QUANTIFICATION OF SUCCESSFUL REMEDIATION OF THE ENVIRONMENTAL CONSEQUENCES RESULTING FROM A MAJOR MINE TAILINGS STORAGE FACILITY BREACH

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ABSTRACT

A breach of the tailings storage facility (TSF) perimeter embankment at Mount Polley's copper and gold mine in British Columbia occurred on August 4, 2014. The breach resulted in the release of an estimated 25 M m^3 of water and solids. The environmental consequences of the breach included substantial physical changes in Hazeltine and Edney Creeks including loss of natural geomorphology and deposit of material from the TSF. Based on the remediation plan, active physical remediation of the environmental consequences was carried out for Hazeltine and Edney Creeks. The objectives as well as designs were agreed through a collaborative working group (the Habitat Remediation Working Group) involving the mine and its consultants, government agencies, Williams Lake First Nation and Xatśūll First Nation. Remediation success was recently quantified, based on an evaluation of habitat gains versus habitat losses, and based on fish productivity gains as measured by habitat suitability index (HSI), and population viability analysis (PVA) modeling, and confirmed by survey data.

Results of HSI modelling confirmed the suitability of the collaborative working group's design criteria, and the construction work for enhancing the productive capacity of Hazeltine and Edney Creek for salmonid species. The success can be attributed to increases in the relative amount of suitable habitat for spawning and rearing fish, and improvements in the quality of spawning substrate. Since the reopening of the remediated creeks, there have been repeat observations of adult Rainbow Trout, Sockeye, and Coho Salmon actively spawning, as well as presence of young-of-year and juvenile Coho Salmon during monitoring surveys. These observations and model results indicate that the constructed fish habitat is better than unimpacted habitat and is ecologically functioning as intended.

When the breach first occurred, there were many publicly expressed views that the environmental consequences could not be remediated. Indeed, in the previous environmental consequence classification guidance, the Canadian Dam Association (CDA; CDA 2013) included a classification criterion based on whether or not remediation could be done. However, the modeling carried out, supported by direct survey results show that with the application of sound geomorphological, river engineering, habitat ecology principles, and skilled equipment operators, coupled with collaborative design and objectives setting, TSF breaches can be successfully remediated.

RÉSUMÉ

Le 4 août 2014, une brèche s'est produite dans le talus périphérique de l'installation de stockage des résidus (ISR) de la mine de cuivre et d'or de Mount Polley, en Colombie-Britannique. La brèche a entraîné le déversement d'environ 25 M m^3 d'eau et de solides. Les conséquences environnementales de la rupture comprennent des changements physiques substantiels dans les ruisseaux Hazeltine et Edney. Les objectifs et la conception ont été définis en concertation au sein d'un groupe de travail impliquant la mine, ses consultants, le gouvernement, est les Premières Nations de Williams Lake et de Xatśūll. Le succès de la réhabilitation a été récemment quantifié, sur la base d'une évaluation de capacité de l'habitat et des gains de productivité des poissons mesurés par la modélisation de l'indice d'adéquation de l'habitat (IHH) et de l'analyse de viabilité de la population (AVP). Les résultats ont été confirmés par les données d'enquête.

Les résultats de la modélisation IHH ont confirmé l'adéquation des critères de conception du groupe de travail collaboratif pour améliorer la capacité de production des ruisseaux Hazeltine et Edney pour les espèces de salmonidés. Ce succès peut être attribué grâce à l'augmentation de la quantité relative d'habitats appropriés pour le frai et l'alevinage, et à l'amélioration de la qualité du substrat de frai. Depuis la réouverture des ruisseaux assainis il a été observé au cours des études de surveillance, et ce à plusieurs reprises, des truites arc-en-ciel adultes, des saumons rouges et des saumons coho en train de frayer activement, ainsi que la présence de jeunes de l'année et de saumons coho juvéniles. Ces observations et les résultats du modèle indiquent que l'habitat piscicole construit est meilleur que l'habitat non impacté et qu'il fonctionne écologiquement comme prévu.

Lorsque la brèche s'est produite pour la première fois, de nombreux avis ont été exprimés publiquement selon lesquels les conséquences environnementales ne pourraient pas être corrigées. Cependant, la modélisation réalisée, appuyée par les résultats de l'enquête terrain, montre qu'avec l'application de principes géomorphologiques, d'ingénierie fluviale et d'écologie de l'habitat solide, en combinaison avec des opérateurs d'équipement qualifiés, à une conception et à une définition d'objectifs communs, les brèches dans les ISR peuvent être remises en état avec succès.

1 INTRODUCTION

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 with a design capacity of approximately 22,000 tonnes per day. The mine employs approximately 350 people when fully operational.

The mine is situated on a hillside, overlooking Polley Lake, which flows into Hazeltine Creek. Polley Lake supports Rainbow Trout (*Oncorhynchus mykiss*), Longnose Sucker (*Catostomus catostomus*), and Redside 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 Arm 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 similarly low gradient and prior to the breach event provided spawning and rearing habitat for several resident fish species as well as several species associated with Quesnel Lake (Figure 1). Of particular economic importance in lower Hazeltine Creek are Sockeye Salmon (*O. nerka*). Edney Creek, a tributary of Hazeltine Creek provides habitat for similar species but is particularly important for the Interior Fraser population of Coho Salmon (*O. kisutch*), which is listed as threatened by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 2016).

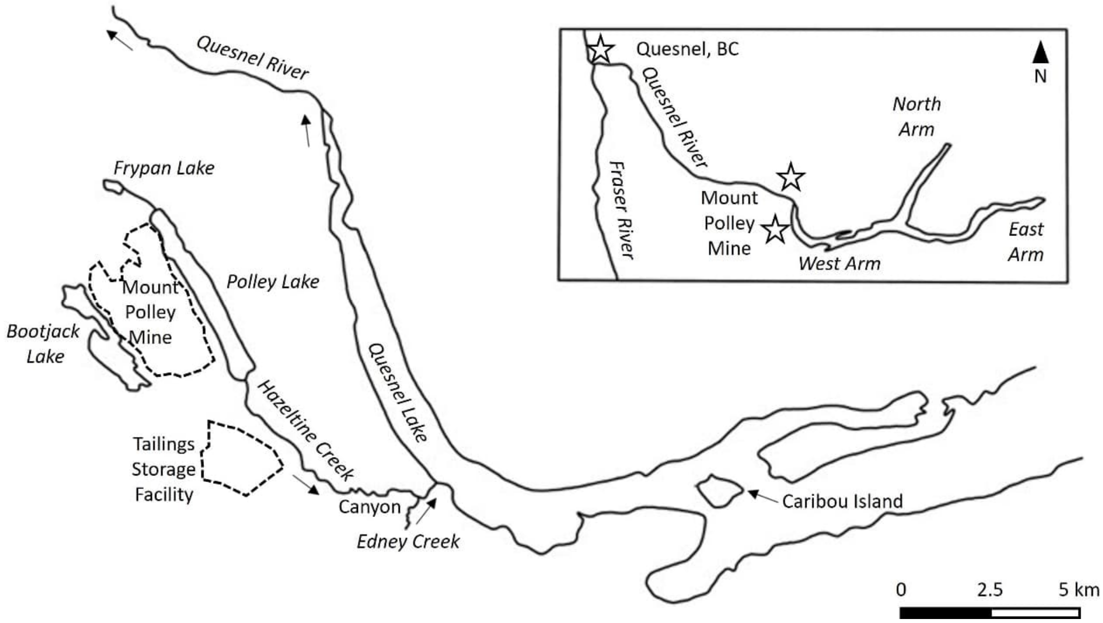

Figure 1: Overview of Mount Polley Mine Site and Hazeltine and Edney Creek

A breach in the perimeter embankment of the Mount Polley Mine Tailings Storage Facility (TSF) on 4 August 2014, resulted in the release of tailings and outwash material that scoured the Hazeltine Creek corridor and lower Edney Creek (Nikl, et al. 2016; Golder Associates 2015). Extensive damage to Hazeltine and Edney Creek altered the channel geomorphology causing loss of in-stream and riparian habitat. Two Rainbow Trout populations were affected: one that originates from Polley Lake, upstream of Hazeltine Creek, and the other that originates from Quesnel Lake, downstream of Hazeltine and Edney creeks. Following the breach, local recruitment (entry of individuals into a population) of juvenile Rainbow Trout from both populations was reduced while Hazeltine Creek and Edney Creek were closed to fish access during ecosystem rehabilitation efforts, and the construction of a new, field-engineered channel (Bronsro, et al. 2016). In lower Hazeltine Creek and Edney Creek, impacts to Sockeye Salmon spawning habitat and spawning and rearing habitat for Interior Fraser population of Coho Salmon, among some other species of fish, were observed.

To restore habitat productivity and capacity of aquatic ecosystems, remediation and rehabilitation efforts were directed by design inputs for rearing and spawning Rainbow Trout and, in the lower reaches, for Sockeye and Coho Salmon, as described in the Remediation Plan (Golder Associates 2015). Habitat remediation was designed to meet regulatory expectations and requirements (Magnan 2014; Hill 2019) with ongoing monitoring to quantify the success of remediation relative to pre-breach levels. This was part of the mine's commitment to their voluntary remediation (i.e., there was no direction issued under the Canada *Fisheries Act*) of the environmental impacts of the breach (Reimer 2014). The scale and design of the remediation work was intended to not only restore, but also enhance the productive capacity of habitat, yielding the potential to provide gains to offset breach-related losses over time.

We present here an overview of the approach to quantifying the outcome of habitat remediation following a major tailings dam breach.

1.1 Remediation Plan Overview

The Remediation Plan identified remedial options for the areas affected from the breach (Golder 2019). The plan's design basis originated from information obtained from the numerous environmental technical studies that had been carried out since the breach (Golder Associates 2015; MPMC 2015; Golder 2016; Golder 2017a; Golder 2017b). The Remediation Plan also linked the remedial options to regulatory requirements, desired outcomes, and specific actions to be taken (e.g., habitat remediation and habitat offsets, monitoring). The overall remedial objective for impacted stream habitats was to restore the life history functions of fish, in particular salmonids, by constructing an engineered stream channel in the otherwise erodible glacial lacustrine native soils below Hazeltine and Edney Creek, incorporating habitat features to support a healthy functioning aquatic ecosystem (Bronsro, et al. 2016).

The remediation of Hazeltine and Edney Creek following the TSF Breach was carried out as articulated in the Remediation Plan (Golder 2019), under the oversight of the Habitat Remediation Working Group (HRWG) which was comprised of the mining company, the company's technical advisors, environmental agencies, Williams Lake First Nation and Xatśūll First Nation, as well as their respective technical advisors. The habitat construction works are concluded and the planning and design for them was carried out through direct collaboration through the HRWG.

Through this process, the primary aquatic objective decided for both upper and lower Hazeltine Creek was the creation of spawning and rearing habitats for Rainbow Trout. Habitat parameters considered in the design criteria for meeting the remediation objective for Hazeltine Creek are provided in detail in the Remediation Plan, but in brief, included the following (Golder 2019):

- A preference for a diversity of habitat types through the creek (i.e., higher channel complexity) such as repeated sequences of riffle, run/glide, and pool habitat types.
- Relatively high percentages of pool habitat (up to 60% surface area of the creek).
- A pool frequency with placement every eight channel widths or less (where possible) and the placement of up to two pools per km with depths for holding fish (greater than 1 m depths).
- Instream cover provided by large woody debris to approach or exceed 20% the surface area within constructed pool habitat.
- Available spawning substrate sizes within all wetted areas of the creek, specifically greater than 25% spawning gravel cover.

1.2 Riparian Revegetation

Site preparation was conducted to serve multiple concurrent purposes. The sites were re-contoured to provide a physically stable landscape, provide a rough and loose surficial texture for sediment and erosion mitigation and decompaction, and to provide planting microsites to enhance plant production (Polster 2009). Much of the remaining topsoil was salvaged and residual topsoil deposits that were formed in the outwash material were utilized to provide a suitable growth medium to support future plant communities. The topsoil provided suitable physical characteristics, nutrients and residual seed bank that would augment biodiversity. Coarse woody debris, salvaged at the time of the breach, was utilized for terrestrial and aquatic habitat features to support not only the future plant communities but also microbial, fungal, animal, and avian communities.

Planted species included a mix of groundcover grasses and forbs, deciduous shrubs and trees and conifers. The ground cover seed was comprised of a blend of native grasses and forbs that was previously developed for mine site reclamation at the Mount Polley Mine (MPMC 2022) and was applied at a target rate of 4 kg/ha. The shrub layer was comprised of sitka alder (A*lnus sinuata*), red osier dogwood (C*ornus stolonifera*), black twinberry (L*onicera involucrata*), willow species (*Salix spp.)* and rose species (*Rosa* *spp*.), and was planted at densities ranging from 1200 stems per hectare in upland areas, to 50,000 stems/ha in the riparian areas. The tree layer was comprised of interior Douglas fir (*Pseudotsuga menziesii*), lodgepole pine (P*inus contorta*) hybrid white spruce (*Picea engelmannii x glauca*), western red cedar (*Thuja plicata*), and sub-alpine fir (*Abies lasiocarpa*). Additional natural stocking was anticipated to emerge and include a variety of local conifers, and also deciduous trees including black cottonwood (*Populus trichocarpa)*, trembling aspen (*Populus tremuloides*) and paper birch (*Betula papyrifera*). Conifers were planted at a density of 1,200 stem per hectare and subsequent survival surveys indicated natural ingress densities exceeding 10,000 stems per hectare in areas (Holmes, 2016). Natural ingress was found to be dominated by black cottonwood.

Small additions of native forest soil were included in planter's bags or in a slurry that seedlings were dipped into. This operational step was included to assist in rapid dissemination of native forest microbiological communities throughout the project area and was found to increase seedling growth and/or nutrition (McMahen, 2020).

2 METHODS

2.1 General

The evaluation of the remedial work considered habitat in the context of its quality, quantity, and projected population recovery for salmonid fish species. Quality and quantity of habitat were evaluated using a Habitat Suitability Index (HSI) and Weighted Usable Area (WUA) approach, while population growth (habitat productivity) was evaluated using Population Viability Analysis (PVA) modelling. PVA modelling was carried out using a commonly used (for this purpose) software package that provides transparency and repeatability of methods (i.e., RAMAS Metapop 5; Akçakaya 2000, 2001, 2008; Larson et al. 2004). The PVA model was compared to measured population levels to validate its reasonableness for that use. The PVA model was not applied to the Sockeye and Coho Salmon because input data on their vital rates lacked sufficient certitude. Therefore, success metrics for the habitat for Sockeye and Coho Salmon in lower Hazeltine and Edney Creeks were based on HSI scores and Habitat Units (HUs), derived from the WUA approach.

2.2 Habitat Suitability Index (HSI)

The HSI is based on the characterization of species-habitat relationships based on published information and on site-specific ecology to best capture habitat requirements of the species under evaluation (USFWS 1981; Schamberger et al. 1982). Model development steps include the identification of model variables (or components) for each life stage, followed by the development of model relationships that reflect the species' biological needs (e.g., food), or previously described or observed trends in habitat use.

The HSI model is based on suitability curves, which can be created for a variety of different physical habitat variables such as water depth, substrate composition or particle size, flows, riparian conditions, and HU types (e.g., pool, run and riffle habitat types for stream assessments). Each curve reflects the expected response of a species to changing environmental conditions, and after establishing the individual suitability curve for different physical habitat variables, a composite HSI model can be formulated. The composite HSI can subsequently be used in combination with spatial information and areal measurements, to create a habitat quality map, and calculate a WUA statistic to estimate the productive capacity of habitat, for the pre-disturbance condition versus post-remediation condition (e.g., Lewis et al. 2004; De Kerckhove et al. 2008; DFO 2015, 2016).

Using the HSI value calculated for each reach, in combination with areal measurements of channel widths and lengths made in GIS software, a weighted usable area statistic was calculated per reach to estimate the productive capacity of habitat for the pre-disturbance condition versus post-remediation condition. The product of the HSI value and area per reach was defined as a HU (e.g., De Kerckhove et al. 2008; DFO 2015, 2016).

HUs calculated for baseline, pre-breach scenarios, including consideration of a significant network of beaver dam barriers, were compared to the results for two post-remediation scenarios to calculate a range in potential gains in HUs. Post-remediation scenarios with beaver dam presence were not considered because the expectation is that beaver will not return to Hazeltine and Edney Creeks in the near future because of current riparian conditions, and also because of the thick layer of coarse substrate (rock) used to create the streambed and banks, which is expected to deter beaver from manipulating the streambed to create dams.

2.3 Population Viability Analysis

The PVA models projected the recovery of Rainbow Trout using age-based Leslie matrices (Leslie 1945) of species vital rates (mortality and fecundity rates). The models also incorporated assessments of habitat quality as correlates of carrying capacity of the system to effectively forecast population trends within the engineered creek (Larson et al. 2004). Modelling was carried out using RAMAS® GIS software (Version 5).

Several cases (or scenarios) were developed and then simulated in RAMAS to represent varying site conditions used to predict the population abundance of the Rainbow Trout population. For the upper Hazeltine reaches, simulation results of the post-breach recovery condition were compared with pre-breach (baseline) population outputs, over a 35-year simulation period following the breach to evaluate the recovery of the Rainbow Trout population. For the lower Hazeltine and Edney Creek reaches, population simulation results for pre-breach and post-remediation were compared over a 40-year simulation period following the breach. A 40-year modelling timeline was used for these reaches to account for the additional years the creeks were closed for construction compared to the upper reaches.

The projected population abundance for each annual time step was compared for the pre-breach baseline conditions versus the post-breach remediation conditions for both upper and lower Hazeltine Creek, separately. Two scenarios were modelled to represent a range of baseline conditions (i.e., one scenario assuming an unobstructed creek for fish passage and one assuming major beaver obstructions on the creek), and two scenarios were modelled to represent a range of post-breach conditions (i.e., one scenario assuming that habitat quality was consistent between pre- and post-breach conditions, and one assuming that remediation efforts improved habitat qualities based on the results of the HSI modelling). These scenarios, summarized in Table 1, were applied to each population. As with the HSI modeling, post-breach scenarios with beaver dam presence were not considered for reasons described above.

Table 1. Summary of Population Viability Analysis Modeled Scenarios.

Scenario	Description	Comments
Scenario 1	Pre-Breach	Upper/Lower Creeks Unimpacted without Beaver Dams
Scenario 2	Pre-Breach Trajectory	Upper/Lower Creeks Impacted by Beaver Dam Obstruction
Scenario 3	Post-Breach Recovery	Upper Creek Fully or Partially Blocked (2014-19) Lower Creeks Fully Blocked (2014-21)
Scenario 4	Post-Breach Enhanced Recovery	Upper Creek Blocked for Construction (2014-19) Lower Creeks Blocked for Construction (2014-21) Remediated Habitat 30% Improved Over Pre Breach

The productivity of both the upper Hazeltine Creek and lower Hazeltine and Edney Creeks systems for Rainbow Trout has been identified by the HRWG as a key element of habitat rehabilitation, particularly in Hazeltine Creek upstream of the Canyon. In this context, a modelling approach was used to provide annual abundance estimates that can then be used to inform habitat offsetting budgets, in the context of evaluating what may be required to fully counterbalance losses in habitat productivity. To do this, demographic models were developed for Rainbow Trout using the PVA method (Akçakaya 2000, 2001, 2008; Larson et al. 2004) to project the recovery of Rainbow Trout populations in upper and lower Hazeltine Creek and lower Edney Creek into the future. Projections of modelled abundance included those for the as-constructed post-breach remediation case versus the historical baseline (Table 1). For each case or scenario that was examined using the PVA tool, simulations of age-based Leslie matrices (Leslie 1945) of species' vital rates (mortality and fecundity rates) were executed within RAMAS software. The abundance of fish per age cohort can be tracked numerically over time, providing a direct link to fisheries productivity (De Kerchove 2015).

3 RESULTS

3.1 Habitat Quality and Quantity

3.1.1 Rainbow Trout

The HSI model results indicated that all reaches in both upper and lower Hazeltine and Edney Creek were improved following remediation. As well, the field-engineered creeks both saw an increase in usable habitat area, thus providing potential to increase the carrying capacity and overall gain in habitat productivity of Rainbow Trout to restore the trout population following the breach.

The HSI score for all three reaches combined, based on a weighted average, was 1.3-times higher for post-remediation habitat versus pre-breach baseline habitat; the post-remediation HSI score was 0.746 versus a pre-breach baseline HSI score of 0.576 (Table 2). Assuming similar flow conditions and standardizing to baseline areas for comparison, the total WUA statistic was 14,799 HU for post-remediation habitat, versus 11,426 pre-breach HU of baseline habitat in upper Hazeltine Creek. This also equates to a 1.3-fold increase in HUs for the post-remediation habitat compared to pre-breach baseline conditions. The food supply component and riparian index were the only components with a lower score post-remediation when compared with baseline habitat. Indeed, these components will improve over time as the riparian vegetation grows and provides ecological functions related to food supply (Richardson and Moore 2010) but for the purposes of modeling recovery, it was conservatively held constant through the 35-year modeling period. Recent monitoring data indicates that Hazeltine Creek macroinvertebrates (fish food organisms) have recovered to a similar level of abundance and diversity (Minnow 2023) as pre-breach, which indicates that model outputs for the food supply component are likely to be underestimates, and therefore so too are the HUs constructed.

The HSI score for all reaches combined in lower Hazeltine Creek and Edney Creek, based on a weighted average, was 1.3-times greater for post-remediation habitat versus pre-breach baseline habitat. The post-remediation HSI score for lower Hazeltine and Edney Creeks combined was 0.766 while the pre-breach HSI score for above and below the Edney Creek confluence was 0.583. Assuming similar flow conditions and standardizing to baseline reach areas for comparison, the total WUA statistic was 4,057 HUs for post-remediation habitat, and 3,090 HUs pre-breach baseline habitat in the lower reaches of Hazeltine Creek. This also equates to a 1.3-times increase in HUs for the post-remediation habitat compared to pre-breach baseline conditions. The pre-breach baseline data does not account for Edney Creek separately but is a combined assessment of both creeks in the Lower Hazeltine habitat area.

As with upper Hazeltine Creek, the food component and riparian index scores for lower Hazeltine and Edney Creeks were lower than for pre-breach conditions, which is expected for a stream that continues to recover.

Table 2. Habitat quality and quantity metrics pre- and post-breach.

Habitat Metric	Habitat Location	Species Group	Pre-Breach	Post-Remediation	Factor of Difference
HSI Score	Upper Hazeltine	Trout	0.576	0.746	1.3
HSI Score	Lower Hazeltine	Trout	0.583	0.765	1.3
HSI Score	Lower Hazeltine	Salmon	0.22	0.28	1.3
Habitat Units	Upper Hazeltine	Trout	11,426	14,799	1.3
Habitat Units	Lower Hazeltine	Trout	3,090	4,057	1.3
Habitat Units	Lower Hazeltine	Salmon	208*	1656**	8.0

*Beaver dams present pre-breach
**Beaver dams absent post-remediation

3.1.2 Sockeye and Coho Salmon

The HSI value for lower Hazeltine Creek and Edney Creek, based on weighted average, was 1.3-times greater for post-remediation habitat versus pre-breach baseline habitat for Coho and Sockeye Salmon. The pre-breach HSI value for above and below the Edney Creek confluence was 0.22, versus the post-remediation HSI value of 0.28 for Hazeltine Creek and Edney Creek (Table 2).

The largest difference in calculated scores between pre-breach baseline and post-remediation habitat for the life stage components was the pool habitat, which was 2.67-times higher for post-remediation habitat. The canopy cover component was the only component with a lower score for post-remediation habitat versus baseline habitat. At the time of the 2021 drone survey, there was a significant portion of the area that was classified as grass or low shrub vegetation which does not provide overhead canopy cover. It is expected that the canopy cover and riparian index will increase as the riparian zones quickly regenerate after the breach and as a result of deliberate remediation efforts in and about the creek.

Assuming similar flow conditions, the total weighted useable area statistic for Coho and Sockeye Salmon increased under post-remediation conditions for all scenarios that were considered. This is similar to the results observed for Rainbow Trout in lower Edney Creek (WSP 2023). Under the baseline (pre-breach) scenarios, the weighted useable area ranged from a minimum of 208 HUs for the Baseline Beaver-Obstructed Scenario to a maximum 1,167 HUs for the Baseline Unobstructed Scenario. Under the post-remediation scenario, the WUA was 1,656 HUs for the Current post-remediation scenario, and up to 1,750 HUs for the future post-remediation scenario, when riparian habitat returns to conditions observed under the pre-breach baseline. This equates to an 8-fold increase in HUs for the post-remediation habitat compared to the pre-breach (baseline) beaver-obstructed condition.

The Baseline Beaver-Obstructed condition is the most plausible baseline scenario of the two scenarios for comparison, because pre-breach beaver dam presence was well documented, and there were no observations of Pacific salmon species above the obstructions. This indicated the dams were likely a significant upstream barrier to fish. The potential impact of the historical presence of the beaver dam network on lower Hazeltine Creek, as determined by GIS analysis, was described by an 83% reduction (i.e., loss of 959 HUs) in the productive capacity of habitat for Coho and Sockeye Salmon. However, under current conditions, beaver populations are not expected to re-establish on Hazeltine and Edney Creek in the near future as the riparian vegetation continues to recover. The hard substrate base of the creek channel, combined with the lack of fines (e.g., mud) are also expected to deter beaver dam-building activities throughout the creek. Therefore, upstream passage to the remediated habitat for Coho and Sockeye are likely to persist.

The Current Post-Remediation Scenario considered present creek conditions, including riparian habitat quality based on recent monitoring data. Recent aerial drone surveys indicate that there is currently a significant portion of the floodplain that is classified as grass or low shrub vegetation, which does not provide significant instream cover for fish, thus reducing the riparian habitat component scores of the HSI. As the canopy cover continues to grow, the riparian habitat component scores will increase, as the vegetation along lower Hazeltine and Edney Creeks will regenerate following the breach and subsequent remediation efforts. Higher component scores will ultimately translate into more weighted useable area.

3.2 Rainbow Trout Population – Projected Recovery

The HSI results, combined with the GIS outputs of accessible (unobstructed) habitat for spawning fish, were incorporated into the PVA models to quantify the relative change in the carrying capacity of the constructed habitat, post-remediation. Inputs for pre-breach carrying capacities included a reduced capacity due to the historical presence of beaver dams to a calculated hypothetical maximum capacity under unobstructed flow conditions in Hazeltine Creek, whereas inputs for post-remediation carrying capacities reflected full creek accessibility for spawning fish under a range of relative increases in habitat quality (i.e., no change, and an increase in habitat quality). The effects of the beaver dam obstructions on the projected population sizes can be best illustrated through a comparison of the outputs of pre-breach baseline scenarios (Scenarios 1 and 2).

The first pre-breach scenario, with the unobstructed condition for upstream movements of fish, projected approximately 130,000 fish at equilibrium for upper Hazeltine Creek and 7,800 fish at equilibrium for lower Hazeltine Creek and Edney Creek (Table 3). The second pre-breach scenario, which is the more realistic baseline prediction given the persistent blockage created by a network of beaver dams, projected approximately 49,000 fish at equilibrium in upper Hazeltine Creek and 1,500 fish at equilibrium in lower Hazeltine Creek and Edney Creek (Table 3). Both the initial abundance and carrying capacity were reduced in the second scenarios (compared to the first). This change, capturing the effects of a beaver dam obstruction for fish, also reduced the final abundance in the modeled period (Table 3) simulated in the second scenarios (Scenario 2 and 4) relative to the unobstructed scenarios (Scenario 3 and 4).

Table 3. Rainbow Trout final population estimates.

Habitat Metric	Habitat Location	Pre-Breach		Post-Remediation	
		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Population Size	Upper Hazeltine	129,803	49,069	129,482	159,401
Population Size	Lower Hazeltine	7,805	1,529	11,767	20,647

The PVA results presented below (Figure 2) focus on a comparison of trajectories, including those from pre-breach baseline scenarios (Scenario 1 and 2), versus post-breach remediation scenarios (Scenario 3 and 4; Table 1). Results are first presented in detail for the Polley Lake population in upper Hazeltine Creek, followed by a comparison of results, including recovery trajectories, for upper Hazeltine Creek and lower Hazeltine and Edney Creeks.

For upper Hazeltine Creek, the post-remediation models show that the recovery of the Rainbow Trout population begins at year 5 (i.e., 2018) when upper Hazeltine Creek is re-opened for spawning fish. Eventually, the increasing trend in annual population size surpasses the initial abundance input (43,203 fish) for the respective scenario, stabilizing or approaching equilibrium after 20 years into the future. As illustrated in Figure 2, the recovery trajectory under post-remediation conditions of improved habitat quality (i.e., Scenario 4) is visibly quicker than the trajectory that assumes that habitat quality remains similar to pre-breach conditions (i.e., Scenario 3). While both scenarios see population sizes projecting to exceed the initial abundance of fish by year 10, the increasing trend in population growth continues in Scenario 4 until year 25 when equilibrium is reached, whereas in Scenario 3, the population stabilizes by year 20. These extra years in population growth for Scenario 4 equate to a final simulated population size that is 1.3-times larger than Scenario 3.

For best comparison to baseline population predictions, both post-remediation scenarios were similar to the beaver dam obstructed baseline scenario with the exception that the effects of the breach were incorporated into the model, including the elimination of recruitment of young-of-year from 2014 to 2017. Immediately following the breach, the population simulated for Scenario 3 was reduced from 43,203 fish in 2013 to only 8,679 fish in 2014 (20% of the initial abundance). The reduction in population size continued as the creek access was closed for remediation work such that by year 4 (2017) of the simulation, the population size was reduced to 1,508 (3% of the initial abundance) for Scenario 3. The rate of decline for Scenario 4 was similar to Scenario 3 in the first four years following the breach, whereby the population of Rainbow Trout also declined to 3% of the initial abundance. The rate of decline for the post-remediation scenarios is primarily reflected by the immediate loss of young-of-year production over a 4-year period. These observations highlight the importance of early action in habitat construction.

In the upper Hazeltine reaches, the recovery projections for Rainbow Trout populations begin to stabilize approximately 20 years after the breach. For the lower Hazeltine and Edney creek, Rainbow Trout population sizes continue to fluctuate in both recovery scenarios for the duration of the 40-year modelling period. The modelled trajectory for lower Hazeltine and Edney Creek, relative to upper Hazeltine Creek, reflect not only the extended time the creeks were closed during construction (from year 1 to 7), but may also be influenced by the longer lifespan and delayed age at maturity in the Quesnel Lake population. Similar to the Polley Lake population, the recovery scenarios incorporating the breach show an overall increasing trend in abundance for the Quesnel Lake population. The population also shows cyclical increases in total abundance every eighth year of the simulation, followed by a minor decline in abundance the following four years of this cycle. The first spike in abundance occurs at year 8 (i.e., 2022) following the reopening of Hazeltine Creek. The magnitude of the population highs and lows in the cycle relative to the growing population abundance is directly linked to corresponding fluctuations in the number of spawning fish. For example, following the initial spike in 2022, the population decreases as the spawning cohort is reduced (less than 200) due to natural mortality and the time lag before new spawners arrive. In 2028, the first cohort that hatched following the reopening of lower Hazeltine Creek in 2022 reaches maturity, resulting in a second spike in abundance.

The predictive accuracy of modelled population sizes for post-breach scenarios was confirmed by calculating relative and absolute differences, with field-based abundance estimates in upper Hazeltine Creek from 2018 to 2021 (Minnow 2019, 2020). For young-of-year, relative differences in projected population sizes were only 6.9% higher for Scenario 3 and 11.3% higher for Scenario 4 across all five monitoring years combined (Figure 3). The net absolute difference over the five-year monitoring program was negative for both post-breach models, with a lower modelled abundance versus field-based abundance (i.e., 18,954 to 22,087 fewer fish). The post-breach models underestimated Young-of-Year (YOY) production for the first three years post-remediation, but overestimated YOY production during 2021 and 2022. Across the 5-year period, the largest relative difference between the projected abundance of YOY versus the field-based abundance estimate was in 2021, when densities of YOY measured in the field were lowest (e.g., densities in Reach 1 were 2 YOY per 100 m^2).

The difference in the PVA outputs versus field-data for young-of-year abundance (Figure 3) may reflect, in part, the effects of natural downstream outmigration beyond the sampled areas on the densities of young-of-year encountered in the field. The positive response by spawning fish to the opening of the creek and installation of fish habitat features may have also triggered intraspecific competition dynamics, leading to larger fish but reduced overall survival. As reported in Minnow (2020), despite the approximately 3.7-fold larger estimated number of YOY in 2018 compared to 2019, the difference in total biomass between the two years was relatively small (i.e., only 1.4-fold larger in 2018 than 2019).

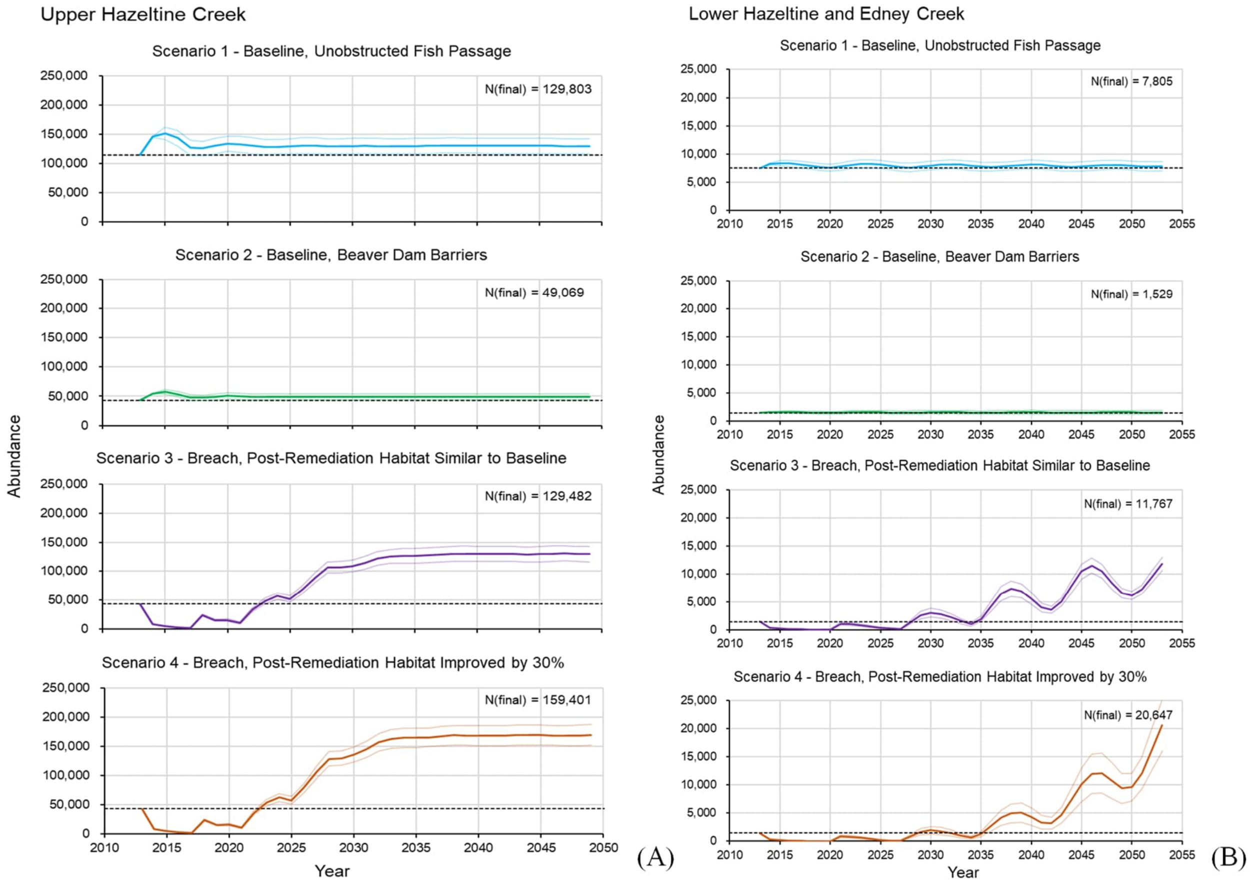

Figure 2: Rainbow Trout Annual Abundance Estimates for Upper Hazeltine (A) and Lower Hazeltine and Edney Creek (B) from Each PVA Scenario (Contours = ±1 Standard Deviation). Dashed line represents initial abundance in pre-breach conditions.

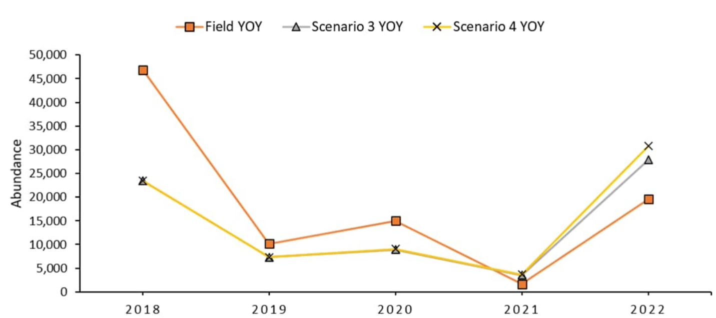

Figure 3: Comparison of Field-Based Estimates versus Model-Derived Estimates of Abundance for Young-of-Year (YOY) Rainbow Trout

4 SUMMARY AND DISCUSSION

Recent evaluations of baseline and post-breach conditions in Hazeltine Creek and Edney Creek concluded that constructed fish habitat is performing as designed and expected for Rainbow Trout populations (WSP 2023). Monitoring of adult Rainbow Trout has also described the successful return of spawning adults from Polley Lake to Hazeltine Creek to spawn during the spring seasons of 2018 – 2022 (Minnow 2022). Riparian vegetation is established, actively growing, and is providing overhead cover in upper sections of the creek where remediation efforts were first initiated after the breach (DWB 2022). Similarly, monitoring of lower Edney Creek by Minnow (2022) concluded that the constructed fish habitat is as good or better than unimpacted habitat and is effectively meeting design objectives. Based on fish usage and spawning survey data collected from 2016 to 2021, it appears that remediation objectives are being met for not only Rainbow Trout, but also Interior Fraser River Coho Salmon (Coho) and Sockeye Salmon (Sockeye) (Minnow 2022). Since the reopening of lower Hazeltine Creek to fall spawning fish, hundreds of spawning Sockeye Salmon have been observed each year since 2021.

The habitat quality and quantity that resulted from the construction is the product of a consultative process (HRWG) that established fish habitat species-specific funtional priorities through direct involvement in priority-setting and in the habitat design. The net gain in quantity and quality of fish habitat (Table 2) is the outcome of building the habitat to align with the priorities (fish species and life history use) and the functional elements (e.g., pools, riffles, large woody debris, etc.) of those designs.

Habitat productivity, quantified through modeling the size of the trout population and verified through comparison to directly measured population estimates, also showed a net gain (Table 3). This gain is likely to be an underestimate because some of the factors that control carrying capacity (e.g., riparian vegetation, canopy cover) are still on a growth and successional trajectory, which will increase the carrying capacity of the newly constructed habitat, and therefore the final population projection.

As of 2023, approximately 113 species of plants were identified in the Hazeltine Creek corridor including 9 tree species, 20 shrub species and approximately 84 herb species. In addition, an unrecorded number of mosses and lichens are also present. Vegetation cover is stable or increasing and appears to be resilient to dry periods. Species diversity is improved as a result of natural recruitment from adjacent unimpacted areas and the seedbank in the remaining soils. The vegetative cover is diverse and similar to early successional forest ecosystems in that area. Some limiting factors are still present and include small areas of compacted ground surface, and the presence of non-target species including agronomic ground covers that have naturally ingressed from unknown sources (DWB, 2024).

These results indicate a strong influence from natural processes in developing the existing plant community. Most species are emerging naturally, and the present community and soil conditions have been augmented by the initial planting. The results also indicate that self-sustaining vegetative communities have developed in many areas, and this is demonstrated by the ongoing recruitment and the presence of naturally ingressed plant species of various age classes.

Forecasting long term benefits to fish populations can be a challenge because of the many factors that may influence the productive capacity of habitat over time, including riparian habitat. Modelling population dynamics also requires a computed projection into the future of a natural population, and one that is subject to intermittent harvest by fishing and predation. This introduces “noise” into those predictions. In contrast, the HSI values and HUs are based on habitat as constructed and as directly measured. For regulatory purposes, such as quantifying gains and losses in habitat quality and quantity, the metrics based on direct measurements provide a more defensible, even if conservative, basis for doing so. The net gain in fish habitat resulting from the remediation work at the Mount Polley Mine is at least 1.3 times higher than the loss.

The quantitative assessment presented here demonstrates that major tailings failures can be successfully remediated, and the benefits of that remediation quantified.

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