed no increase in growth rate during the same time period. This phenomenon is so important that fisheries scientists recommend that escapement goals should be designed to produce "nutrient capital" within watershed that will help support the next generation of fish.

During mining, salmon will be excluded from the middle and upper portions of Stream 2003 where most spawning and rearing occurs for a long period of time. The "nutrient capital" built up over hundreds of years would be lost when the upper portion of the stream 2003 drainage is removed through mining. Diminishing or eliminating salmon production (e.g. eggs and carcasses) from a stream due to natural or anthropomorphic causes, such as strip mining may be self perpetuating. Without necessary nutrients from salmon eggs and carcasses, remaining downstream stream 2003 stocks are likely to decline further.

A reconstructed stream drainage without nutrients from salmon carcasses is not likely to be productive (Bilby et al 1996 and Larkin and Slaney 1997).

The concurrent loss of most of the wetlands, which are the other major source of stream nutrients in the stream 2003 drainage headwaters , will further reduce stream productivity (Hood et al 2008, Meyer et al 2003, and Nagorski et al 2007). As previously stated the productivity of a salmon stream is based on marine derived nutrients (MDN) from salmon carcasses and the flow of organic matter, nutrients, and the consistent flow of high quality ground and surface water from its drainage basin (Piccolo et al 2009, Mathisen et al 1998, and Schlosser 1991). Wetlands have been identified as a major terrestrial contributor of organic matter and nutrients to salmon streams (Hood et al 2008, Pess et al 2002, and Nagorski et al 2007). A recent study in S.E. Alaska concluded that "Organic nutrients derived from wetlands comprise the bulk of the stream water organic nutrient budget on an annual basis" (Hood et al 2008). The loss of wetlands has been correlated with declines in salmon production (Pess, et al 2002). All of the wetlands, which currently comprise 43% of the proposed mine area and provide ground water discharge, ground water recharge, and carbon export/food chain support to streams 2003 and to a degree 2002, and 2004, will be destroyed by mining. Even if stream 2003 could be reconstructed, the loss of both of the major sources of stream productivity would make it very difficult if not impossible to restore it to its former level of productivity

There is nothing in the scientific literature to indicate that it is technically or economically feasible to reconstruct thousands of acres of replacement wetlands on top of porous mine tailings in the Chuitna River drainage. Unless both the amount and function of current wetlands can be replaced, stream productivity and fisheries production can not be restored to premining levels of productivity. The National Academy of Science recommends not destroying filling fens and bogs, both found in the Chuitna claims area, because they are "difficult or impossible to restore" (National Academy of Science 2001). For certain types of wetlands such as peat bogs which grow at a rate of less than 1mm annually, replacement is not feasible within geological time. Wetlands whether natural or constructed exist because of the presence of surface or near surface water. The extensive wetlands in the Chuitna River drainage exist in part because weathered volcanic ash a few feet below the surface forms clay like impermeable layer which holds water. Deeper layers of compacted ash act as an aquaitard confining the water table below it and forcing seeps and springs out of the hillsides and into adjacent drainages. Once the existing wetlands and the impermeable soils that currently maintain these wetlands are removed by mining there is nothing to provide a base for construction of new wetlands. There are no studies in the scientific literature which indicates that wetlands have been restored on coal mine spoils on the scale which would be required in the Chuitna River drainage. The risk of failure for many wetlands restoration projects is high, particularly in Alaska where no projects of this type have been documented (Kusler, 2004 and National Academy of Sciences, 2001).

4. **Mining will adversely affect water quality for fish and aquatic life:** Information provided by Pac rim contractors indicates that water quality will change as a result of mining in the Chuitna River drainage. Potential water quality changes include lower Ph, higher turbidity, and releases of heavy metals such as copper. Fish and their food organisms in the Chuitna River drainage have adapted to the unique water quality conditions present in the Chuitna River and its tributaries over thousands of years. Water quality is defined by dissolved elements, marine derived and terrestrial nutrients, and physical factors such as temperature, pH, conductivity, and turbidity. Anadromous species such as salmon, trout, and whitefish also depend on subtle chemical clues present in surface waters in to locate both their natal streams, and spawning locations within tributaries.

Surface water chemistry will be altered by pumping water out of the pit to allow mining and rerouting surface water away from the pit area and into streams. Data collected by Pac Rim contractors indicates that one or more of the aquifers in the mine areas contains elevated levels of copper, zinc, iron, aluminum, manganese and lead. Zinc and manganese levels in ground water within the proposed Chuitna mine area are approximately 4 times and aluminum 20 times greater than average surface water levels in stream within the proposed Chuitna mine area . All of these metals are toxic to fish and aquatic life at levels in the part per billion to part per million ranges. Aluminum interferes with phosphorus metabolism in plants which form the basis of the aquatic food chain in streams. It also precipitates on fish gill membranes inhibiting exchange of oxygen and carbon dioxide which results in asphyxiation. Copper is toxic to rainbow trout at 1.4 parts per billion, and elevated levels (5-20 ppb.) destroys the olfactory organs which anadromous fish use to locate prey and spawning streams. Zinc is toxic in the part per billion range and accumulates in and damages gills, liver, and kidneys. Copper, zinc and lead bioconcentrate (build up to high levels over time) in aquatic organisms. Copper and zinc also act synergistically in the aquatic environment so that the toxicity of the combination is greater than the individual elements.

Toxicity of these heavy metals is greater at reduced pH levels. Because both bog and upland soils in the mine area are acidic with pH values ranging from 3.2 to 6.1 there is significant potential for acid run off from exposed soils to lower the pH of surface waters during mining. Reductions in pH result in reduced stream productivity and the health of juvenile anadromous fish. It is important to note that Pac Rim has applied for “site specific criteria” for copper, zinc, aluminum, lead, manganese, and iron which would allow them to discharge these metals in greater concentrations than natural levels in Chuitna River tributaries and state water quality regulations allow.

In addition to the general debilitating effect of degrading water quality as a result of mining and exemptions for state water quality there is an additional problem that must be considered. Mining operations in Alaska have frequently violated their water quality permits. For example the Red Dog Mine has been cited for over a thousand water quality violations to date.

5. **Loss of genetically unique salmonid stocks and their habitat:** The genetic makeup of salmonid stocks in streams 2002-2004 may be a serious impediment to successful restoration of the salmonid ecosystem in mined streams. There is mounting evidence from Alaska and elsewhere that Coho, Chinook, sockeye and likely other salmonids with a high level of fidelity to individual spawning and rearing streams, are comprised of demes or small locally interbreeding groups (demes) that are genetically adapted to the unique ground and surface water flow, temperature, and water quality conditions in their natal streams, or at specific locations within their natal streams.. If these streams or portions of them are destroyed by strip mining as proposed, it is very unlikely that the unique stream flow, temperature, and water quality conditions which currently exist in these streams and these salmonids are adapted to, can be recreated.

Similarly if genetically unique salmon stocks which are adapted to spawning and rearing in these headwaters streams are blocked from using former habitat for many years to accommodate mining, these demes may die out rather than spawn in another location. This phenomenon has been observed in sockeye salmon which, when blocked from accessing traditional upstream spawning areas by beaver dams or man made structures, die without spawning. Because of these adaptations to the unique physical, water quality, and stream flow conditions currently found in Chuitna River tributaries it may not be possible to restore these tributaries to their former level of productivity even if a stable stream channel could be reconstructed

6. **Past stream stabilization and stream bank restoration projects are not analogous to watershed reconstruction in the Chuitna River drainage**: I caution ADNR decision makers not to accept claims that reconstruction of strip mined salmon streams, their watersheds and associated aquifers are feasible based on anecdotal reports of reclamation of placer mined streams, stream bank restoration, or return of streams to old channels such as Moose Creek in the Matanuska River drainage. The damage to salmon streams from alluvial placer mining and is very different from strip mining, which may encompass entire drainages and alter both the surface topography, subsurface geology and the aquifers down to several hundred feet. The objective of most of these stream projects has been to stabilize a short section of an existing stream channel and not reconstruct an entire drainage, stream channel and aquifer.

Although there may have been some benefits to fish, I have not been able to find any reports or scientific studies documenting that these stream relocation or stabilization projects have benefitted fish. Most of these projects such as the USFS projects on Resurrection Creek have attempted to restore both sinuosity and rearing habitat to a stream impacted by placer mining in the early 1900's by moving and grading spoil piles and providing instream cover. Placer miners channelized the stream and left spoil piles in the flood plain but did not destroy the shallow aquifer that provides ground water flow to the stream. It appears that the USFS projects have increased rearing habitat for Chinook and Coho salmon by connecting formerly isolated channels in mine spoils, but no data has been made available to document this. Similarly, it is likely that the rerouting of Moose Creek back into its original channel has provided access to additional upstream spawning and rearing habitat for salmon in previously inaccessible upstream waters but no scientific data is provided to support this. However, this project like the others does not provide any indication of the likelihood of success in completely reconstructing a salmon stream, recreating the existing water chemistry, recontouring and revegetating its drainage, reconstructing all of its wetlands and rebuilding its aquifers from basement sediments on up in the Chuitna River drainage.

7. **A great deal of new information that raises questions about the feasibility of restoring anadromous within the Chuitna River drainage to their premining level of productivity has become available since the 1990 Diamond Chuitna Coal Project Final Environmental Impact Statement.** When the Diamond Chuitna Coal Project Final Environmental Impact Statement was completed in 1990 very little was known about the physical, chemical and biological components of salmon habitat, and the function of in stream flow and ground water, marine derived nutrients, and wetlands in the productivity of salmon streams. Studies of salmon salmon genetics, the effects of mining on salmon streams, and the restoration of salmon streams were in their infancy. The impetus for much of this research was the continued decline of salmon stocks due to human activities. Since 1990 a great deal of scientific research on these subjects has been completed and information has become available. This information support the conclusion that strip mining for coal will severely impact current anadromous waters in the Chuitna River drainage and that it is very unlikely that these waters could be restored to their premining level of productivity

Thank you for your consideration of my request that you grant the Petition to Designate the Streambeds of Anadromous Water Bodies and Riparian Areas within the Chuitna River Watershed, Alaska. as Unsuitable for Surface Coal Mining Pursuant to AS. 27.21.260. If you have any questions you can contact me at the address shown above.

Sincerely,

Lance Trasky

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For citations not listed here please refer to my 2009 report, Report on Chuitna Coal Project Aquatic Studies and Fish and Wildlife Protection Plan which has been previously provided to ADNR

CONSERVATION

Shifting habitat mosaics and fish production across river basins

Sean R. Brennan[1]*, **Daniel E. Schindler**[1], **Timothy J. Cline**[1], **Timothy E. Walsworth**[1], **Greg Buck**[2], **Diego P. Fernandez**[3]

Watersheds are complex mosaics of habitats whose conditions vary across space and time as landscape features filter overriding climate forcing, yet the extent to which the reliability of ecosystem services depends on these dynamics remains unknown. We quantified how shifting habitat mosaics are expressed across a range of spatial scales within a large, free-flowing river, and how they stabilize the production of Pacific salmon that support valuable fisheries. The strontium isotope records of ear stones (otoliths) show that the relative productivity of locations across the river network, as both natal- and juvenile-rearing habitat, varies widely among years and that this variability is expressed across a broad range of spatial scales, ultimately stabilizing the interannual production of fish at the scale of the entire basin.

The generation and maintenance of biological complexity over ecological and evolutionary time scales ultimately depend on processes that generate habitat heterogeneity across landscapes (*1*). Such heterogeneity is produced from interactions between local geomorphic features (e.g., topography) and environmental forcing (e.g., regional climate). Habitat can be described as a mosaic of environmental conditions arranged across landscapes but, importantly, the spatial configuration of habitat patches shifts through time as prevailing environmental conditions interact with geomorphology, successional processes, and the biological responses of locally adapted populations (*2*–*4*). This concept—the shifting habitat mosaic—has been empirically tested at small scales (*5*, *6*), but how these dynamics play out across a range of spatial scales has never been quantified, specifically in terms of how they influence the reliability of ecosystem services.

The argument to conserve biodiversity often focuses on ecosystem stability and how biologically diverse communities tend to spread the risk of collapse or poor performance (*7*–*9*). Less common, however, is to consider the continuum of spatial and temporal scales dictating the processes that generate ecosystem heterogeneity, its hierarchical structure, and thus, resilience. The concept of shifting habitat mosaics integrates how different dimensions of ecological diversity (e.g., habitat variation, locally adapted populations, and variable life histories) interact to contribute to resilience as ecosystems respond to a heterogeneous and ever-changing environment over a continuum of spatial and temporal scales. The persistence of biological communities at short (*5*, *6*) and long (*10*) time scales is ultimately linked to whether organisms have the ability to exploit shifting mosaics of environmental conditions in space and time. Thus, understanding how shifting habitat mosaics influence the reliability of ecosystem services is crucial, especially in the current era of rapid industrial and urban growth threatening biodiversity worldwide (*11*).

We quantified how shifting habitat mosaics influence the reliability of Chinook and sockeye salmon fisheries at the mouth of the Nushagak River flowing into Bristol Bay, Alaska by reconstructing production and migratory patterns of

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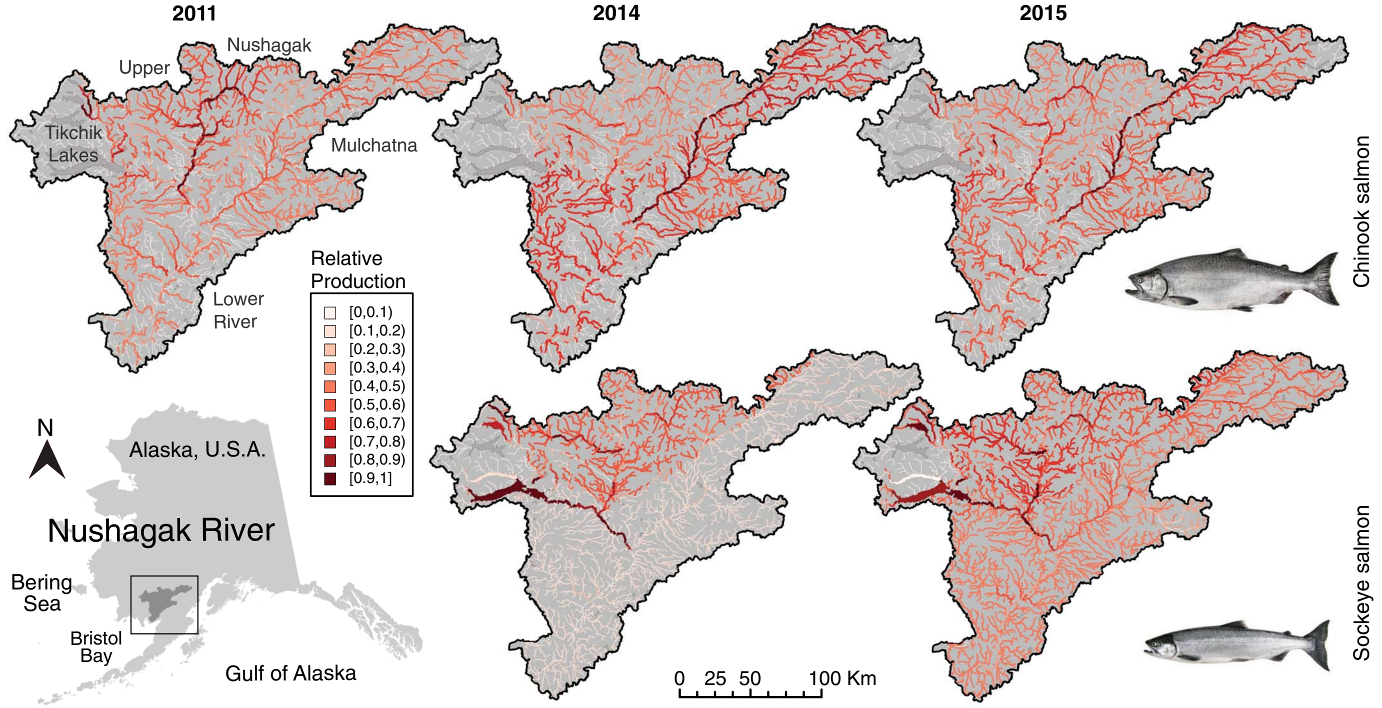

Fig. 1. Productive habitats for salmon shift across river basins. Areas of high Chinook salmon production in 2011 shifted from the upper Nushagak River to the Mulchatna River in 2014 and 2015. Sockeye salmon production was concentrated in Tikchik lakes in 2014 but was more evenly distributed in 2015 including across riverine habitats.

these species using strontium isotopic (^{87}Sr/^{86}Sr) variation across this watershed. Natal origins and movement patterns of juveniles were inferred from profiles of ^{87}Sr/^{86}Sr ratios recorded in otoliths of each species (*12*). Production and habitat-use patterns were reconstructed by calculating the most likely geographic locations of 1377 returning adult salmon (>250 fish per species per year) at each snapshot in time recorded by the otolith during each fish's juvenile freshwater residence (*12*). To do so, we quantified conditional probabilities of ^{87}Sr/^{86}Sr ratios, geomorphic habitat preferences, prior locations, and directional movements (*12*). Because otoliths grow proportionately with the length of fish, we could infer how habitat mosaics contribute to the total growth of fish before entering the ocean (*12*). By analyzing otoliths collected from individuals captured at the river's coastal terminus during annual returns in 2011, 2014, and 2015, our analysis spanned spatial scales ranging from the entire basin to individual streams (stream orders 3 to 9), and temporal scales including interannual variability in returns, the age structure of each year, and the months to years of habitat use during freshwater residence. This breadth of spatial and temporal scales provides a test of how shifting habitat mosaics influence fish-production patterns in free-flowing rivers.

The Nushagak River (35,000 km^2) flows into Bristol Bay, which is distinctive in the region for its vast riverine habitats in addition to large lakes. It is remote, pristine, and defined by substantial landscape heterogeneity. Physiographically, the basin is composed of four regions: the Tikchik lakes and the upper Nushagak, Mulchatna, and lower rivers. These are geologically and geomorphically distinct, generating variations in ^{87}Sr/^{86}Sr ratios, temperature, precipitation, and hydrology. Variation in how this landscape heterogeneity filters overriding climatic conditions generates a mosaic of habitats that contribute to the production of salmon. Furthermore, precise natal homing of adult salmon leads to a hierarchical, locally adapted population structure. Because ^{87}Sr/^{86}Sr ratios vary widely across the basin (fig. S1) and are temporally stable (*12*), the Nushagak River provides an ideal system in which to test how shifting habitat mosaics influence landscape patterns of fish production.

Chinook and sockeye salmon exhibited heterogeneous production patterns across the basin during each return year, and patches of high and low production shifted between years (Fig. 1). Regions of high Chinook salmon production in 2011 were in the upper Nushagak River in the northwest portion of the watershed. These shifted eastward to the Mulchatna River in 2014 and 2015. Similarly, the production of sockeye salmon shifted from being concentrated in the Tikchik lakes in 2014 to being more evenly distributed across both lake and riverine habitats in 2015. Spatial production patterns of both species also differed among the contributing age classes within return years (Fig. 2 and fig. S2). In 2014 and 2015, the production of freshwater age 0 sockeye salmon (salmon that spent <1 year in fresh water, i.e., "sea-/river-type" sockeye) primarily originated from riverine habitats compared with those fish that spent at least 1 year in fresh water, which are typically associated with lake habitats (i.e., "lake-type" sockeye salmon) (Fig. 2).

Juvenile Chinook and sockeye salmon also exhibited a variety of habitat-use strategies among return years to achieve growth in fresh water before migrating to the ocean (Fig. 3, A and E). For Chinook salmon, these different strategies resulted in patchy spatial patterns of juvenile growth, which shifted interannually (Fig. 3, I to K). In some return years, the distribution of total growth across the riverscape differed markedly from the natal production pattern that same year. For example, production of Chinook salmon in 2011 was concentrated in the upper Nushagak River (Fig. 1); the spatial pattern of total freshwater growth, however, was more evenly distributed with the Mulchatna River (Fig. 4I). The amount of growth achieved in the lower river was also much higher in 2014 relative to other years (Fig. 4, I to K).

We also quantified how individuals and populations differentially used the lower river as rearing habitat for accumulating growth as well as a migratory corridor to the ocean (*12*) (movie S1). Depending on the return year, between 8 and 20% of Chinook and sea-/river-type sockeye salmon exhibited forays in the lower river (e.g., Fig. 3, A to C), where they achieved between 10 and

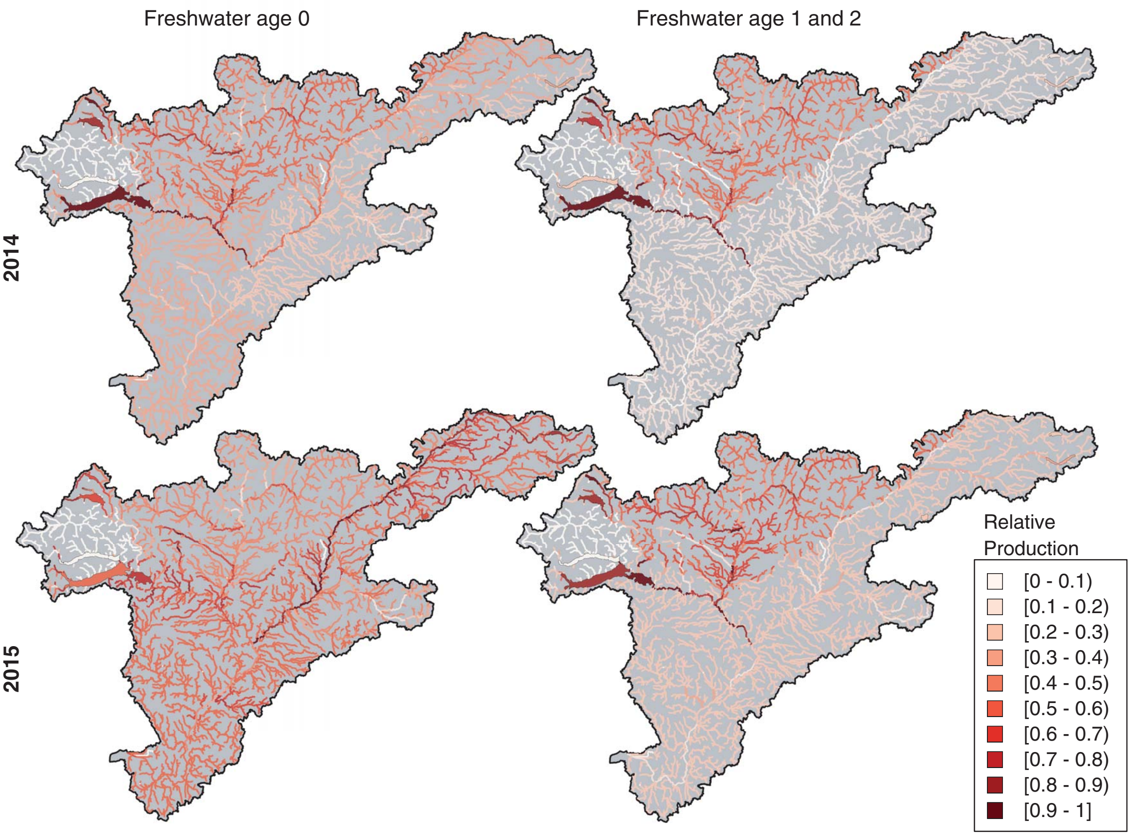

Fig. 2. Habitat and life history diversity interact to shape spatial production patterns. In 2014 and 2015, there was relatively high production of freshwater age 0 fish from riverine habitats.

Exhibit 3
Page 2 of 5

50% of their total body mass before migrating to the ocean (Fig. 3, D and H). Furthermore, the infrequent use of the lower river by lake-type sockeye salmon (Fig. 3, D and H) illustrates how the strategy of using the lower river was not species specific, but rather was more related to the general life history of locally adapted salmon populations.

Interannual variability in the production of salmon from the Nushagak River ecosystem was maintained across the spatial hierarchy of the river network, indicating that a range of spatial scales contributes to variance dampening of salmon resources observed at the river basin scale (Fig. 4, A and B). For both species, we observed variance dampening from fine through aggregated spatial scales (stream orders 3 to 9). Deviations of these observations from a simulation of independent population dynamics (*12*) (Fig. 4, A and B) indicated that production dynamics are not random across the basin. Both species exhibited such deviations at intermediate stream orders, suggesting a strong interaction between the environment (Fig. 4, C to E) and large-scale habitat features that produced independent dynamics among their populations.

Habitat conditions conducive for survival and growth of salmon throughout the Nushagak basin likely vary as a function of how local geomorphic features filter prevailing environmental forcing. This heterogeneity enables the opportunity for juveniles to find suitable growth conditions among the array of habitat options that mosaics provide. Similarly, fisheries in Nushagak Bay benefit from favorable conditions persisting somewhere in the basin for at least one of the age classes exhibiting a particular habitat-use strategy. Freshwater habitats are linked to marine survival not only through the body size achieved by juvenile fish, but also through variation in the timing of their entry to the ocean and whether they meet favorable conditions (*13*, *14*). Correspondence among the spatial scales of environmental variation and shifts in production (Fig. 4, C to E) suggests that environmental heterogeneity plays an important role in shaping how growth and production of salmon vary among locations through time.

Our results demonstrate how multiple dimensions of biocomplexity operating across a continuum of nested spatial and temporal scales integrate to stabilize salmon production and fisheries at the scale of the Nushagak River watershed. Furthermore, we show that shifting habitat mosaics play out at large and intermediate scales in addition to the well-documented cases on small spatial scales for providing resiliency to ecosystem services.

Ultimately, entire landscapes are involved in stabilizing biological production. For conservation, and management more broadly, this makes it difficult to prioritize some habitats over others and emphasizes the critical role of evaluating multiple landscape-use scenarios in the face of increasingly uncertain futures (*15*). For the restoration of affected areas, it emphasizes the need to coordinate efforts across large spatial

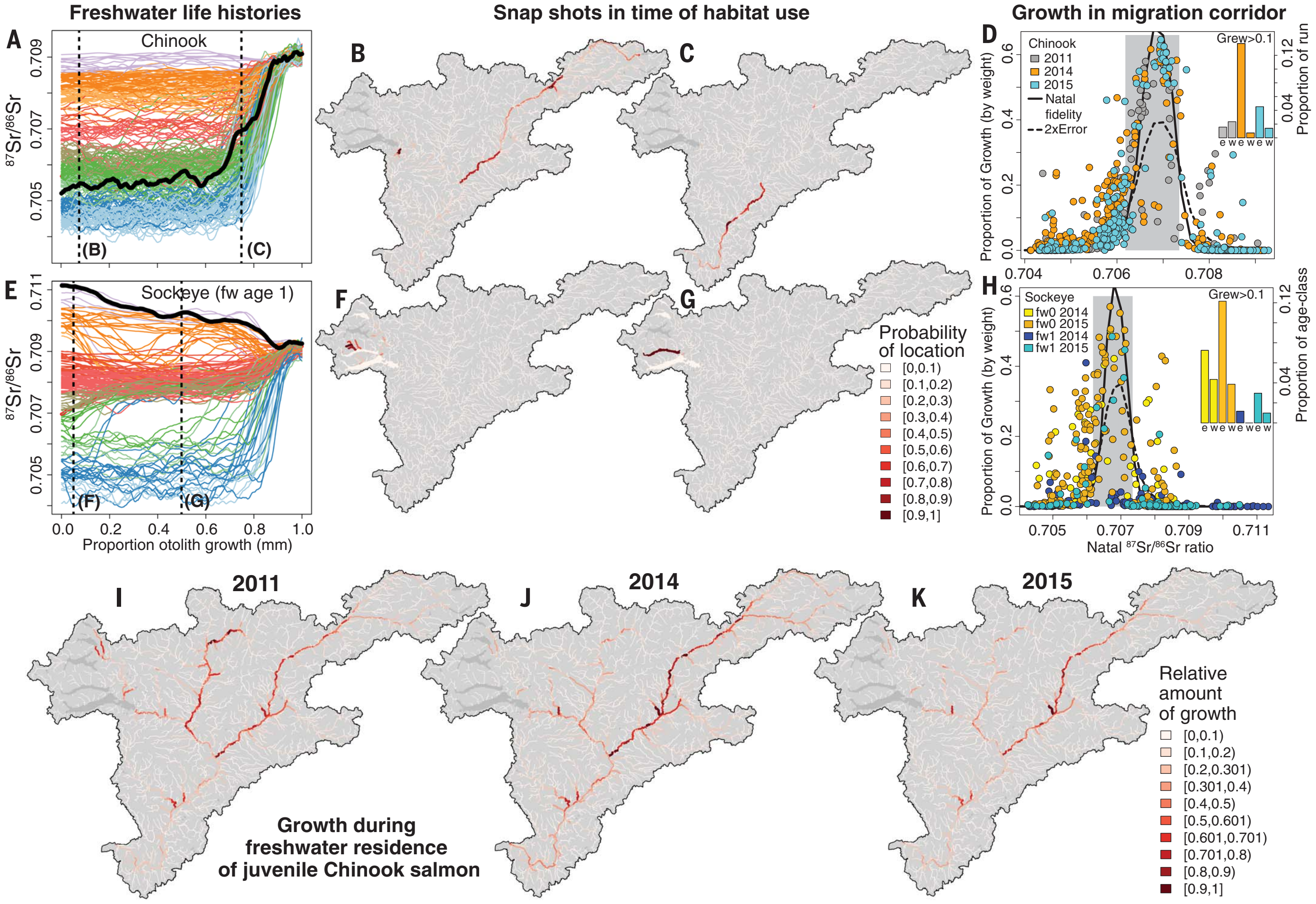

Fig. 3. Diverse freshwater life histories, use of migration corridors, and shifting patterns of growth. Freshwater life histories (**A** to **C** and **E** to **G**) and the amount of growth achieved in the lower river migration corridor of Chinook (**D**) and sockeye (**H**) salmon of the Nushagak River differed among return years ("e" and "w" correspond to fish originating from the eastern or western parts of the basin, respectively). Fish that plot above the black lines and outside of the gray box grew substantially in the lower river but originated elsewhere. Snapshots of habitat use (B and C, F and G) of individual fish [bold lines in (A) and (E)] correspond to positions in the otolith indicated by vertical dotted lines in (A) and (E). Isotope profiles [(A) and (E)] are color coded on the basis of each fish's natal ^{87}Sr/^{86}Sr ratio. (**I** to **K**) Spatial patterns showing how the total amount of freshwater growth (body mass) achieved by juvenile Chinook salmon was distributed across the basin and shifted among return years.

Exhibit 3
Page 3 of 5

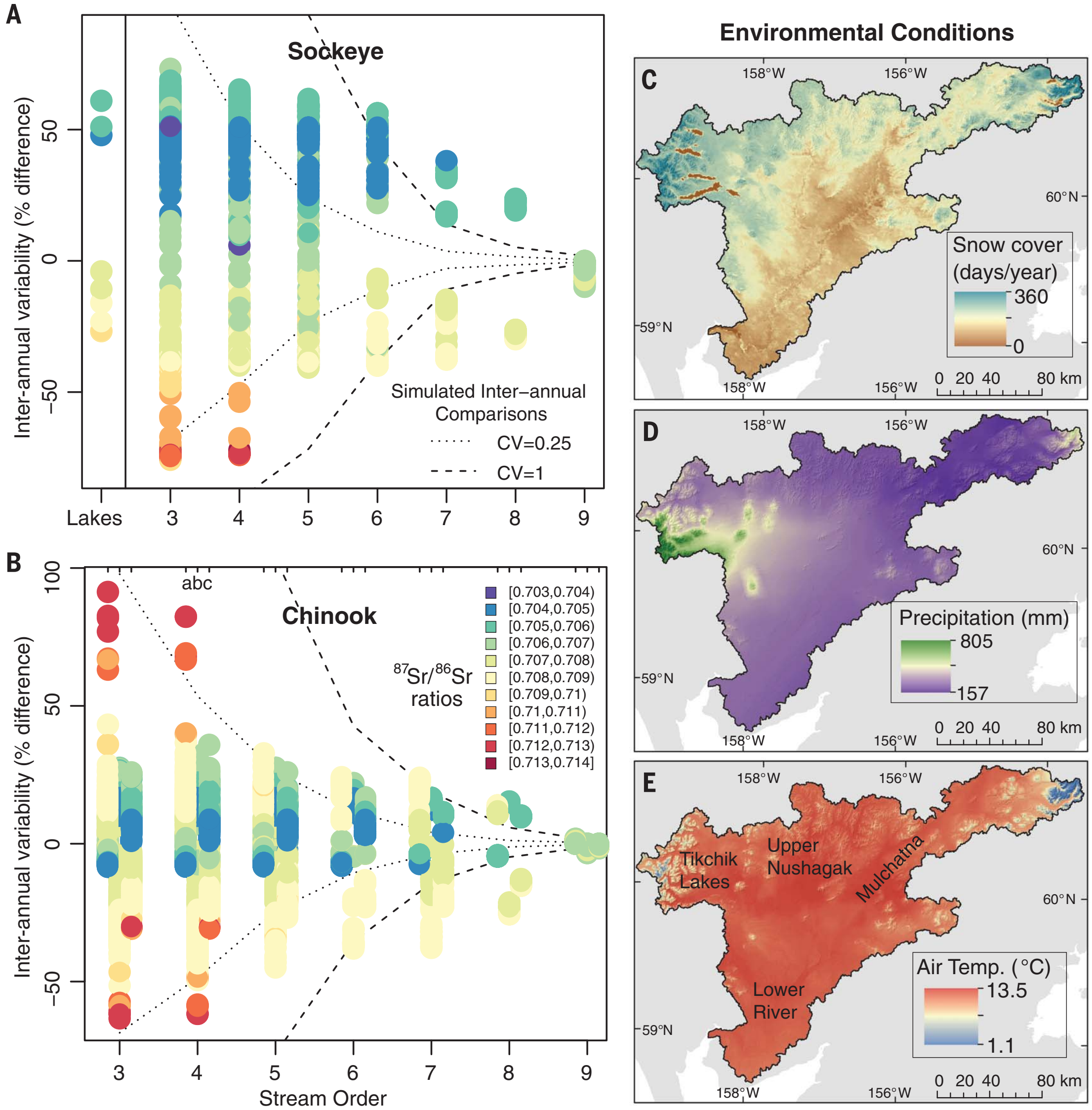

Fig. 4. Shifting habitat mosaics damp variance in production across nested spatial scales. Each spatial scale (stream orders 3 to 9) contributed to the reliability of Nushagak River salmon production. (**A**) Percentage difference in sockeye salmon production of each stream reach among return years aggregated by stream order. (**B**) Comparisons among Chinook salmon return years (a: 2014 versus 2011; b: 2015 versus 2011; and c: 2015 versus 2014). Dotted lines represent simulations in which each unique stream reach is an individual population with independent production dynamics. (**C** to **E**) Multiscale variability in environmental conditions: mean snow cover (days/year from 2011 to 2016) (C), decadal mean summertime precipitation amount (millimeters from 2000 to 2009) (D), and air temperature (°C from 2000 to 2009) (E).

scales and to avoid independent small-scale projects (e.g., tributary by tributary) (*16*, *17*). Such approaches are unlikely to restore a system's resiliency to the levels that we observe across intact landscapes and riverscapes.

Shifting habitat mosaics are a central feature of what makes ecosystems resilient. Because patterns of high and low production, or conditions most suitable for growth, shift among locations through time, the biological performance of a landscape tends to be more reliable at aggregate spatial scales (*1*, *8*). This means that conservation of the processes that generate and maintain heterogeneity and connectivity across landscapes (e.g., fires, floods, and migration) is as important as the biological communities that they support (*10*).

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SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/364/6442/783/suppl/DC1
Materials and Methods
Figs. S1 to S5
Tables S1 to S16
Movie S1
References (*18*–*43*)

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Exhibit 3
Page 4 of 5

Science

Shifting habitat mosaics and fish production across river basins

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A portfolio of habitats

To conserve species, we must conserve their habitat. This concept is well known, but the reality is much more complex than simply conserving a particular area. Habitats are dynamic and vary across both space and time. Such variation can help to facilitate long-term persistence of species by allowing local movement in search of the best conditions. Brennan *et al.* clearly demonstrate the benefit of the habitat mosaic to Pacific salmon by characterizing how both climate and population productivity vary over time and space in an Alaskan river system.

Science, this issue p. 783

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APPLIED ECOLOGY

Risks of mining to salmonid-bearing watersheds

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Mining provides resources for people but can pose risks to ecosystems that support cultural keystone species. Our synthesis reviews relevant aspects of mining operations, describes the ecology of salmonid-bearing watersheds in northwestern North America, and compiles the impacts of metal and coal extraction on salmonids and their habitat. We conservatively estimate that this region encompasses nearly 4000 past producing mines, with present-day operations ranging from small placer sites to massive open-pit projects that annually mine more than 118 million metric tons of earth. Despite impact assessments that are intended to evaluate risk and inform mitigation, mines continue to harm salmonid-bearing watersheds via pathways such as toxic contaminants, stream channel burial, and flow regime alteration. To better maintain watershed processes that benefit salmonids, we highlight key windows during the mining governance life cycle for science to guide policy by more accurately accounting for stressor complexity, cumulative effects, and future environmental change.

INTRODUCTION

Mining for metals and coal provides resources used by humanity but has the capacity to harm aquatic ecosystems. Mining can alter water and sediment chemistry, water cycling, physical habitat, and the health of organisms ranging from microbes to mammals, including humans (*1*–*5*). Mining impacts span vast scales of time and space. For example, in the Rio Tinto in Spain, pollution from primarily copper mining has persisted for over 5000 years (*6*). Pollution can extend tens to hundreds of kilometers downstream from mining operations (*1*, *7*, *8*). Globally, extracted mining wastes now cover ~1 million km^2 (*9*), and on the basis of publicly available data, mine waste reservoirs currently store 44.5 billion m^3 of tailings, enough to bury 59 km^2 Manhattan Island under 750 m (*10*).

From 2008 to 2017, the U.S. government spent 2.9 billion U.S. dollars (USD) addressing hazards posed by approximately 22,500 abandoned hardrock mine features, and many billions more USD are required to continue mitigation and cleanup (*11*). In the Canadian province of British Columbia (BC), the estimated reclamation liability for current major mine projects is 2.8 billion Canadian dollars (CAD) (*12*). At the same time, the social pressure to increase metal mining in North America is forecast to greatly increase, especially to support low-carbon technologies that reduce greenhouse gases (*13*). Considering that mining activities can have impacts that are long-lasting, spatially extensive, and costly to mitigate, there is a clear need to effectively link the science and known complexity of mining impacts to risk assessment and decision-making, particularly in ecosystems that support species of cultural and economic importance.

Here, we review how metal and coal mining can affect Pacific salmonid fishes (specifically, the genera *Oncorhynchus* and *Salvelinus*) and the watersheds that support them in northwestern North America. We define this region as extending from the eastern edge of the Columbia River Basin, west to the Washington State coastline, and north through BC and Yukon Territory and the state of Alaska (Fig. 1). We focus on salmonid-bearing watersheds for several reasons. First, salmonids are ecologically, culturally, and economically important species, including for Indigenous communities and rights holders. Salmonids are often the focus of environmental concerns related to mining impacts (*14*). Second, northwestern North America holds substantial coal and metal ore reserves and encompasses thousands of historical, current, and proposed mines (Fig. 1) yet still has some of the most productive and least disturbed salmonid habitat remaining on Earth (*15*, *16*). Therefore, this region represents a convergence of valuable mining reserves underlying watersheds supporting cultural keystone species, some of which are legally protected by treaties and legislation such as the U.S. Endangered Species Act and Canada's Species at Risk Act (*17*). Third, salmonids migrate across a wide range of habitats during their life cycles and can be exposed to many different pathways of impacts. In other words, if mining policies and regulations can be designed to protect salmonids, then it is likely that they are also protective of many aspects of watershed health.

We integrate and synthesize knowledge from multiple disciplines of the natural sciences including hydrology, river ecology, aquatic toxicology, and salmonid biology as well as components of mining policy such as environmental impact assessment. Wherever possible, we cite peer-reviewed studies conducted within northwestern

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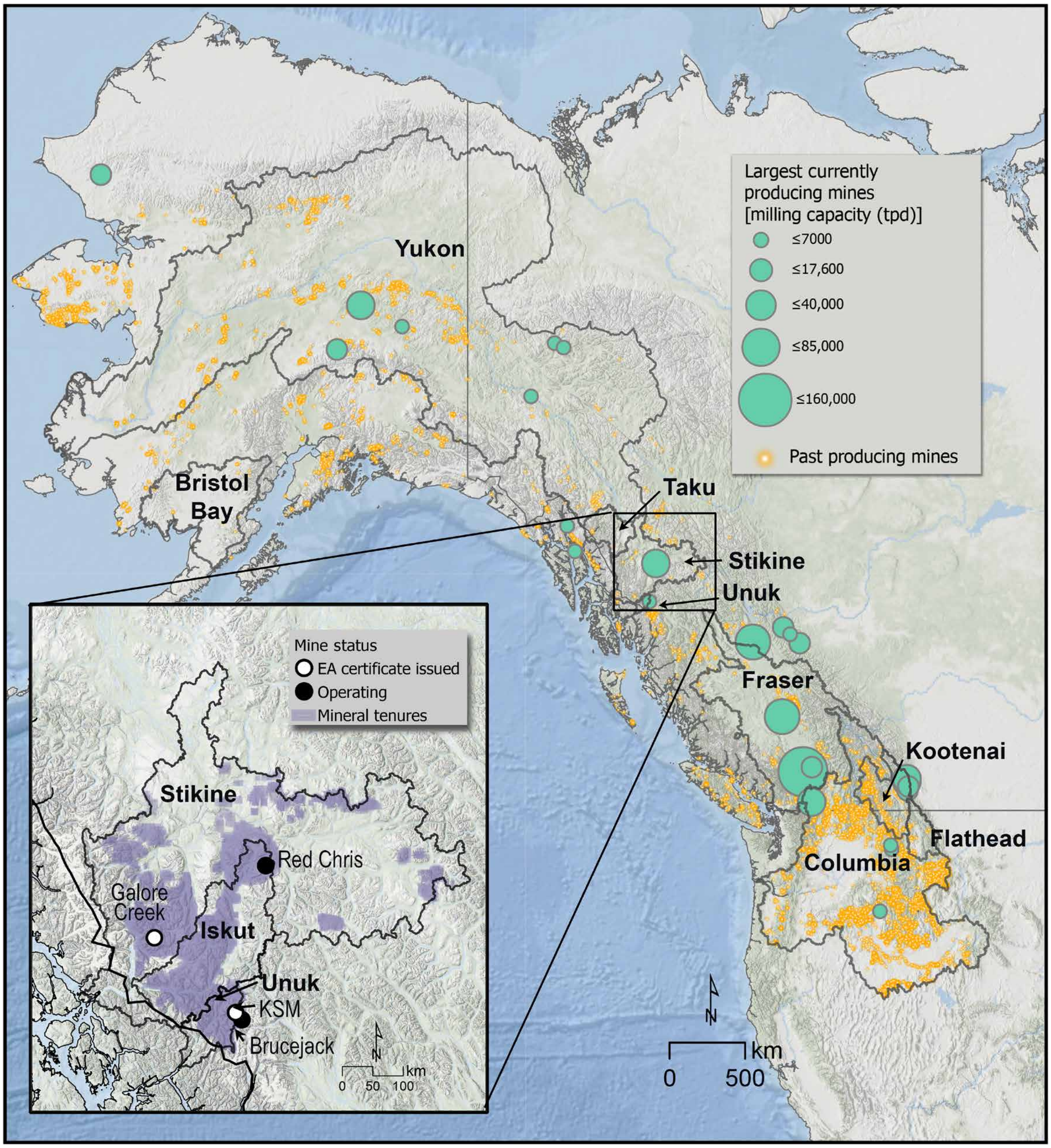

Fig. 1. Current and past producing metal and coal mining locations in northwestern North America. Outlined watersheds are referenced in the text. Teal circles represent the largest currently operating mines in the region (*n* = 26), where sizes are proportional to daily milling rate in metric tons per day (tpd). The inset illustrates the high density of mineral tenures (purple polygons) in the BC extent of the Stikine, Iskut, and Unuk Rivers. Data sources and definitions of "producer" and "past producer" are found in Supplementary Text.

North America. When necessary, we cite general textbooks and peer-reviewed studies outside of the focal region but with transferable and relevant knowledge. Information related to mining operations, current and historical production, case studies of impacts, and regulation and policy are often found in gray literature. Therefore, to provide a more robust assessment of the mining landscape of northwestern North America, we combine information from sources such as agency reports (e.g., British Columbia Chief Inspector of Mines Annual Report), federal/state/provincial-hosted databases [e.g., U.S. Geological Survey (USGS) Mineral Resources Data System], formal disclosure documents (e.g., legal filings with the Canadian Securities Administrators at sedar.com), and technical documentation posted on company websites (e.g., mining project overview descriptions). Our objectives are to (i) describe the extent of mining in northwestern North America, (ii) provide an overview of large-scale mining techniques and how they interact with salmonid-bearing watersheds, (iii) summarize pathways of impacts to salmonid-bearing watersheds, and (iv) highlight key windows during the mining governance life cycle where science can be used to better guide mining policy.

SALMONID-BEARING WATERSHEDS

As context for considering the risks of mining in northwestern North America to salmonid-bearing watersheds, we provide an overview of key attributes of these systems and salmonid life histories. Salmonids are a unique group among freshwater taxa in our study region due to their large home ranges and inclination to permeate all accessible reaches of a watershed's stream network during all seasons. Northwestern North America includes some of the longest remaining stretches of predominantly free-flowing rivers on the continent, such as in the Yukon and Fraser Rivers (*18*), ecologically important unconstrained river valleys that originate from glaciated mountains (*19*), and large intact forests, such as the boreal and coastal rainforests of BC and Alaska. As salmonids from the same river system move throughout a watershed, their exposure and sensitivity to potential mining impacts vary in a complex manner across time and space. Pacific salmonid species have adapted to thrive in dynamic and varied aquatic habitats that drain into the Pacific Ocean (*15*, *20*, *21*). Geological processes such as glacier advance and retreat (*22*), bedrock weathering, mass wasting of slopes, soil evolution, and fluvial geomorphic forces continue to shape these systems (*23*). In some cases, salmonids rapidly colonize new habitat formed by processes such as retreating glaciers (*22*, *24*). These cross-scale processes drive slow and rapid shifts in the locations, types, and amounts of freshwater habitats (*25*, *26*). Seasonal patterns of river flows and water temperatures along with the shifting physical distribution of habitats collectively define the amount, location, and suitability of productive salmonid habitat, which tend to shift within and across watersheds from year to year (*27*, *28*). These watershed dynamics not only drive system complexity and resilience (*15*, *29*) but also pose challenges for human infrastructure and attempts to assess and mitigate risks of development, including mining activities.

Within the family Salmonidae, we focus on native salmonids in the genera *Oncorhynchus* and *Salvelinus*, which include freshwater-resident trout such as cutthroat trout (*Oncorhynchus clarkii*), char such as bull trout (*Salvelinus confluentus*) and Dolly Varden (*Salvelinus malma*), and anadromous Pacific salmon such as Chinook, coho, sockeye, and pink (*Oncorhynchus* spp.) that perform extensive migrations between marine and freshwater habitats. When salmonids migrate, spawn, and die in high numbers in freshwater habitats, they import marine-derived nutrients (*30*, *31*) and provide a critical source of nutrients and energy to local consumers, ranging from grizzly bears (*32*) to resident fishes and aquatic invertebrates (*33*–*35*).

The population status of salmonids varies across northwestern North America. Watersheds in BC and Alaska still contain many diverse, resilient, and productive salmon stocks (*36*). However, especially toward the southern extent of their range, many populations of anadromous salmonids have been extirpated by human activities or are of conservation concern (*37*). Resident salmonids are also threatened in many regions; for example, the Flathead River watershed is one of the last remaining strongholds in the United States for nonhybridized native westslope cutthroat trout (*Oncorhynchus clarkii lewisi*) (*38*). Habitat degradation and loss, with the additional challenge of ongoing climate change (*39*), are threatening the productivity and resilience of salmonid-bearing watersheds and the benefits that they provide (*40*).

Different salmonid species and locally adapted populations have distinct life histories and habitat requirements [reviewed in (*41*)] that determine the duration and magnitude of their potential exposure to freshwater stressors. Spawning generally occurs once annually, when a single female may deposit hundreds to thousands of eggs in a gravel nest (redd) buffered by cool, flowing water. Depending on the species, individuals may spawn once during their lifetime (semelparous) or multiple times (iteroparous). After incubating as eggs in gravel for several months, larval fish emerge and rapidly grow into fry. Many species occurring in watersheds that connect to the ocean will migrate to the ocean after several weeks to several years in fresh water and eventually return to their natal freshwater stream or lake to spawn (anadromous). Some of these species will stay in fresh water their entire life, migrating between streams and lakes (adfluvial) or remaining in streams and/or large rivers (fluvial), resulting in one or more life stages overlapping in river habitats. This creates a high potential for exposure to acute stressors. Alternatively, for anadromous salmon species that immediately go to the ocean following emergence, such as pink salmon (*Oncorhynchus gorbuscha*), the time frame for exposure to acute stressors in fresh waters is seasonally narrow. Given that salmonids use different habitats across their life cycle, they can be exposed to cumulative stressors across multiple life stages and habitat types (*42*).

Salmonids are a cultural keystone species to many people in northwestern North America (*43*). Indigenous peoples have harvested migratory anadromous salmon for millennia, and this reliable source of food contributes to the cultural stability of their communities (*44*, *45*). Salmon fisheries are critically important to the food security and identity of coastal peoples (*46*–*48*). Salmon consumption represents an estimated 5.3% of protein and 45.5% of vitamin D intake by some contemporary First Nations peoples in BC (*46*). About one-third of Alaska-wide subsistence diets, as measured by weight, consists of salmon (*49*). Anadromous salmon also support globally important commercial fisheries. Millions of sockeye salmon are harvested in coastal commercial fisheries each year in Bristol Bay, Alaska, and these fisheries have sustained high harvests for over a century (*15*). The nearly 100,000 km^2 comprising the Tongass National Forest of southern Alaska supports an annual average of 48 million salmon for commercial fisheries, with a dockside value of 88 million USD (*50*). Similarly, recreational fisheries for salmonids support robust economies, with anglers and guide outfitters investing in gear, travel, and other costs in pursuit of a diversity of salmonids, from salmon in the ocean to anadromous steelhead to inland westslope cutthroat trout (*51*).

THE MINING LANDSCAPE OF NORTHWESTERN NORTH AMERICA

Below, we describe the density, types, and sizes of mining operations that overlap with salmonid-bearing watersheds in northwestern North America. We focus on metallic mineral and coal extraction because these mining activities represent some of the largest operations in terms of earth moved, ore processed, and economic impact (Figs. 1 and 2, Supplementary Text, fig. S1, and table S1) (*52*). Using data maintained by U.S. and Canadian governments, we conservatively estimate that, at a minimum, 3654 mines existed as past producers at least as far back as 1857 (Fig. 1; additional data source details are found in Supplementary Text). The USGS Mineral Resources Data System includes underground, surface, and placer mines. Data to determine mine size are often lacking from individual records, but our database query was targeted to minimize the number of small placer mines represented (see Supplementary Text). In

Fig. 2. Representative mining operations in northwestern North America. (**A**) Open-pit operations with a wet tailings impoundment facility beginning to take shape in the background (Red Chris Mine, BC; Garth Lenz). (**B**) Open-pit placer operations with a pit lake used for recirculating sluicing water (Atlin, BC; Jackie Caldwell). (**C**) Legacy underground operations adjacent to a glacial river (Tulsequah Chief Mine, BC; Christopher Sergeant). (**D**) Mountaintop removal coal mining (Elk Valley, BC; Garth Lenz).

contrast to hardrock mining, which removes nonfuel metals and minerals from solid ore beneath the ground, placer mining relies on water and gravity to concentrate valuable minerals such as gold that have been mobilized from their original deposits and now lie in surface sediments. The BC and Yukon MINFILE Mineral Inventories only include underground and open-pit operations. We found that data on active placer mining in BC and Yukon locations are not currently accessible in public databases. Additional mechanized placer mining operations in Alaska that are regulated by the U.S. Army Corps of Engineers are also not fully accounted for in our estimates. Considering these limitations, it is likely that the density of past producing mines in the southern portion of the Columbia Basin appears higher than in other portions of our study region (Fig. 1) because historical documentation was more broadly available in comparison to more northern areas. Currently active mining operations vary greatly in their styles of operation, capacities, and spatial footprints. The Highland Valley Copper Mine in south-central BC is the largest open-pit copper mine in Canada (and in our focal region) and, in 2017, mined nearly 119 million metric tons of earth and milled more than 52 million metric tons of ore (see Supplementary Text). In BC and the Yukon Territory, an emerging demand for minerals and precious metals has led to 41 major projects planned or under construction as of 2020, which collectively represent investments of 28 billion CAD (*53*).

Canadian mineral and coal "tenures"—which are land use agreements such as leases, licenses, or claims—provide individuals and companies the rights to explore and develop specific ore deposits over stipulated periods of time, but further permitting is needed to begin full-scale operations. Some watersheds contain such high densities of mining tenures that considerable portions of these watersheds are already staked for potential mining. For example, 59% of the Unuk River Basin is covered by mineral tenures, equaling approximately 88% of the BC portion of the watershed (Fig. 1). In the Iskut River, the largest tributary to the Stikine River, nearly the entire riparian corridor and 54% of the lower river's watershed are covered by tenures that overlap with rearing, migrating, and spawning habitat for salmonids (Fig. 1). Thus, many major salmonid-bearing watersheds have potentially high exposure to future impacts from mineral and coal mining operations.

Our review of publicly available data found little systematically collected information related to the processing rates and value of placer mining operations (Fig. 2B). These typically occur in valley bottoms and riparian areas and affect the hydrology, water quality, and channel morphology of fish-bearing rivers. While these operations are relatively small and tend to have low acid-generating potential (*54*), studies of specific watersheds suggest that the cumulative biological and physical impacts of placer mining may be substantial. Heavy metals such as arsenic and mercury can be released through the excavation process (*55*) and become toxic to salmonids (*56*). Extensive placer mining in the Fraser River greatly modified the physical habitat by altering natural sediment composition and transport rates (*57*). The State of Alaska has listed more than 193 km of streams impaired by placer monitoring activities that lead to excessive turbidity levels (*58*). Despite this evidence of the potential for environmental harm, BC and Yukon appear to not have any publicly available data on the numbers of placer mines. Thus, there appears to be less regulatory oversight of placer mining.

MINING OPERATIONS

In this section, we provide general descriptions of mining practices to provide context for the possible pathways of impacts on salmonid-bearing watersheds discussed later. In northwestern North America, most mining operations extract hardrock minerals (primarily metals) or coal by creating underground tunnel complexes or excavating large open pits at the earth's surface (Figs. 2 and 3). Mining

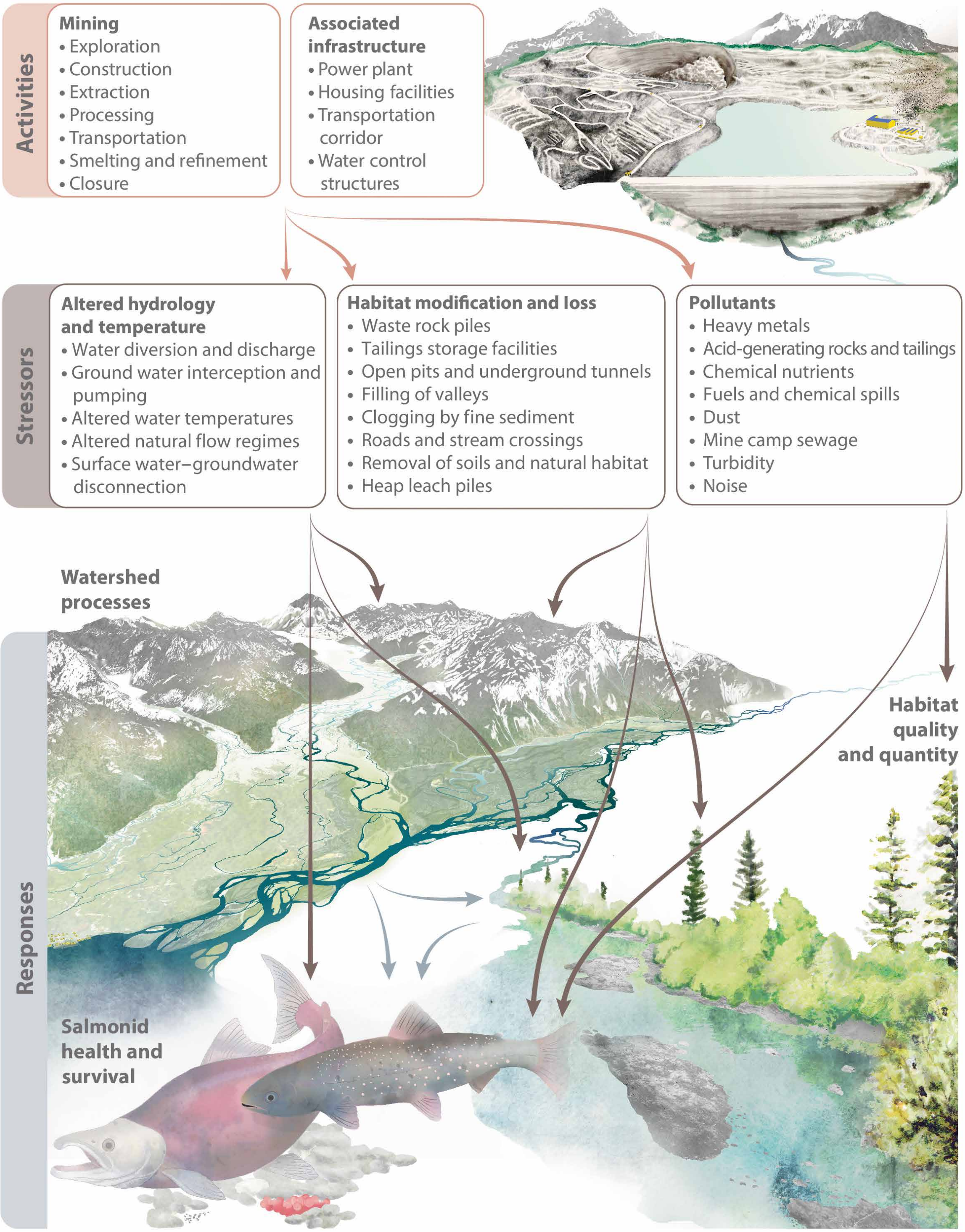

Fig. 3. Mining activities and pathways of impacts to salmonid-bearing watersheds. The different stages of mining activities and associated infrastructure can result in combinations of stressors that, in turn, influence the watershed processes that shape and define salmonid-bearing watersheds from headwaters to outlet, alter habitat quality and quantity, and directly influence salmonid health and survival (brown arrows). These pathways of impacts can have internal feedbacks and connections (gray arrows). Illustration by Cecil Howell.

typically produces ore, tailings, and waste rock. While coal mined for energy generation is sometimes washed before shipment, it does not always produce tailings. Mining generally consists of seven stages (with some differences between hardrock and coal operations): (i) **Exploration** locates and identifies potential mineral resources; (ii) **construction** involves a multiyear effort to prepare the land and build infrastructure before mining occurs; (iii) **extraction** (also known as production) removes the overburden and isolates rock containing metals or coal; (iv) **processing** pulverizes rock and uses metallurgical separation to isolate the target ore concentrate from waste material, which for metal mining is typically >99% of the total material mined (*59*); (v) **transportation** conveys intermediate and target products, fuel and chemical supplies, and waste material; (vi) **smelting and refining** heat or chemically process ore concentrate to remove the target metals; in northwestern North America, this stage is typically outsourced to China, which hosts the largest proportion of world smelter production and capacity (*52*); and (vii) **closure** occurs after a mine ceases to produce ore, and the site is either abandoned or reclaimed, maintained, and monitored for long-term water quality, dust, and visual impacts. It is outside the scope of this review to provide in-depth descriptions of each type of mining operation in northwestern North America. Therefore, we concentrate on commonalities across metal and coal mining and refer readers to more detailed operational descriptions in books such as the work of Whyte and Cumming (*60*). While not a focus of this review, we also note that phosphate mining is a large industry in parts of our study region such as southeastern Idaho. Similar to coal mining, phosphate mines use strip mining and open-pit techniques and can potentially elevate selenium concentrations to levels that create adverse effects to aquatic ecosystems (*61*, *62*).

Exploration involves a range of technologies and approaches. Standard geologic mapping augmented by geochemical analysis of soils is commonly used to determine mineral composition within a watershed (*63*). Remote sensing by aircraft or satellite can provide hyperspectral imagery of the gross geologic structure of potential deposits. Gravimetric, magnetic, seismic, electromagnetic, and electrical surveys are also used for mineral exploration. Test bore holes must be drilled to refine locations of valuable ore and support mine design and economic feasibility analysis. Habitat disturbance resulting from activities such as drilling (*64*) and frequent helicopter landings can range from minimal to long-lasting impacts on the land.

Throughout the life cycle of a mine, the associated infrastructure needed for operation includes plants for electrical generation and transmission, housing facilities, roads and potentially ports for transportation, and pipelines for conveying water and other substances (Fig. 3). There are two primary methods for accessing and extracting metallic ore or coal: surface and underground mining. Surface mining methods include placer mining, strip mining, mountaintop removal, and open-pit mining (Fig. 2). Strip and mountaintop removal methods involve dragging and/or blasting overburden to uncover subsurface coal seams or relatively shallow minerals. Strip mines sequentially backfill their excavations with part of the excess material, while mountaintop removal deposits waste rock in adjacent valleys. Open-pit designs use blasting and earthmoving equipment to excavate terraced depressions tens to hundreds of meters deep, usually requiring commensurate water table drawdown and groundwater management. Placer mining mechanically sorts target minerals out of alluvial deposits via gravity settling and, for gold mining, sometimes requires the addition of elemental mercury as a chemical amalgam. Underground mining also relies on blasting and earthmoving equipment but, in contrast to open-pit designs, creates a system of tunnels and underground rooms. Underground mining generally has a smaller aboveground footprint and produces less waste rock than open-pit mining, but it can lead to sinkholes and land subsidence.

Metallic ore bodies, rocks containing economically valuable concentrations of minerals such as gold and copper, typically host very low percentages of the targeted mineral (*9*). In a large mine operation, ore is transported to a processing plant, normally on-site, where it is crushed and ground to fine particles (clay to sand, 2 μm to 2 mm), sometimes physically separated or concentrated, and then chemically treated to concentrate target metals for refinement or smelting, which is typically conducted off-site. Low-grade ore—containing, for example, concentrations of metal less than 1 g of gold per metric ton of rock—may also be processed using chemical leaching on large piles of uncrushed ore. Ore is heaped onto large open-air pads with a synthetic liner and irrigated with a cyanide or acid solution that dissolves the metal. The resulting leachate is collected and processed for the target metals.

The concentrate produced by grinding and chemical treatment leaves a slurry of fine particles and chemical additives called tailings. Tailings are composed of a mix of liquid and solid particles that is piped away for storage in tailings impoundment facilities contained by embankment dams (*9*). Tailings dams are usually constructed with mine waste rock or, alternatively, with the coarser fraction of the tailings themselves. Less commonly, tailings are dewatered, filtered, and stored in an unsaturated form in engineered piles called dry stacks. Over the past four decades, only 3 to 6% of new tailings facilities use this dry-stack technology (*10*). All tailings impoundments, dams, and associated liners leak to some extent over time (*9*). Waste rock, uneconomic grade rock that occurs alongside the target ore, is broken up and stacked in large piles adjacent to aboveground or underground mine operations and generally lacks any sort of underlying liner. Such waste rock accumulations are often the largest sources of contaminants at mine sites (*65*, *66*). Where ore bodies are disturbed by mining and contain substantial concentrations of sulfide minerals, both tailings and waste rock can react with water, air, and bacteria to generate acidic and metal-laden effluent, known as acid mine drainage or acid rock drainage (*67*).

Transportation of fuel, consumable reagents, extracted minerals, ore concentrate, and other mining products to and from the mine site typically requires substantial investment in transportation corridors such as pipelines, roads, culverts, railroads, tramways, ferry terminals, and associated ports and storage facilities. Trucking, shipping, or piping of concentrated slurries may depend on seasonal conditions that allow transport over, through, and around mountain passes, along river and stream corridors, or around lakes and wetlands. Construction of transportation corridors requires dredge and fill activities in, around, and upslope of waterways.

Following closure, mine sites continue to be chemically and physically active over geologic time scales (*6*, *7*). Large mine sites in particular are so profoundly and irreversibly altered from their natural state that even after reclamation efforts (e.g., recontouring, revegetation, and infrastructure removal) are complete, active water treatment may be needed in perpetuity. In some cases, sites are abandoned without reclamation. This can be a consequence of insufficient bonding to finish reclamation, lack of regulatory enforcement, financial hardships experienced by the project owner, or extensive environmental damages. Some abandoned mine sites are also legacies of old mining laws before any financial assurances were required (*68*). Abandoned and partially remediated sites leave local communities or governments with an indefinite financial and ecological burden (*11*).

PATHWAYS OF MINING IMPACTS ON SALMONID-BEARING WATERSHEDS

Across the seven stages of mining described above (exploration, construction, extraction, processing, transportation, smelting and refining, and closure), mining activities and their associated infrastructure introduce stressors that present risks to watersheds and the salmonids that they support (*1*, *4*). These stressors can directly and indirectly affect all freshwater life stages of salmonids. We categorize impacts to salmonids using three interrelated categories of stressors (*69*): (i) altered hydrology and temperature, (ii) habitat modification and loss, and (iii) pollutants (*7*, *14*, *70*, *71*). These stressor categories modify important watershed processes, habitat quality and quantity, and the health and survival of individual fish and populations (Fig. 3).

Altered hydrology and water temperature

Mining alters the natural flow patterns of ground and surface waters by dewatering open pits, filling streams and wetlands with waste rock dumps and tailings impoundments, and intercepting or rerouting stream channels around mine infrastructure. While water treatment and storage facilities provide options for managing water quality and quantity in the short term, treating wastewater to match the natural flow regime "in perpetuity" creates an expensive post-mining legacy that can be challenging to maintain. In North America, these issues have been well studied in the coal mining regions of the eastern United States (*72*, *73*). In northwestern North America, little published information exists regarding the alteration of flow regimes by surface and underground mining, but there is evidence that (i) waste rock piles from coal mining in southern BC dampen flow regime response to precipitation events and increase dissolved ion loads (*74*) and (ii) open-pit mines with acid-generating rock have the potential to overflow after closure and threaten downstream salmonid habitat (*75*). This is a critical area for continued research, because in parallel with mining activities, climate change is shifting the seasonal and spatial patterns of precipitation, air temperature, streamflow, and water temperature. These changes are exacerbated by rapid glacier retreat, warming air temperature, less precipitation falling as snow, and more frequent extreme precipitation events such as those brought about by atmospheric rivers (*22*, *76*–*78*).

In addition to modifying streamflow patterns, water and tailings impoundment facilities modify natural thermal regimes of river valleys, either cooling or warming surface waters depending on the timing and method of releasing water (*79*). At northern latitudes, groundwater plays a critical role in salmonid growth and survival—especially for eggs incubating in gravels—by warming waters, providing refugia, slowing the onset of freezing during winter, and cooling waters during summer (*80*, *81*). Open pits, water and tailings impoundments, diversion channels, and roadways alter natural connections between surface water and groundwater (*82*), reducing the ability of streams to buffer extreme temperatures during periods of low discharge. Deviations from the streamflow and water temperature patterns to which local fish populations adapt can influence the timing of key life history events such as spawning and migration or alter growth and survival via direct (e.g., stream drying and exceedance of thermal tolerances) or indirect (e.g., alterations to food webs and reductions in available habitat) pathways (Fig. 3). Complex groundwater–surface water connections and the variety of pathways to organismal responses make translating impacts to fish populations challenging. Impact assessments and mitigation plans may rely on flow-habitat models [e.g., Physical Habitat Simulation System (PHABSIM)] (*83*) to translate risks to fish populations, but these require assumptions that are difficult to evaluate and can underestimate the water needs of fish (*84*).

Habitat modification and loss

The footprint of mines and their associated infrastructure can modify or eliminate salmonid physical habitats through the displacement, filling, rerouting, or permanent burial of stream channels and wetlands (*85*). We consider salmonid habitat to consist of physical attributes such as the arrangement of substrate and cover, as well as chemical and biological attributes that control salmonid growth and survival, such as the concentrations of trace metals in water and the availability of suitable invertebrate prey. Aquatic habitat can be altered directly from the construction of mine infrastructure or indirectly via modified streamflow and sediment regimes. Tailings and other fine sediments from mined areas can be transported into streams by erosion, potentially resulting in clogging of coarse bed material and even stream blockage, flooding, and/or channel entrenchment (*86*). Tailings impoundments are often one of the largest components of a mine's footprint and displace streams and land surfaces that would otherwise support aquatic and terrestrial life. For example, the Thompson Creek molybdenum mine in the Salmon River watershed of Idaho is currently inactive but maintains an approximately 240-m tailings storage dam that impounds a 130-ha reservoir (U.S. Army Corps of Engineers National Inventory of Dams; https://nid.usace.army.mil/). These reservoirs can fail with catastrophic consequences (*7*). On 4 August 2014, a failure of the 40-m tailings dam at the Mount Polley Mine released 7.3 million m^3 of metal-laden mine waste into Quesnel Lake, an important sockeye salmon (*Oncorhynchus nerka*) nursery lake in the upper Fraser River watershed of BC (*87*). Before reaching Quesnel Lake, the tailings slurry scoured, deforested, and buried 9.2 km of the Hazeltine Creek riparian zone and mainstem, which was a known salmonid spawning and rearing habitat (*88*, *89*). Although much of this discharge was deposited into lake sediments greater than 100 m in depth, mine waste resuspends in surface waters during spring and fall mixing of the water column (*89*), and the potential for long-term effects to the lake food web remains unknown. Researchers conservatively estimate that more than 130 tailings dam failures have occurred in the United States and Canada since 1910, accounting for 43% of all such failures globally during the past 100 years (*90*). Tailings dams, which must be maintained in perpetuity, are generally more prone to failure than water-retaining dams due to their unconsolidated earthen material construction that is typically built in stages over the course of many years as the impoundment facilities grow (*7*, *90*).

While tailings impoundments are conspicuous and receive attention due to their high potential impact, other mining structures such as waste rock piles, open pits, underground tunnels, and electrical transmission and transportation corridors also contribute to physical habitat modification and loss. Electrical transmission and transportation–related impacts can not only be direct, such as poorly

Exhibit 4
Page 7 of 18

constructed culverts creating barriers to movement, but also indirect by facilitating increased human access to remote areas, enabling the formation of mining districts or other industrial development. The BC Northwest Transmission Line was built at a cost of $746 million CAD and includes 2100 km of wires to increase the feasibility of mining projects and attract more exploration in remote portions of northern BC (*91*). Access roads built for new mine projects may hinder fish passage via stream crossings, bridges, and culverts (*92*). They may also promote the erosion of fine sediments into aquatic habitats, undercut slopes and increase landslide risk, restrict floodplain and channel migration, intercept groundwater, simplify habitat, mobilize methylmercury and other atmospherically deposited pollutants from disturbed soils, modify animal behavior, and contribute vehicle-related pollutants (*93*). Access by rail or road to and from ports, where concentrates are shipped elsewhere for smelting, poses additional threats when large vehicles filled with ore concentrate and/or mining-related chemicals are transported over sensitive landscapes and waterbodies. Construction and use of ports for ore concentrate loading may pose risks to coastal environments, including estuaries of salmonid-bearing watersheds. Mining community infrastructure may stress adjacent stream systems with issues related to sewage, garbage, loss of vegetation and shade, noise and air pollution, and invasive species introductions (*94*, *95*).

Pollutants

Mining for metals and coal alters the physical attributes and the geochemical stability of the disturbed geologic materials, often leading to pollution of downstream receiving waters. Chemical pollution can range from chronic, low-level metal leaching at the river-reach scale to catastrophic, sudden failures with watershed-scale impacts. Metal contamination in stream waters or sediments can be detected up to hundreds of kilometers from their source (*8*, *96*), and their presence can impose direct and indirect deleterious health effects on salmonid-bearing watersheds. In addition to metals, pollutants leaching from disturbed mine operation areas can include sulfate, nutrients, and nitrates from nitrogen-containing explosives (*97*–*99*). Leaching also occurs on road systems and power corridors from exposed soils, fossil fuel combustion, and spilled haul materials.

Pollution can continue long after mine closure, especially where acid-generating rock is present and tailings impoundment facilities exist. Long-term metal pollution results largely from oxidative chemical reactions acting upon sulfide minerals in the exposed metalliferous ore or coal seams, tailings, and waste rock (*4*). Acid mine reactions in sulfide-bearing metal ores and coal deposits are common, largely unavoidable, and can persist for millennia if they are not proactively managed (*67*, *100*). Increasing the surface area of the ore body by multiple orders of magnitude, as is done in the milling process where rock is broken and crushed, greatly accelerates and sustains acid rock drainage and other reactions that release trace elements (*101*). Acidic conditions dissolve trace metals, allowing them to be easily transported downstream, where shifts in redox conditions can cause them to precipitate and sorb to streambed sediments (*102*). Tailings may also contain processing chemicals such as petroleum by-products, acids, and cyanide (*4*). While modern smelting operations are typically outsourced to Asia, atmospheric circulation patterns return some pollutants to northwestern North America. Industrial emissions from eastern Asia contribute to global pollution associated with acid rain, heavy metal fallout, and carbon pollution (*103*). They can also travel back across the Pacific Ocean and contribute to increased atmospheric deposition of trace metals within sections of northwestern North America such as Alaska (*104*) and Oregon (*105*).

Direct impacts to salmonids resulting from elevated concentrations of metals from mining have included the interruption of upstream migration [Atlantic salmon (*Salmo salar*) in New Brunswick, Canada] (*106*) and the extirpation of local populations (Chinook salmon in Idaho, USA) (*107*). Olfaction and antipredatory behavior may be impaired by metal-rich water (*108*–*111*), and the ability of salmonids to use spawning gravels may be degraded because of iron hydroxides precipitating and coating the streambed (*112*). In heavily polluted waters, acute exposure of salmonids such as rainbow trout (*Oncorhynchus mykiss*) to elevated metal concentrations can result in death within hours to days (*113*, *114*). Sublethal concentrations of copper may reduce the migration success and seawater adaptability of anadromous salmonids such as coho salmon (*115*). In the Coeur d'Alene River basin in Idaho, elevated levels of arsenic, cadmium, lead, and zinc created by a high density of hardrock mining operations were correlated with less abundant native fish assemblages and decreased aquatic insect diversity and abundance, even 70 years or more after cessation of mining (*116*, *117*). These correlations may in part reflect that highly mobile salmonid species such as cutthroat trout may be able to avoid habitat with high metal loads relative to more sedentary fishes with small home ranges such as sculpin (*Cottus* spp.) (*116*).

Pollutants from mining-disturbed areas can propagate across food webs and affect salmonid food sources. Altered water chemistry downstream of mines can result in corresponding decreases in benthic invertebrate richness and abundance, changing community composition to favor pollutant-tolerant species (*97*, *99*). Selenium is a common element found in metal and coal geology that is essential for life in trace amounts but tends to bioaccumulate in the food chain (*118*). When chronically leached into downstream surface and groundwaters from mine sites, selenium can reach concentrations that are toxic to fish and all aquatic life, potentially resulting in deformities and ultimately reproductive failure (*99*, *119*). Fish are also directly affected because of ingestion of contaminated prey (*120*).

In summary, cumulative stressors resulting from mines can cause direct and indirect harm to salmonid-bearing watershed health via multiple pathways of impact. Evidence of direct impacts on salmonids exists and speaks to the importance of effective mining governance.

THE SCIENCE OF MINING POLICY

Mining in northwestern North America is governed by regulations, laws, and policies that vary by jurisdiction. In addition to analyzing potential environmental impacts, mining governance also considers other factors such as economics, human values, and community well-being. While science is only one of several dimensions of mining decision-making, it plays a foundational role in the accurate characterization of environmental impacts. In this section, we highlight key windows for science to guide mining policy. This is not intended to be a comprehensive review of mining policy, which is beyond the present scope.

The following regulatory processes and policies define the mining governance life cycle: (i) **Preproject** policies can include land-use designations or plans that govern whether a region is deemed appropriate for resource extraction; (ii) **impact assessment** informs

Exhibit 4
Page 8 of 18

project permitting, including the approval or rejection of the project, and associated mitigation strategies; (iii) **operations** consist of regulation, monitoring, enforcement, and mitigation of mining operations and their potential impacts; and (iv) **closure** of operations transitions the mine from being active to inactive and can govern abandonment, remediation, or reclamation. Depending on individual mining projects, these phases may not occur in order and may overlap in time. Even when these four general categories of mining policy occur at discrete stages of an individual mine's operations, there are strong cross-dependencies. For example, mitigating project impacts is a key activity during mining operations, but the efficacy of these mitigations is mainly considered during the impact assessment phase.

Preproject

Before the impact assessment of a specific mining project, forward-looking planning processes at the regional or watershed scale can establish a collaborative conservation and long-term development vision for the area. Such efforts avoid the pitfalls of single-project cumulative effect assessments (*121*, *122*) and identify specific areas where mining poses risks that cannot be mitigated, are not in the public interest, and should not proceed.

There are various policy tools that could be implemented to advance regional planning. For example, in the Taku River watershed, the Taku River Tlingit First Nation established the Wóoshtin Yan TOO.AAT Land Use Plan with BC, which defined 13 protected areas covering 560,000 ha and established resource management zones, cultural areas of significance, salmon ecosystem management areas, and critical aquatic habitat areas. The Nation and BC also have a Shared Engagement Agreement that outlines the way both parties will engage on land development projects. In addition, Canada's federal Impact Assessment Act (2019) allows for the use of regional assessments as a planning tool to guide the protection or development of regions under pressure. Both the Impact Assessment Act and BC's Environmental Assessment Act (2018) (*123*) were recently updated to include provisions for early engagement among proponents, regulators, other governments, Indigenous Peoples, and the public. Incorporating the values and priorities of local stakeholders and Indigenous rights holders may allow people who bear the immediate burden of the environmental impacts or benefits of mining to shape the vision of their place. However, other applicable legislation in these watersheds [e.g., the National Environmental Policy Act (NEPA)] (*124*) and the Yukon Environmental and Socio-economic Assessment Act (*125*) do not have these provisions.

Given the many cumulative risks associated with mining in a large region and across administrative boundaries, it is important to ensure that scientific predictions of impacts are undertaken at the appropriate scale. Ideally, major mining project proposals—especially those that cross international jurisdictions—would automatically trigger federal-, regional-, and/or watershed-scale planning and assessment. Project-specific permitting should consider plans that integrate current and future additional projects across the entire watershed or region, ecological values of the region, goals and values of rights holders and stakeholders (including those across international boundaries), and potential cumulative effects. These considerations could be used to develop scenarios for future social-ecological alternative states of the ecosystem based on the complete development of natural resources in that watershed.

Impact assessment

Across northwestern North America, the process of assessing the potential environmental impacts of a proposed project and approving its construction may be overseen by federal, municipal, provincial, state, territorial, and/or First Nations and Tribal entities. The lead entities for each assessment depend on the project location, its size, and the types of permits and approvals required. The predominant modern legal tool for evaluating and/or approving proposed mines is impact assessment. Throughout the review, we use this term broadly to cover other jurisdiction-dependent terms such as environmental assessment (EA), environmental impact statement, or risk assessment. Impact assessment is intended to weigh predicted impacts against the public interest and likelihood of significant adverse effects to inform decision-making and ensure the development of proper mitigation measures (*123*, *126*–*128*).

There is general scientific concern that impact assessments do not always meet internationally accepted standards for environmental review and decision-making, including scientific rigor, open data and methods, and independent review (*123*, *129*). A recent study on the role of science in Canada's impact assessment processes concluded that proponent-collected data for a single project do not and cannot capture systemic cumulative effects (*123*). These flaws can result in assessment reports that neither accurately weigh environmental risks nor provide realistic predictions of economic benefits, thus compromising decision-making and environmental protection (*123*, *129*–*132*). Although there have been recent efforts in Canada, for example, to provide more publicly available data related to cumulative effect estimation, data and impact prediction models associated with specific project assessments are consistently unavailable to the public. Project assessments that often rely on proprietary and non–peer-reviewed data stand in contrast to the global expectation in the research community for scientific data and methodologies to be open, freely available, and meeting standards of interoperability, reuse, and peer review within the constraints of applicable data privacy laws (*133*, *134*).

Considering the foundational importance of impact assessment to mining governance, it is critical to determine whether assessments provide accurate estimates of risks. While there are many examples of mines causing harm to freshwater ecosystems via a variety of direct and indirect pathways, these examples do not reveal whether harm is commonplace or rare. Ideally, to determine the extent to which assessed impacts are comprehensive and accurate, researchers would undertake studies that systematically compare the predicted impacts outlined during the impact assessment process with observed project impacts over the life of the mine. To our knowledge, there is only one such study in North America. The authors found that 16 of 25 hardrock mines exhibited poorer water quality than predicted in the environmental impact statements (EISs), representing clear failures in water quality mitigation (*135*). Thus, measured impacts exceeded predicted impacts for the majority of mines studied. Kuipers *et al.* (*135*) concluded that additional similar studies have not happened because (i) impact assessment predictions, along with baseline and operational water quality data, are sometimes unavailable or proprietary; (ii) data that are available can be spread across multiple repositories using combinations of microfiche, paper, and digital records; and/or (iii) available data do not have sufficient temporal, spatial, or methodological replication to facilitate robust comparative statistics (*135*, *136*). In summary, while there are many examples of mines causing harm to freshwater ecosystems via a variety of direct and indirect pathways, a lack of transparency and access to data throughout the mining governance cycle currently prohibits a robust and systematic analysis of predicted versus observed impacts.

In light of these challenges, we outline four key scientific questions intended to promote a transparent discussion of whether impact assessment processes are sufficiently considering risk and uncertainty in complex and dynamic salmonid-bearing watersheds: (i) To what extent is stressor complexity acknowledged and analyzed? (ii) Are cumulative effects sufficiently inventoried and quantified? (iii) Are long-term mitigation strategies based on proven technology and robust to future change? (iv) Are climate change risks incorporated into impact assessment and mitigation strategies?

To what extent is stressor complexity acknowledged and analyzed?

Our understanding of the pathways of mining impacts on salmonid-bearing watersheds will continue to evolve. Therefore, science-based mining policy must strive to minimize lags in applying new knowledge and, when necessary, acknowledge the uncertainty presented by the complex interactions of multiple stressors. Mixtures of metals leaching into rivers via mining projects provide a useful illustration. The current regulation of mining pollution is typically based on water quality standards developed from acute or chronic dose-response relationships for single stressors, evaluated for a limited number of organisms, usually in laboratory settings. However, we note that under the National Pollutant Discharge Elimination System, the U.S. Environmental Protection Agency recommends whole effluent toxicity testing with sensitive aquatic organisms to better assess potential problems caused by mixtures of pollutants (https://epa.gov/npdes/permit-limits-whole-effluent-toxicity-wet). Relying solely on acute and chronic water quality criteria overlooks the indirect effects and multiple interacting pathways of contaminant exposure, which can alter individual behavior or ecological interactions with directly affected species. In addition, the toxicity of some metals to aquatic organisms is controlled by other components of water quality that affect metal speciation (e.g., dissolved organic carbon or pH) or competition for biotic ligands [e.g., calcium (Ca^{2+})] (*137*). Factors such as dissolved organic carbon that can reduce the toxicity of metals such as copper tend to occur at low levels in the steep-sloped and thin-soil mountain environments found throughout northwestern North America (*138*). In addition to water quality conditions, additive or synergistic effects of multiple metals are not considered when establishing water quality criteria (*139*). Metal concentrations are time-consuming and expensive to monitor (*140*), can be difficult or impossible to reduce at large legacy sites with preexisting contamination (*71*, *141*, *142*), and their effects on aquatic organisms can be complex to quantify (*139*, *143*). While postmining pollution trajectories can be reversed even in severely degraded watersheds, restoration activities often begin many years after mining operations cease, can cost tens of millions of dollars for individual projects, and may not demonstrate ecosystem benefits for one to several decades after restoration begins (*107*, *144*).

Are cumulative effects sufficiently inventoried and quantified?

Current environmental legislation in the United States and Canada typically requires the assessment of cumulative effects relative to the scale of an individual proposed project rather than taking a regional multiproject approach.

Previous studies from the past two decades have noted the tendency for cumulative effect analyses to underestimate impacts and be overly narrow in scope, which can collectively introduce considerable scientific uncertainty (*121*, *123*, *145*, *146*). Underpredictions of risk and impact are exacerbated when multiple mines and other resource extraction activities such as logging occur within a single watershed yet are evaluated in isolation (*147*–*149*). The additive or synergistic amplification of mining activities (Figs. 3 and 4) (*150*) may put salmonid-bearing watersheds at risk when mine assessment, permitting, and development occur within one jurisdiction but impacts extend far downstream and span multiple jurisdictions. Narrow scoping of the spatial scale of impacts can exclude downstream governments and communities from the processes governing mine assessment, permitting, and regulation (*151*). Riverine transport of mining pollution and its associated risks can extend far downstream. For example, selenium and nitrate contamination from the Elk Valley metallurgical coal mines in southeastern BC have been measured over 250 km downstream, crossing the international boundary into U.S. and Tribal territories (*8*). The long-distance migration of salmonids, which can exceed hundreds of kilometers, potentially exposes individual fish to multiple mines or other development projects throughout their lifetime. The spatial and temporal extent of accounting for environmental risks should be aligned with the true scale of impact, which can often stretch from headwaters to estuary (*152*).

Are long-term mitigation strategies based on proven technology and robust to future change?

A critical source of uncertainty in predicting mining impacts is verifying the efficacy of long-term mitigation, including infrastructure such as water treatment facilities, tailings reservoir liners, and water control structures. Despite the consideration of mitigation measures in modern impact assessment processes, mining continues to harm watersheds. Recent publicized examples of unforeseen impacts within the salmonid-bearing watersheds of northwestern North America include the following: (i) a catastrophic tailings dam collapse at the Mount Polley Mine in BC (*87*); (ii) excessive and continuous discharge of polluted water at the Buckhorn Mine in Washington State (*153*); (iii) filling of open pits and stalled water treatment due to unforeseen permafrost thaw at the Red Dog Mine in Alaska (*154*, *155*); (iv) extreme rains leading to untreated mine-contact water discharge to the Yukon River from the Minto Mine in the Yukon Territory (*156*); and (v) a salmonid fish kill at Line Creek Coal Mine in BC due to water treatment plant malfunction (*157*). There is evidence that the water quality values predicted during the impact assessment process and the mitigations needed to properly treat water are overly optimistic and often fail (*135*), but as we note above, formal studies on this are exceedingly rare.

Mitigation technology for projects that move into operational phases should be fully funded, proven, and scalable before mine production begins, rather than based on theoretical or laboratory-tested technologies that lack validation at the scale of the operating mine. This not only is limited to wastewater management but also extends to mitigation and compensation for degraded physical salmonid habitat. Many projects result in an overall loss of important habitat when mitigations fall short of predicted effectiveness (*158*). In general, there is a need to develop consistent, quantifiable milestones that rely upon empirical data and verified methods for evaluating and adaptively correcting mitigation technologies when they fail to meet performance expectations (*159*). When mitigation for large-scale projects may not be feasible because of a lack of proven technology or the practical challenges of remote settings, this should be accurately conveyed and considered during impact assessments.

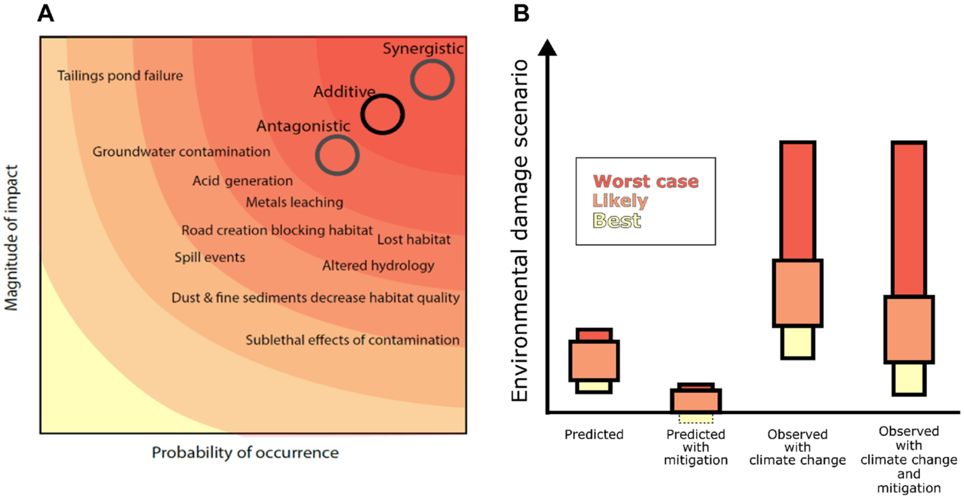

Fig. 4. Conceptual diagrams of cumulative and assessed risks resulting from mining activities. (**A**) Mining activities pose risks that vary in magnitude of impact × probability of occurrence. Yellow, lower risk; red, higher risk. Activities are placed for illustration purposes only, and the actual placement of individual activities relies on specific project details. As reviewed in (*150*), combined risks, which are represented by circles, can be antagonistic (combined effect of multiple stressors is less than the sum of individual effects), additive (combined effect is the sum of individual effects), or synergistic (combined effect is greater than the sum of individual effects). (**B**) Scenarios of environmental damage predicted during the impact assessment process and the proposed mitigation strategies can have unacknowledged uncertainty introduced by poorly quantified cumulative effects and climate change. In some cases, project proponents may assert that the proposed mitigation will improve environmental conditions (light yellow bar below the horizontal axis).

Are climate change risks incorporated into impact assessment and mitigation strategies?

Climate change and associated natural hazards intensify environmental risks and pose direct challenges to the performance of mining infrastructure and mitigation technology (Fig. 4) (*156*, *160*, *161*). As noted earlier, climate change is shifting the patterns of extreme precipitation events and the resulting riverine flow regimes. The steady transition from mainly ice- and snow-fed runoff patterns to mixed snow- and rain-fed runoff patterns will challenge engineers to design adaptive facilities that can withstand environmental changes occurring over decades to centuries. In southeastern Alaska and northern BC, up to 97% of extreme precipitation events occur because of tropic-originating atmospheric rivers (*162*). The frequency of these events is expected to increase through the 21st century (*78*), resulting in a greater number of rain-on-snow runoff events. Mine infrastructure has typically been built under the assumption that the current variability of the physical environment will not change (*156*, *161*). For example, infrastructure built to withstand an extreme precipitation event with a recurrence interval of 1 in 200 may wrongly assume that this magnitude will remain static over time (*163*, *164*). Robust infrastructure is especially important for projects in northwestern North America such as Kerr-Sulphurets-Mitchell, a proposed mine crossing the Unuk and Nass River watersheds (Fig. 1) that proposes to store and treat water for at least 200 years after mine closure (*165*).

It is impossible to predict with certainty whether water storage and treatment infrastructure will be able to withstand the unknown envelope of environmental variability and unforeseen extreme weather events and earthquakes over two centuries. Climate shifts are already affecting operations at the Red Dog Mine near Kotzebue, Alaska, one of the world's largest zinc mines that began in 1989; accelerated permafrost thaw due to increasing air temperatures has overwhelmed wastewater treatment and water management facilities and led to tens of millions of USD in infrastructure upgrades (*154*, *155*). Discharge from Red Dog Mine eventually drains to the Wulik River, an important salmonid watershed for the people of Kivalina, Alaska (*14*, *166*). When mining projects are confronted with climate change–induced uncertainty, scenario analysis could be a key tool for illuminating future problems that are difficult to estimate in the present with statistical certainty. Scenario analyses are a form of visioning exercises that use a structured process for exploring the potential opportunities, risks, and decision-making necessary to adapt to alternative visions of future environmental conditions (*167*). In some cases, climate change may create an especially complex future by improving the suitability of watershed habitat for salmonids. For example, glacier retreat is opening up hundreds of kilometers of new salmon habitat in the mountainous regions of northwestern North America over the coming decades; thus, mines may compromise the viability of habitat that is not important for salmon now but will be in the future (*26*). Actual mining risks could be much greater than assessed (Fig. 4B), and future-looking analyses of habitat potential could clarify these unassessed risks.

The intrinsic complexity of salmonid-bearing watersheds under climate change pressures suggests that impact assessments should adhere to precautionary approaches and use ongoing environmental effects monitoring during all stages of mining activities to allow for adaptation of reclamation efforts when environmental conditions change. To design infrastructure that accounts for the environmental variability brought about by climate change and the dynamic nature of watersheds, rigorous baseline data collection is critical for properly capturing system variability. For example, river discharge data should be collected consistently (e.g., at the 15-min or hourly time scale) with few temporal gaps for a minimum of 5 to 10 years, but as much as 15 years of initial data collection may be required until hydrologic metrics can be accurately calculated (*168*) and used for infrastructure design. The Alaska Highway Drainage Manual (*169*) recognizes the importance of surface water variability when designing bridges and culverts, stating, "A complete [discharge] record is usually defined as one having at least 10 years of continuous record. Twenty-five years of record is considered optimal." Hourly to daily water quality measurements are often necessary to accurately define extreme conditions (*170*), but mine monitoring programs typically prescribe weekly to quarterly measurement intervals that are unlikely to efficiently detect trends and the true range of water quality variability.

Project approval or denial

After completing the impact assessment, which can take several years, decision-makers render a decision on the fate of the project. When faced with substantial uncertainty or lack of robust baseline data, impact assessment and permit processes for proposed mines are increasingly considering "no-go" as a valid response. Mechanisms for this exist in both the United States and Canada. For example, in the United States, an Environmental Assessment (EA) is guided by NEPA. If significant project impacts are expected, then a broader EIS will follow. Under an EA process facilitated by a lead federal agency, all project assessments must include a "no action alternative" to provide reasoned context for understanding the significance of the negative environmental impacts of a proposed project (Canadian laws require a "no project" option). In some cases, the analysis of potential project impacts generated by the EA process supports the decision of a federal agency to deny the issuance of individual permits. For example, at the conclusion of the EA and Clean Water Act review processes for the Pebble Mine in 2020, the U.S. Army Corps of Engineers did not issue the Section 404 Clean Water Act permit. This decision delayed the potential construction of the mine, located within the greater Bristol Bay watershed of Alaska (Fig. 1), where it was determined that construction would result in adverse impacts to wetlands that could not be adequately mitigated (*171*). While politics can undoubtedly play a role in these types of decisions (*172*), we make the point here that mechanisms are in place that allow for the denial of key permits, but this is not the case for all agencies. In the United States, for example, the Bureau of Land Management and Forest Service may require modifications to a mining plan, but they cannot deny it outright. In Canada, recent rejections include the New Prosperity Gold-Copper Mine Project (*173*), Grassy Mountain Coal Project (*174*), and the Morrison Copper-Gold Project. For the Morrison Project, BC officials specifically stated that "there remain uncertainties and risks to fish and water quality," which were deemed not in the public interest (*175*).

Operations

During operations, mining projects generally monitor for environmental impacts that exceed regulatory thresholds. If monitoring detects environmental harm or a failure of mitigation technology, then mining operations and mitigations should, in theory, be adjusted to maintain performance. As noted in the "Impact assessment" section above, there are several major scientific challenges with this in practice. There are issues with data transparency in some mining sectors. Mitigation approaches can fail. Climate change and associated natural hazards are changing. Monitoring programs may not be designed to capture the true scope of impacts, especially as scientific knowledge evolves. To illustrate this point, as methods of toxicity determination increase in sensitivity and sophistication, there is growing evidence that some contaminants have impacts at lower concentrations than previously assumed. For example, toxicity thresholds for selenium have been revised downward over time (*176*).

We recommend that working groups across all levels of affected governments be formed to consolidate basic mining information into publicly available, user-friendly, and annually updated data portals that transcend political boundaries. Many data sources on mine locations, reclamation costs, and other basic operational details are unavailable or diffuse (see "The mining landscape of northwestern North America" section above, the "Closure" section below, and the Supplementary Materials). Before consideration of a new mining operation begins, all potentially affected jurisdictions should agree to consistent protocols that lead to a collaborative, watershed-scale monitoring and evaluation program. This program should include agreement on specific monitoring objectives and define the final reporting based on those objectives. The envisioned final reporting products would guide monitoring program design, including defined roles and responsibilities, identification of reference sites, sufficient sampling frequency, and a high likelihood to detect changes to the environment due to potential mining impacts (*177*). Trade-offs in impact assessment and monitoring design are expected for any monitoring program, but it is important for all potentially affected jurisdictions to explicitly acknowledge potential funding gaps and formally agree upon compromises made during permitting and monitoring program development.

Collison *et al.* (*178*) recently highlighted a regulatory loophole that may enable harm to freshwater systems from mining operations once the impact assessment process has concluded. Their systematic examination of approved and operating mines in BC found that 65% requested amendments after approval, with 98% of requests approved. Almost half of the amendments were assessed as having the potential to harm aquatic ecosystems, such as increasing the authorized amount of harm to fish habitat or increasing water extraction. Most amendments were issued within less than 2 years of mine approval and were not subject to the same level of scientific and public scrutiny as the impact assessment process. Although the first documented case of amendment-related "scope creep," this regulatory challenge likely applies to impact assessment laws in other jurisdictions.

Closure

The reclamation and closure of mines can be expensive, and there can be challenges with financial liability. Bonds based on reclamation estimates are intended to guarantee that mining companies will bear the cost of standard mine reclamation and closure (*179*). Small placer operations may be exempt from bonding. Of the 26 largest operating metal and coal mines in our study region (teal circles in Fig. 1), 21 provide publicly available bond amounts or company-estimated reclamation and closure costs. At the time of our research, bonding and financial assurance costs ranged from 95,000 USD for the Golden Chest Mine in northern Idaho to nearly 586 million USD for the Red Dog Mine in northwestern Alaska (Fig. 1, fig. S1, and table S1). Individual bond amounts are not publicly available for the five mines creating the Teck Coal Elk Valley complex (Elkview, Fording River, Line Creek, Coal Mountain, and Greenhills), but together, their reclamation liability amounts to 1.4 billion CAD, and the current bond amount is approximately 900 million CAD, representing an approximately 500 million CAD shortfall (*12*). Although reclamation bond amounts are subject to high uncertainty (*180*), available information indicates that it will take billions of dollars to reclaim northwestern North America mine sites.

Intuitively, bond amounts should increase with mine size and environmental risk. We found that although bond amounts tend to increase with ore milling rate, there was no clear correlation between bond amount and mine size (fig. S1). Therefore, it is difficult to evaluate the consistency across bond estimates and whether they represent an accurate financial estimate of potential reclamation (fig. S1 and table S1). We were able to extract consistent estimates of milling rate across northwestern North America's large mines, but that is only one indicator of a mine's environmental footprint and potential liability. Other mine characteristics such as disturbed area, acid-generating potential, water quality treatment needs, and equipment removal are included in the overall calculation (*181*), but we did not find sources for consistently extracting this additional information. The financial liability of mining companies for their environmental legacy warrants further attention and supports the notion that the development of financial assurance at each mine site should include a transparent review process with consistent reporting listing how each variable adds up to the final amount.

Policy in transboundary watersheds

Mining policy is complicated in our study region by watersheds that span international boundaries between the United States, Canada, and Indigenous territories. These "transboundary" watersheds represent complicated sociopolitical landscapes, where governance of water, fisheries, and resource extraction are often conflicting or inadequately defined (*182*). This can cause fragmented and inconsistent decision-making regarding the siting of mines, EA, permitting, and regulatory enforcement. For example, water quality criteria can differ across adjacent segments of the same watershed, with associated inconsistencies in the methodologies for calculating, monitoring, and regulating exceedances (*183*, *184*). Likewise, the inherent downstream transport of mine effluent complicates effective permitting and oversight of mines because the assessment of risks in one jurisdiction may not adequately account for the consequences of impacts realized in another jurisdiction (*151*, *184*). Although downstream jurisdictions may be invited to provide public comments during the assessment process, they are often excluded from formal decision-making and have limited avenues for legal recourse.

One avenue for improving transboundary impact assessment is the International Joint Commission (IJC), which exists to oversee the Boundary Waters Treaty of 1909 and to prevent and resolve disputes regarding U.S.-Canada transboundary lakes and rivers (*185*). The IJC set precedent in our study region when they intervened on behalf of the United States and Canada in 1985 to evaluate the potential impacts of a proposed open-pit coal mine in the BC headwaters of the transboundary Flathead River. Following 3 years of impact assessment undertaken by a binational team of scientists, the IJC ruled against the approval of the mine based on the potential impacts to water quality and critical spawning and rearing habitat for transboundary bull trout populations (*186*). This precautionary ruling by the IJC is an example of a watershed-scale impact assessment process that relied upon binational, transparent, and objective science to inform preservation of the Flathead watershed's endangered salmonid populations (*187*).

LOOKING AHEAD

In this review, we have linked current scientific understanding of watershed ecology and salmonid biology with the pathways of mining impacts to salmonids and their habitats. The body of knowledge presented here supports the notion that the risks and impacts of mining have been underestimated across the watersheds of northwestern North America. To facilitate future transparent discussions of risk and scientific uncertainty, we posed four questions related to watershed stressor complexity, cumulative effects, long-term risk mitigation, and climate change. Considering these existing uncertainties, the application of the precautionary principle would help to ensure the protection of salmonid-bearing watersheds and the benefits that they provide for diverse peoples. There are many existing opportunities throughout the mining governance life cycle to improve the science behind mining policies, such as with regional planning, strengthened impact assessment, independent research and monitoring, and harmonization of data collection. Given that mining plays a role for the needs of society, there is an urgent need for current and future mining projects to be operated in such a way that protects our last remaining healthy watersheds and abundant salmonid populations.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at https://science.org/doi/10.1126/sciadv.abn0929

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Risks of mining to salmonid-bearing watersheds

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