

Aquatic habitat remediation following a mine tailings storage facility embankment breach

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Abstract

The Mount Polley Mine in British Columbia, Canada, is an open pit and underground copper and gold mine. In August 2014, the failure of a glacial lacustrine layer beneath the perimeter embankment of the tailings storage facility (TSF) resulted in the release of a slurry of water, tailings, and dam construction material. The material released from the breach and the resulting debris flow resulted in physical impacts to adjacent creek and lake environments. Following the TSF breach, an adaptive remediation framework was developed to guide and communicate the process of investigation, pollution abatement measures, and remediation of areas affected by the breach. Following the initial response that was focused on the immediate need of establishing safe work conditions and controlling further release from the TSF, a tabular format remediation plan was used to communicate short-term actions, such as re-establishing an erosion-resisting creek channel, presumed longer-term actions based on information yet to come in, and steps being taken to address those information gaps to the public, government and Indigenous groups on whose traditional territory the mine is located. A conceptual, and then final, remediation plan was developed while remedial actions based on decisions already being made were implemented. Remedial construction in the creek habitats concluded in the fall of 2021, in time for a run of sockeye salmon to spawn in the newly constructed channel.

The preliminary assessment of effects on aquatic and terrestrial resources found that copper, the contaminant of primary concern associated with the tailings, had low bioavailability. This was a key finding that helped focus remediation efforts on impacts associated with physical scouring of natural sediments, soils and vegetation, and deposit of tailings in riparian areas and water bodies. In creek habitats, the overall remediation objective was to restore the life history functions of fish by first constructing an erosion-resistant, field-engineered stream base in the otherwise erodible glacial lacustrine native soils underlying the area, onto which habitat features (cover, riffle-to-pool ratios, substrate, etc.) were added to enhance aquatic ecosystem functions for spawning and rearing fish. Adjacent riparian areas were stabilised through contouring and planting a mix of local species to establish a successional vegetation community. Evaluation of post-construction habitat suggests that remediation will restore the productive capacity of the aquatic ecosystem for salmonids, and that recovery will be relatively quick, with projected population sizes stabilising above historical levels within 20 years of the TSF breach event. In the lake habitats, monitored natural recovery was recommended based on a net environmental benefit assessment that found that physical removal of deposited tailings would be detrimental to natural recovery already taking place.

Keywords: habitat reconstruction, remediation framework

1 Introduction

1.1 Overview of the mine site and environmental setting

The Mount Polley Mine, located in south-central British Columbia (BC), Canada, near the town of Likely (Figure 1), is an open pit and underground copper and gold mine operating at a deposit formed approximately 200 million years ago and classified as an alkalic copper-gold porphyry. Primary ore minerals are chalcopyrite

and bornite (copper sulfide minerals). Mining commenced in 1997, produces approximately 22,000 tonnes per day and employs approximately 350 persons when fully operational.

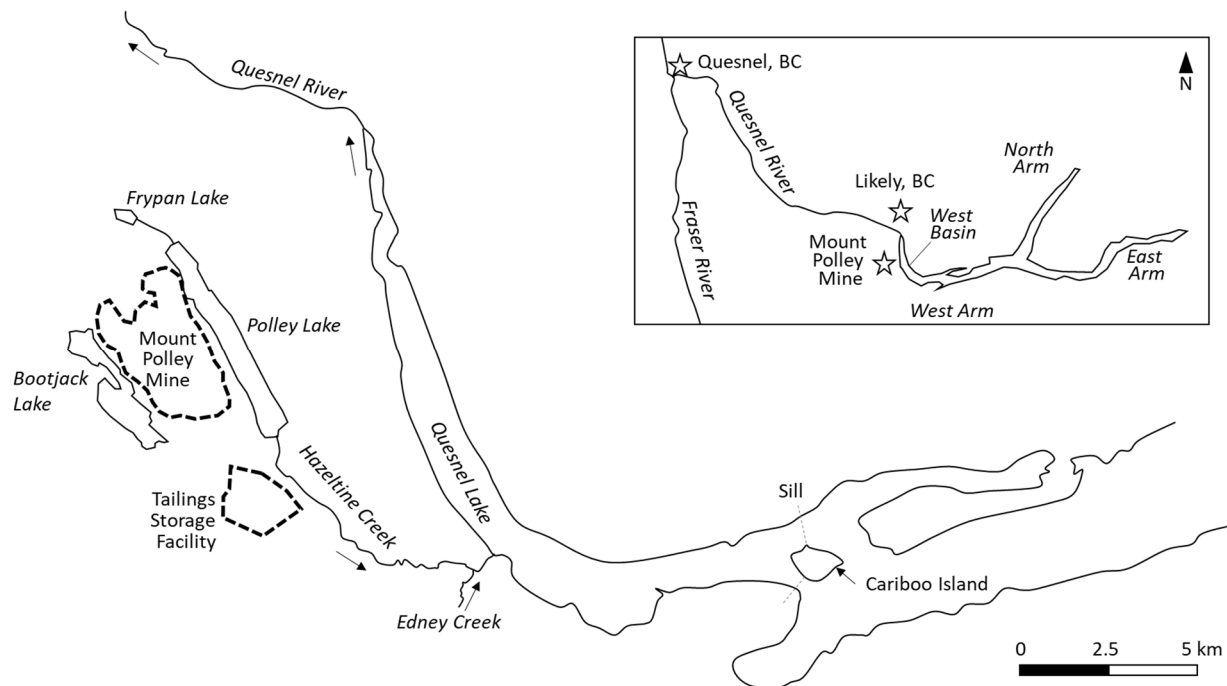


Figure 1 Location and layout of the Mount Polley Mine

The mine is situated on a hillside between two small lakes: Polley Lake and Bootjack Lake. Polley Lake has a surface area of approximately 4 km², and mean and maximum depths of 18 and 35 m, respectively. The present configuration of Polley Lake is not its natural form; Polley Lake was dammed, and its drainage modified to provide water to hydraulic mining activities that occurred in the region during the early 1900s. The lake supports rainbow trout (*Oncorhynchus mykiss*), longnose sucker (*Catostomus catostomus*), and reidside shiner (*Richardsonius balteatus*).

Rainbow trout from Polley Lake are primarily outlet spawners and migrate to the low-gradient upper reaches of Hazeltine Creek in spring (April–May). Hazeltine Creek flows from Polley Lake into the West Basin of Quesnel Lake, a distance of about 9.2 km. Approximately 1.3 km of the middle reaches of the creek are situated in a canyon, where the steep banks and high longitudinal gradient create a narrow, structurally controlled valley that prevents upstream passage of fish. The lower reaches of the creek are again low gradient and prior to the breach event (Section 1.2) provided spawning and rearing habitat for several resident fish species as well as several species associated with Quesnel Lake. Following remediation of the lower reaches, sockeye salmon have resumed spawning in this creek. Edney Creek is a small tributary to the lower reaches of Hazeltine Creek and provides similar fish habitat.

Quesnel Lake is the deepest fjord-type lake in the world, with a total surface area of 266 km² (Laval et al. 2008). The deepest part of the lake is in the East Arm (511 m), and in the vicinity of the mine, the West Basin of the West Arm is 133 m deep. The West Basin is separated from the rest of the West Arm by a 35 m deep sill at Cariboo Island. Quesnel Lake supports some 20 species of fish, including commercially, recreationally, and culturally important salmonids (e.g. sockeye, coho, and Chinook salmon [*Oncorhynchus* spp.], trout [*O. mykiss*, *Salvelinus* spp.]), as well as benthic (burbot [*Lota lota*], suckers [*Catostomus* spp.]), and forage (chub, dace, shiners [e.g. *Mylocheilus* sp., *Rhinichthys* sp.]) species.

1.2 Overview of the TSF breach event and initial response

On 4 August 2014, the failure of a glacial lacustrine layer beneath the perimeter embankment of the tailings storage facility (TSF; ‘the breach’) resulted in the breach of a 250 m section of the embankment, resulting in a release of a slurry of water, tailings, and dam construction material. The cause of the breach is reported on

in a panel report (Independent Expert Engineering Investigation and Review Panel 2015). The TSF for the Mount Polley Mine is located on the southeast side of the mine site (Figure 1).

The material released from the breach and the resulting debris flow resulted in physical impact to Hazeltine and Edney creeks, Polley Lake and Quesnel Lake (Nikl et al. 2016). Approximately 1.36 km² of the breach-impacted area was scoured of forest and topsoil (floodplain zone). Tailings were also deposited on top of the relatively undisturbed forest floor across an additional 1.0 km² of the breach area. It is estimated that approximately 12.8 million m³ (M m³) of tailings were discharged to Quesnel Lake (plus an additional 5.8 M m³ of native soil and TSF water), and that 1.6 M m³ of tailings were deposited in the Polley Flats area and the Hazeltine Creek corridor.

The initial stage of response focused first on immediate needs of establishing safe access and controlling the further release of tailings. This involved stabilisation and containment of the breach and the tailings remaining in the TSF, removal of the bulk of the spilled tailings, construction of sediment control ponds, and construction of a new creek channel and other erosion control measures. A Habitat Working Group (HWG), including the mine owner and representatives from regulatory agencies and local Indigenous communities, was established early in the response to collaborate on the design and remediation of aquatic habitat. Subsequent stages of the response involved a series of extensive environmental impact studies and site investigations (Golder Associates Ltd. 2016, 2017a, 2017b; Kennedy et al. 2016; Mount Polley Mining Corporation 2015; Nikl et al. 2016) and planning for and implementation of remedial actions, which were the subject of a formal remediation plan.

2 The remediation plan

Aquatic habitat remediation was implemented as soon as safe access was established, initially to stabilise the Hazeltine Creek corridor and install erosion control measures in the otherwise erodible glacial lacustrine native soils exposed by the scouring forces of the TSF breach. Given the urgent nature of this work, the new channel was designed based on river geomorphological aquatic habitat design principles (Slaney & Zaldokas 1997). This stream base also provided a foundation for the first stage of remedial design, which was the integration of three specific channel meander patterns. Each pattern is associated with features of the overall channel of Hazeltine Creek, specifically the lower floodplain, the mean annual flood (MAF) channel, and the low-flow channel:

- The primary meander pattern is exhibited by the lower floodplain; this part of the overall floodplain will be engaged by flows associated with freshet. Installation of the erosion-resistant primary meander channel took 174 days and required 20,000 loads of rock delivered by 40-tonne off-road rock trucks (Bronsro et al. 2016).
- The second meander pattern is displayed by the MAF channel (Bronsro et al. 2016). This channel can convey the average peak discharge of Hazeltine Creek throughout the year; flows overtop the channel during freshet and enter the lower floodplain. The MAF channel meanders off the centre line of the lower floodplain.
- The tertiary meander pattern is associated with the low-flow channel. This channel meanders off the centre line of the MAF channel. It will concentrate low flows during late summer, fall and winter.

The formal remediation plan was developed later to identify proposed remedial options where remediation activities were not previously selected during the initial response and ongoing site works, as described above. Figure 2 outlines a high-level process flow for evaluating habitat losses from the breach event, identifying habitat designs where it was reasonable to construct habitat, quantifying habitat 'debits' and 'credits', and quantifying offset requirements as part of the mine's voluntary remediation measures. The process also incorporated monitoring and feedback loops to address the potential need to repair or adjust constructed habitat, and to establish when remediation activities have concluded.

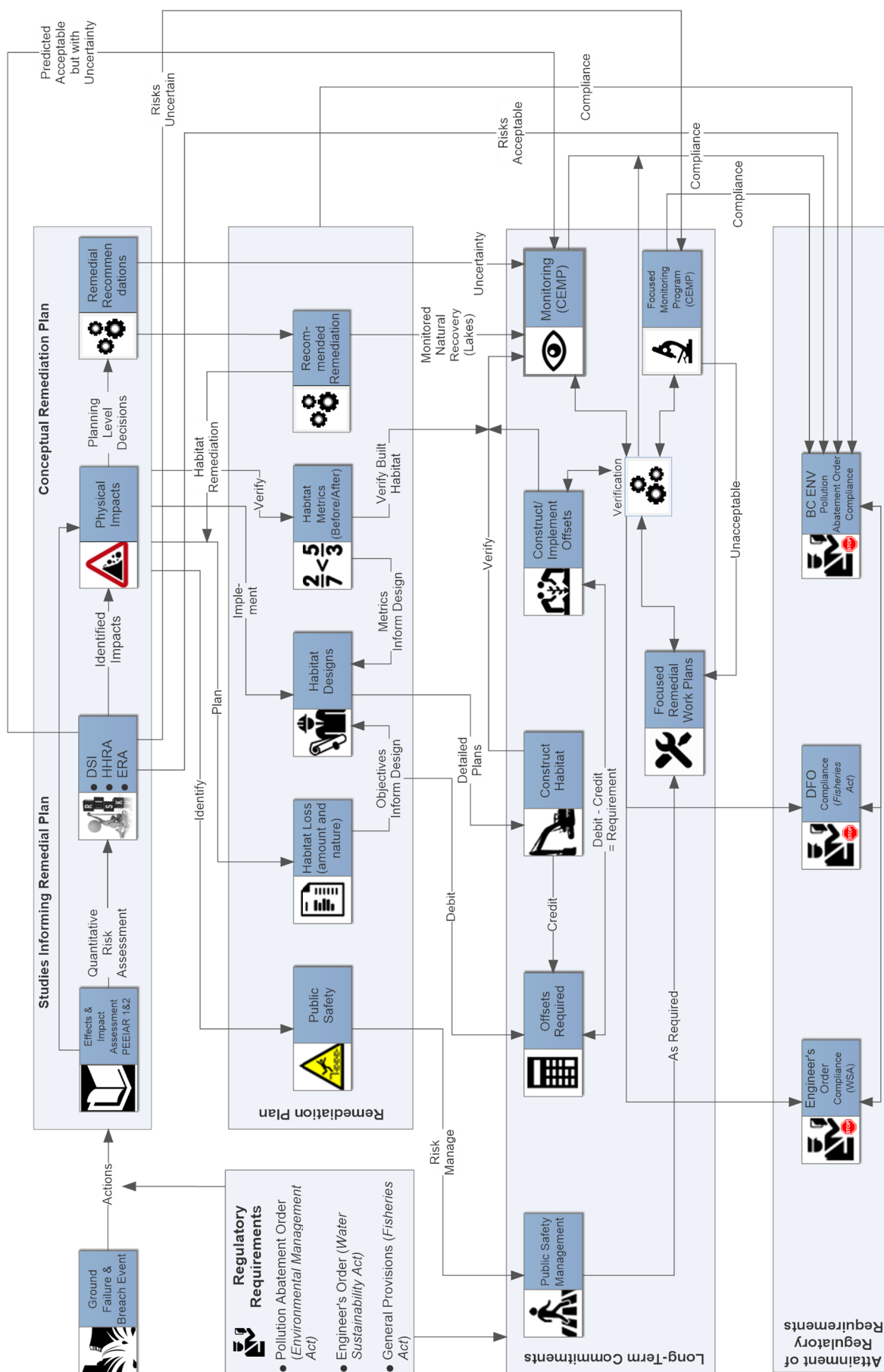


Figure 2 Remediation plan component linkages

The remedial design basis was linked to three potential outcomes from the impact studies and later site investigations, specifically that remediation may be required to address:

- Human health risks related to contaminants.
- Ecological risks related to contaminants.
- Ecological risks related to physical effects to habitat.

Copper was identified as the principal contaminant of primary concern (COPC) associated with tailings, irrespective of whether tailings were deposited to land or water. Numerous lines of evidence showed that the copper associated with tailings had low metal leaching/acid rock drainage potential due to the neutralising characteristics of the mineralogy (Kennedy et al. 2016) and low bioavailability from sediment, water, and soil. Where some copper uptake was noted to occur, toxicity testing did not indicate that the degree of bioavailability/exposure was harmful (Golder Associates Ltd. 2017b). Rather, the tailings had deficiencies in terms of structure or nutrient/organic carbon, which are important non-contaminant stressors. The specific attributes contributing to the deficiency varied somewhat by media (e.g. total organic carbon in sediment; plant-available nutrients and bulk density in soil) but were broadly related to the fact that the tailings lack the heterogeneity and nutrient processing that is part of a healthy soil or sediment ecosystem. This deficiency is expected to decrease over time as organic carbon and biological function return to the system. No other chemical constituents were found to be a significant ecological risk that was attributable to the TSF breach (Golder Associates Ltd. 2017b), and no chemical stressors were considered to present risks to human health (Golder Associates Ltd. 2017a).

Based on these findings, the driver for remediation planning was ecological risk associated with the physical effects to habitat, particularly creek habitat. The remedial plan was accepted by government and the pollution abatement order that had been issued was rescinded (Hill, pers. comm., 12 September 2019; <https://www.imperialmetals.com/assets/docs/mt-polley/2019-09-12-pao.pdf>). The overall remedial objective, developed by the HWG for impacted creek habitats, including associated riparian areas, was to restore the life history functions of fish by constructing detailed habitat features on and adjacent to the main channel morphology established early in the response. The planning for and implementation of creek remediation activities is described in Section 3.

The effects in Quesnel and Polley lakes also arose from the physical impacts of the breach outflow. In littoral areas associated with creeks, remediation is being addressed through the process described in Section 3. For benthic habitats in the two lakes, net environmental benefit analysis (NEBA) was used to compare three categories of sediment remediation: dredging, carbon amendment, and monitored natural recovery (MNR). NEBA is a method developed to identify and compare alternative site management options, often for contaminated sites or for oil spill clean-up (Efroymsen et al. 2003). The focus of this methodology is attainment of net environmental benefit, which is the balance of the environmental benefit achieved from a management option with the environmental costs associated with the option (e.g. habitat disruption). A framework for undertaking NEBA is illustrated in Figure 3.

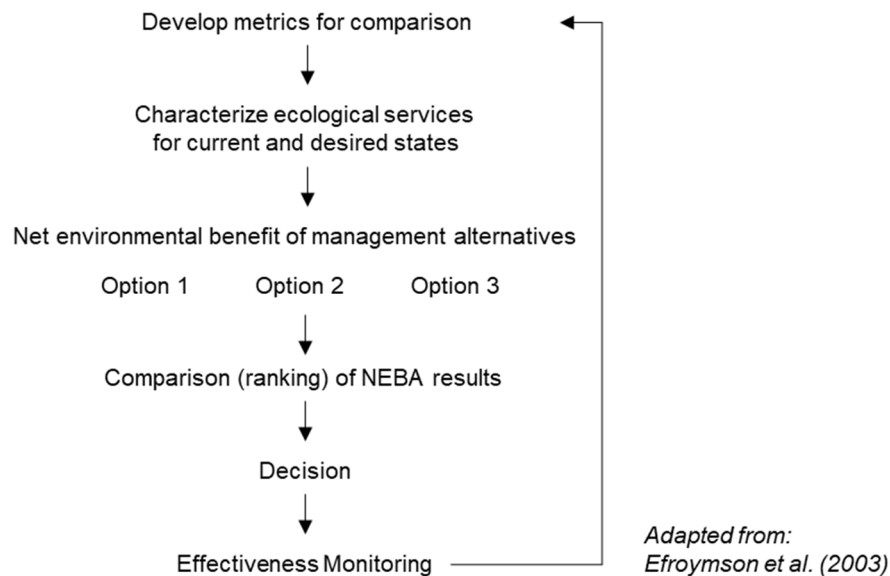


Figure 3 Framework for net environmental benefit analysis

‘Environmental benefit’ addresses a range of natural resource ‘services’, from habitat that supports ecological function (water quality, fish habitat, bird nesting) to direct human uses (e.g. recreation, fisheries) and passive values (e.g. existence value, aesthetic value). For this particular exercise, the variables selected for comparing the potential remediation options were as follows:

- Net benthic invertebrate productivity – the expected gains from remediation less the losses from those activities.
- Effects to water quality – the expected changes in characteristics such as turbidity, which has the potential to affect aquatic life and drinking water.
- Effects to adjacent terrestrial areas – such as from tree clearing for staging areas.
- Effects to air quality – this variable focused on air emissions from construction equipment and potential transport of material for disposal.
- Effects to recreational activities – this considered the increase in truck traffic through adjacent communities as well as alienation of construction areas for boaters and fishers.
- Effects to aesthetics – noise and light have the potential to disrupt enjoyment of the lakes by residents and visitors.

The options were categorically ranked relative to one another without weighting one variable more strongly than the other (Figure 4). Based on the metrics for comparison of the net environmental benefits associated with each conceptual remediation option, dredging would have the greatest potential to have higher environmental costs and would result in the lowest net environmental benefits (benthic invertebrate productivity) because dredging would result in extended perturbations (estimated to take >30 years; Golder Associates Ltd. 2019) at the lakebed. Given the observations of a recovering lakebed at the time the remediation plan was prepared (i.e. species richness was similar to the unimpacted lakebed areas and abundance was increasing though not yet within the range of natural variability), the time benefit of recovery between the initial impact of the event and the initiation of dredging would be reversed. There is also no basis from which to expect that the post-dredged lakebed would be more highly productive. The addition of carbon is a concept that comes from laboratory tests where carbon was added and restored growth to pre-impact conditions. This does not mean that it would result in certainty of benefit if scaled up from lab to field, especially given that organic carbon in the sediments is increasing due to natural processes and there would be a time delay to develop this remedial option from concept to final design. MNR was expected to result in

the greatest net benthic invertebrate productivity and would not be expected to cause further environmental effects (beyond those caused by the event itself). MNR was ultimately selected as the preferred remediation approach, and no physical remediation works have been planned.

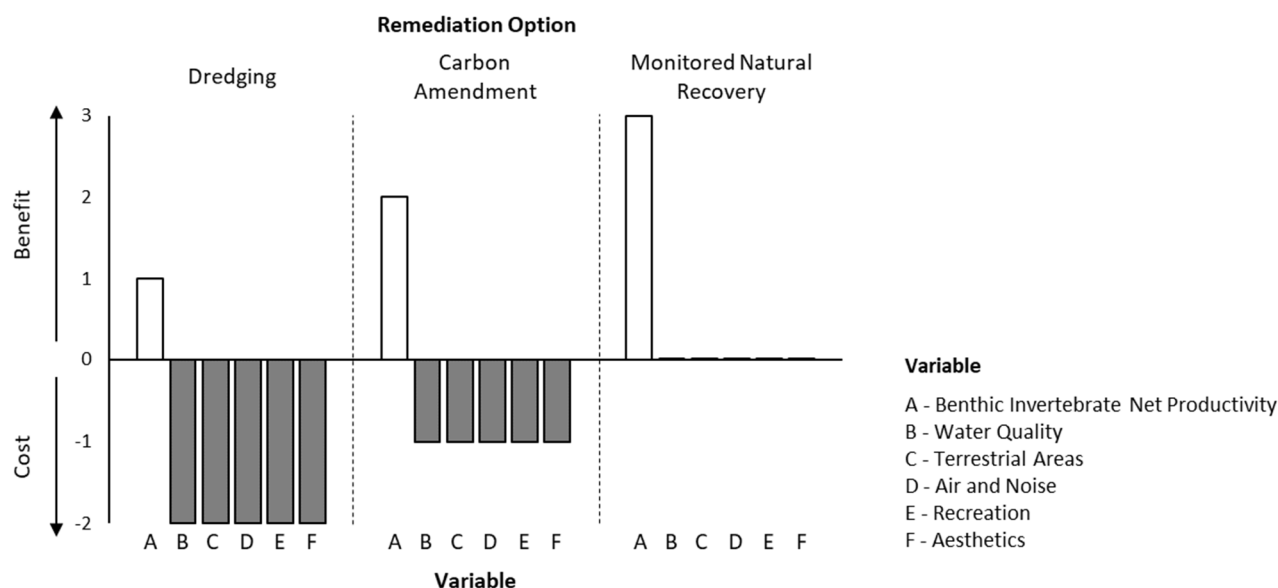


Figure 4 Net environmental benefit analysis of dredging versus carbon amendment versus thin-layer capping versus monitored natural recovery

3 Creek remediation and evaluation

The process of design for the second stage of remediation of creek habitat, including in-stream features and riparian areas, began with the determination of the habitat objectives for each stream reach or ecological unit based on expected fish presence and life history requirements for those species, and consistent with stakeholder expectations for restoring the productive capacity of fish habitat (Department of Fisheries and Oceans 2012; Minns et al. 2011). Each ecological function was linked to a known 'pathway of effect' (e.g. deposit of unsuitable material, alteration of riparian habitat, loss of access) to help inform the type of physical remediation that would be needed. An example of these linkages for Hazeltine Creek is provided in Table 1. Prior to the breach, Upper Hazeltine Creek was documented to be an important spawning and rearing area for rainbow trout, whereas the lower reaches of the creek were known to support several resident and migratory species, including sockeye salmon. For areas used by salmonids for spawning and rearing, in-stream habitat features such as step-pool channels interspersed with riffles and shallow rapids and spawning gravels were prescribed, along with placement of large woody debris and boulders at meander points and channel margins, to provide cover and shade for rearing fish, and to enhance turbulence for hydraulic refugia.

Riparian areas link terrestrial and aquatic ecosystems and provide ecological functions such as improving water quality, providing bank stability, contributing organic matter (e.g. leaf litter and large woody debris) to waterbodies, and providing cover and habitat complexity. Remediation of riparian areas included design principles intended to increase the topographic heterogeneity (Larkin et al. 2008) in the riparian zone using trees recycled from the breach and creating a 'rough and loose' surface treatment (Polster 2009), followed by planting with early successional stage plant species such as willow (*Salix* spp.) and cottonwood (*Populus* spp.) wattles and stakes, and seeds of native ground covers (e.g. fescue [*Festuca* spp.], fireweed [*Epilobium angustifolium*], lupine [*Lupinus* spp.]). Both the in-stream and riparian features were also expected to support the ecological function of a diversity of aquatic organisms (e.g. benthic invertebrates, periphyton) in the stream, as well as wildlife species with aquatic diets (e.g. birds, amphibians). Although beaver (*Castor canadensis*) also has the potential to recolonise Hazeltine Creek as riparian food supplies recover, the extent

of future recolonisation is unknown because of the installation of a hard substrate foundation throughout the creek that may not be suitable for beaver activity and dam building.

Table 1 Example linkages among pathways of effect, creek ecological functions, and indicator fish species for Hazeltine Creek

Ecological function	Potential pathway of effect				Indicator fish species
	Deposition of material	Alteration or removal of structure	Alteration of riparian habitat	Exclusion from habitat	
Upper Hazeltine (H1)					
Spawning	•	•		•	Rainbow trout
Rearing	•	•	•		
Overwinter	•	•			
Migration	•			•	
Lower Hazeltine Creek (H2)					
Spawning	•	•			Rainbow trout; coho, Chinook and sockeye salmon; kokanee; mountain whitefish; burbot
Rearing	•	•	•		
Overwinter	•	•			
Migration	•				

Follow-up monitoring and evaluation against the predefined success criteria identified at the habitat objectives stage (Table 2) were used to adjust or repair installed habitat features, as well as to determine the long-term benefits of habitat enhancements relative to the temporary impact incurred from the TSF breach. As an example of the value of the monitoring program, using drone photography and a geographical information system platform, Ogilvie et al. (2018) documented that after two freshet periods post-construction, the engineered channel and habitat components were physically stable. Of 770 habitat features surveyed, 757 had not moved. The 13 features that did show movement in the aerial survey were inspected, and where anchoring hardware had failed, it was replaced with more reliable anchoring systems.

A series of modelling tools were also used to evaluate whether habitat functions for fish have been restored and to describe the recovery of fish and fish habitat through the verification of the quality of the constructed habitat. Post-construction quality was compared with baseline conditions for the accounting of residual effects. Residual adverse effects were to be addressed by efforts to counterbalance the loss of fish and fish habitat through positive contributions to the aquatic ecosystems (measures to offset; Department of Fisheries and Oceans 2019a, 2019b). Therefore, the modelling tasks were conducted to quantify not only the extent and duration of residual effects to the productive capacity of fish habitat from the TSF failure, but also the potential for the enhancement of fisheries productivity from creek remediation into the future.

The focus of the modelling work to date was the productivity of the Hazeltine Creek–Polley Lake system for rainbow trout, which was identified by the HWG as a key element of habitat rehabilitation. Population variability analysis (PVA) was used to model population production as a surrogate for fisheries productivity over time, by simulating pre-breach and post-construction population sizes based on age-related parameters, such as age at maturation, life expectancy, fecundity (number of eggs), proportion of mature fish, and survival rate for young-of-year, juvenile, and adult age classes. Using an age-structured model means that the probability of surviving from one life stage (or age) to the next determines the growth or decline of the

population. The abundance of fish per age cohort can be tracked numerically over time, providing a direct link to fisheries productivity (de Kerchove 2015).

Table 2 Metrics for defining quality of stream habitat and channel structure and form

Habitat parameter	Quality rating		
	Poor	Fair	Good
Bankfull width-to-depth ratio	>25:1	16–25:1	≤15:1
Entrenchment ratio	<1.4	1.4 to 2.2	>2.2
Channel complexity	<2 mesohabitat units / 10 × Wbf	2–3 mesohabitat units / 10 × Wbf	3 mesohabitat units / 10 × Wbf
Percentage pool (by area)	<15	15–40	40–60
Pool frequency (mean pool spacing)	>10 channel widths/pool	>8–10 channel widths/pool	<8 channel widths/pool
Holding pools (adult migration)	<1 pool/km >1 m deep with good cover (30% of pool area)	1 to 2 pools/km >1 m deep with good cover (30% of pool area)	>2 pools/km >1 m deep with good cover (30% of pool area)
LWD pieces per channel length, measured as bankfull width	<1	1–2	>2
Percentage wood cover in pools* (i.e. wood cover as a percentage of pool area)	pools in reach average 0 to 5% LWD cover	pools in reach average 6 to 20% LWD cover	pools in reach average >20% LWD cover
Spawning substrate size, quality and area	size mostly <6 or >60 mm; >25% fines (<2 mm); <10% spawning gravel area within wetted area of all habitats surveyed	size 6–60 mm; 15 to 25% fines (<2 mm); ≤25% spawning gravel area within wetted area of all habitats surveyed	size 6–60 mm; ≤15% fines (<2 mm); >25% spawning gravel area within wetted area of all habitats surveyed

Note: LWD = large woody debris; Wbf = bankfull width. Modified after Hickman & Raleigh (1982); Johnston & Slaney (1996); Newbury & Gabourey (1993); Slaney & Zaldokas (1997).

For each scenario evaluated, the PVA models incorporated assessments of habitat quality as correlates of carrying capacity of the system to effectively forecast population trends (Larson et al. 2004). Habitat quality of physical habitat features was described using a Habitat Suitability Index (HSI), providing a numerical index (0–1) that represents the capacity of habitat to support a population (Schamberger et al. 1982; United States Fish and Wildlife Service 1981). Inputs to the model were similar to the design parameters for the creek, with modifications to fit the HSI, and consisted of habitat parameters such as water depth, channel width, habitat type (e.g. pool, run or glide, riffle), substrate composition (proportion of organics, proportion of various particle sizes), in-stream cover, and riparian cover. Pre-breach conditions were identified from aerial photographs and other pre-breach datasets.

The modelling approach described above was initially used for the reaches of Upper Hazeltine Creek for which habitat remediation had been completed. The PVA model estimated an approximately 50% reduction in the total population (i.e. consisting of individuals in both the creek and Polley Lake) in the first year

following the breach, and a reduction in recruitment potential for the four years that the upper creek reaches were blocked off for construction. However, the PVA simulated the abundance of juvenile rainbow trout by the end of a 35-year modelling period to be almost four times higher in the post-remediation scenario than in the baseline condition. Full signs of recovery are expected within 10 years of the breach, although some fluctuations in population sizes may persist as the age structure of the population stabilises.

The higher abundance of juvenile rainbow trout following remediation was not unexpected given that at the time of modelling, the HSI score for the post-construction habitat was 1.5-times higher than the pre-breach baseline habitat, and that the engineered design of the creek resulted in an increase in the relative area of riffle habitat from 14 to 30% and pool habitat from 13 to 50% (Golder Associates Ltd. 2021). Indeed, only three weeks following the conclusion of in-stream works in the last section of Hazeltine Creek (lower Hazeltine Creek), sockeye salmon had returned to spawn (personal observation of the authors), indicating that their homing cues to their natal streams were offset by their propensity to also enter new streams. Following the breach, some scientists speculated that the Horsefly sockeye run, a major run in the Quesnel Lake system, would be severely depleted. However, although the federal fisheries department has not released a numeric analysis of the data, local residents in Horsefly, BC, described the impacted cohort of sockeye salmon as 'returning in droves' (Mindus 2018).

Population and habitat suitability models are being updated as additional ecological data are collected via monitoring, as well as when each remediation area is completed. The fish production results from either updated or new models for Hazeltine Creek and Edney Creek, supported by monitoring data, will ultimately be used to provide new information and update the offsetting accounting budgets described in the remediation plan. The proposed fish population indicators (e.g. fish abundance) are preferred indicators for estimating offsetting accounts budgets for large-scale projects because they are directly linked to productivity, which is consistent with the preferred methods recommended by Minns (1997). It is expected that the evaluation of Hazeltine Creek will demonstrate the successful return and recovery of the rainbow trout population and that creek remediation efforts will have resulted in a measurable reduction in overall adverse residual effects and related offset requirements beyond existing remediation efforts in the creek.

4 Habitat offsetting

It was expected that additional habitat would need to be provided to offset for the loss of habitat use following the breach and before habitat remediation was undertaken. The HWG had the role of evaluating and prioritising offsetting options to be constructed. To assist the HWG in prioritising offsetting options, residual effects and preliminary offsetting estimates were prepared, and potential offsetting opportunities were identified.

Where possible, the residual effects of the breach were estimated for aquatic habitats by first comparing the before and after condition of a given ecological unit (EU) to quantify spatial and temporal losses of productive use of the habitat. Habitat Equivalency Analysis (HEA) was then used to calculate the area of habitat that would be required to offset the lost productivity of a given EU from the time it was damaged to the time it was reconstructed. This allows for an accounting of productivity lost over the time since the breach and allows a mechanism to make adjustments based on habitat verification monitoring of remedial or offset habitat construction.

HEA is a procedure initially developed by the National Oceanic and Atmospheric Administration (1995) and provides a framework for determining the area required for compensatory restoration (i.e. offsetting) for temporary habitat disturbances (Kohler & Dodge 2006). The main assumption underlying HEA is that the losses of habitat resources can be compensated for (offset) by habitat replacement projects that provide additional resources of a similar type. The more commonly used methods apply subjective offsetting ratios (Clarke & Bradford 2014; Bradford et al. 2016). A key difference in this application of such ratios in land development scenarios is that the habitat loss is complete and permanent (e.g. where a shoreline area is filled in for construction of a land-backed wharf or a stream is covered by a structure), whereas the nature of habitat impact resulting from the breach event is a temporary disturbance and/or reduction in function

(e.g. productivity, organism movement), provided that the loss has been rehabilitated. The HEA approach is thus a more appropriate means of estimating the amount of habitat that would offset such impacts because it recognises the temporary nature of the 'injury'.

HEA uses a discounting algorithm to value a natural resource asset that is equal to all future services of that asset after degradation due to injury. The formula to calculate the level of ecological services gained and lost is a percentage increase from a baseline level for each year of assessed losses and potential gains are added for the duration of years lost over the compensatory action period. A discount rate (usually 3%) is applied each year to actualise the losses or gains as a percentage rate, and per time services provided sooner are more highly valued than those provided later.

This evaluation resulted in one of the following determinations for each EU:

- No offsetting required: this category was applied to EUs that were: (1) not physically affected by the breach; (2) access to the habitat was restored before it affected a given ecological function (e.g. spawning, rearing); or (3) the quantum reconstructed habitat was greater than the damaged habitat and lost productivity.
- Offsetting required: this category was applied to EUs for which a spatial or temporal deficit in productivity was quantified. The HEA will need to be re-run when the remediation activities are completed to finalise the offsetting requirement as part of the verification steps in the remediation plan (Figure 2).
- To be determined: this category was applied to EUs for which the losses in productivity could not yet be quantified or where traditional offsetting approaches may not be suitable.

The federal regulatory agency responsible for fish and fish habitat management in Canada identifies effective offsets as those that prioritise benefit for the specific fish populations and areas that are affected by a disturbance (Department of Fisheries and Oceans 2013). Although the remediation was carried out voluntarily by the mine, it sought to follow the methods, approaches and outcomes advocated by the national policymaker. Following this guidance, the HWG developed indicators and metrics based on Loughlin & Clark (2014) to compare the difference between pre- and post-breach effects to fish and fish habitat as a basis for determining whether residual effects were present and to whether offsets would be required.

Increasing the productive capacity of the habitat is the key objective of offsetting activities to support healthy and productive fisheries under the *Fisheries Act* (Department of Fisheries and Oceans 2019a, 2019b; Government of Canada 1985). Fisheries productivity can be measured directly through measurement of production rates of fish species of interest, or indirectly through measurement such as catch per unit effort, biomass, or fishing yield (Bradford et al. 2016; de Kerckhove 2015; Minns 1997). Fish population indicators (i.e. fish abundance, fish age class structure, fish condition factor) are preferred indicators for estimating residual effect, particularly for large-scale projects, because they are directly linked to productivity. In comparison, fish habitat suitability and availability indicators (e.g. habitat function metrics, mesohabitat type, microhabitat features) measure productive capacity, which does not directly translate to fish abundance, community structure or health (Bradford et al. 2016; de Kerckhove 2015).

Table 3 summarises offsetting calculations for the two EUs in Upper Hazeltine Creek, as estimated by HEA. The baseline service level was set at 100%, and it was assumed that the baseline service level would never be reached without remediation due to the nature of the physical impact of the TSF breach event. The calculations show that an additional 15 to 30% of offsetting area over and above the pre-event area would be needed to address the years of productivity loss from the time of the event to the time when baseline service levels are attained post-recovery. These offsetting calculations are updated as remediation activities are completed, and as further information is obtained regarding actual fisheries productivity, through the modelling described above and through post-remediation monitoring.

Table 3 Preliminary offsetting calculations for Hazeltine Creek

Variable	Unit	Ecological unit	
		H1	H2
Injured area	m ²	44,650	17,966
Pre-injury (baseline) service level	%	100	100
Pre-restoration service level	%	0	0
Time for 100% natural baseline recovery		Infinite	Infinite
Natural recovery level	%	0	0
Time for baseline habitat to return from restorations	Years	7	10
Size of compensatory replacement as estimated by HEA	m ²	53,314	26,046
Area remediated to date	m ²	15,266	0
Remaining area for remediation or offsetting	m ²	38,048	26,046

5 Summary

The TSF embankment breach at the Mount Polley Mine resulted in the mobilisation of 25 million m³ of tailings and outwash material that scoured the Hazeltine Creek corridor, and which was deposited adjacent to the creek as well as in Polley Lake and Quesnel Lake. Given the non-metal leaching and non-acid-generating nature of the tailings (Kennedy et al. 2016), the impacts of this breach event were physical, rather than chemical, in nature. The physical impacts on Hazeltine and Edney Creeks were considerable. The channel geomorphology was entirely altered where affected and had to be rebuilt. The riparian zone was similarly significantly changed with the loss of vegetation and forest soils. The ultimate remediation design, a product of biological, engineering, and construction expertise and local environmental knowledge from a HWG has produced a rebuilt river that is physically stable (Ogilvie et al. 2018). The constructed habitat is also biologically productive, as demonstrated through the recent use of by spawning fish, as well as habitat suitability and population viability models. Verification of these preliminary results continues.

Although the task was viewed as being insurmountable following the breach, the application of sound engineering and biological principles, the input of stakeholders and the fact that mining companies are experts in the handling and movement of large amounts of materials in challenging landscapes were factors that, when integrated, resulted in a creek being reconstructed that has additional habitat capacity than pre-breach, and consequently is expected to have higher fish productivity.

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