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RESEARCH ARTICLE

Identifying a pathway towards recovery for depleted wild Pacific salmon populations in a large watershed under multiple stressors

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Abstract

1. Pacific salmon (*Oncorhynchus* spp.) support coastal and freshwater ecosystems, economies and cultures, but many populations have declined. We used priority threat management (PTM), a decision-support framework for prioritizing conservation investments, to identify management strategies that could support thriving populations of wild salmon over 25 years. We evaluated the potential benefits of 14 strategies spanning fisheries, habitat, pollution, pathogens, hatcheries and predation management dimensions on 19 conservation units (CUs)—genetically and ecologically distinct populations—of the five Pacific salmon species in the lower Fraser River, British Columbia, Canada.
2. The PTM assessment indicated that under the current trajectory of 'business as usual', zero CUs were predicted to have >50% chance of thriving in 25 years. Implementation of all management strategies at an annual investment between 45 and 110 million CAD was, however, predicted to achieve >50% chance of thriving for most CUs (n = 16), with nearly half (seven CUs) having a > 60% chance, indicating there is a pathway towards recovery for most populations if we invest now. In fact, substantial gains could be made by investing in five

combined habitat strategies, costing 20M CAD annually. These habitat strategies were estimated to bring 14 of 19 salmon CUs above this 50% threshold.
3. Co-governance between First Nation and provincial and federal Canadian governments to manage salmon populations and harvest, and improved CU-level monitoring emerged from the expert elicitation as critical 'enabling' strategies. By improving the feasibility of different management options, co-governance brought an additional five CUs above the 60% threshold.
4. *Synthesis and applications*. Supporting wild salmon in the face of cumulative threats will require strategic investment in effective management strategies, as identified by this priority threat management (PTM) assessment. PTM uses the best available data to objectively assess the potential outcomes of management alternatives. With renewed commitments from provincial and federal Canadian governments to protect and restore salmon populations and their habitats, positive conservation outcomes following implementation of targeted management strategies may be within reach.

KEYWORDS
conservation decision science, cross-realm research, fisheries, Fraser River, habitat restoration, Pacific salmon, priority threat management, resource management

1 | INTRODUCTION

As biodiversity loss outpaces conservation efforts globally, timely implementation of conservation action is a key challenge of our time (WWF, 2020). Three principal issues can lead to failed species recovery: insufficient funding for recovery actions (Buxton et al., 2020), delays in action (Martin et al., 2012) and conflicts of interest between social-economic values and conservation (McCune et al., 2013). Migratory fishes such as Pacific salmon *Oncorhynchus* spp. exemplify these issues. These species pass through multiple ecosystems and jurisdictions throughout their life cycle, and exhibit high natural variability in their productivity that can mask patterns of decline, making recovery challenging (Gayeski et al., 2018; Malick et al., 2017). Wild Pacific salmon are foundational to the spiritual, cultural, subsistence and economic practices of Indigenous peoples throughout the coastal region of the Northeast Pacific (Garibaldi & Turner, 2004). They support commercial and recreational salmon fisheries in the Northeast Pacific ocean averaging nearly five billion USD in valued output, three billion USD in Gross Domestic Product, and create over 39,000 Full Time Equivalent jobs annually to the United States and Canadian economies combined (Gislason et al., 2017). Despite this, in recent decades the overall abundance and fisheries catch of Pacific salmon in British Columbia (BC) have declined, putting these ecosystems and cultures at risk alongside the salmon themselves (Argue et al., 1983; Beamish et al., 2004; Reid et al., 2022). Population diversity has also been declining (Price et al., 2021; Slaney et al., 1996). Conditions leading to the decline and repressed recovery of Pacific salmon are complex and interacting (Cohen, 2012a; Sobocinski et al., 2018; Figure 1), and in Canada management bodies charged with salmon governance, including recovery initiatives are also responsible for supporting harvest interests. This conflict has contributed to the slow reaction of management bodies to address these pressures (Cohen, 2012b).

The Fraser River, BC, is one of the major systems in the Northeast Pacific where several salmon populations are now at historic lows (DFO, 2020a; Reid et al., 2022). The Fraser River supports five Pacific salmon species found in Canadian and US waters and historically produced more salmon than any other river on the Pacific coast (Northcote & Atagi, 1997). The lower Fraser River is the bottleneck through which all Fraser salmon travel and is part of the traditional and unceded territories of more than 30 First Nations, who have relied on the Fraser and its network of tributaries for harvest, trade and other cultural practices for millennia. Aside from salmon, the region supports the majority of BC's population and agricultural output, as well as Canada's most active port (Port of Vancouver), and a large international airport (Groulx et al., 2004). As a result of agricultural, urban and industrial development, 85% of the wetlands and floodplain have been lost to diking, draining and ditching, 64% of the streams have been lost or are inaccessible because of dams, floodgates and road culverts, and surrounding forests have been logged, culminating in the loss of significant salmon habitat (Birtwell et al., 1988; Boyle et al., 1997; Finn et al., 2021). In response to the cumulative impacts to salmon and their habitats since colonialization, there is increasing interest in developing new governance frameworks grounded in Indigenous stewardship practices and laws (Atlas et al., 2021; Carlson et al., 2001; Gayeski et al., 2018). In particular, a framework that can support government mandates for wild salmon recovery by providing a rapid assessment of management

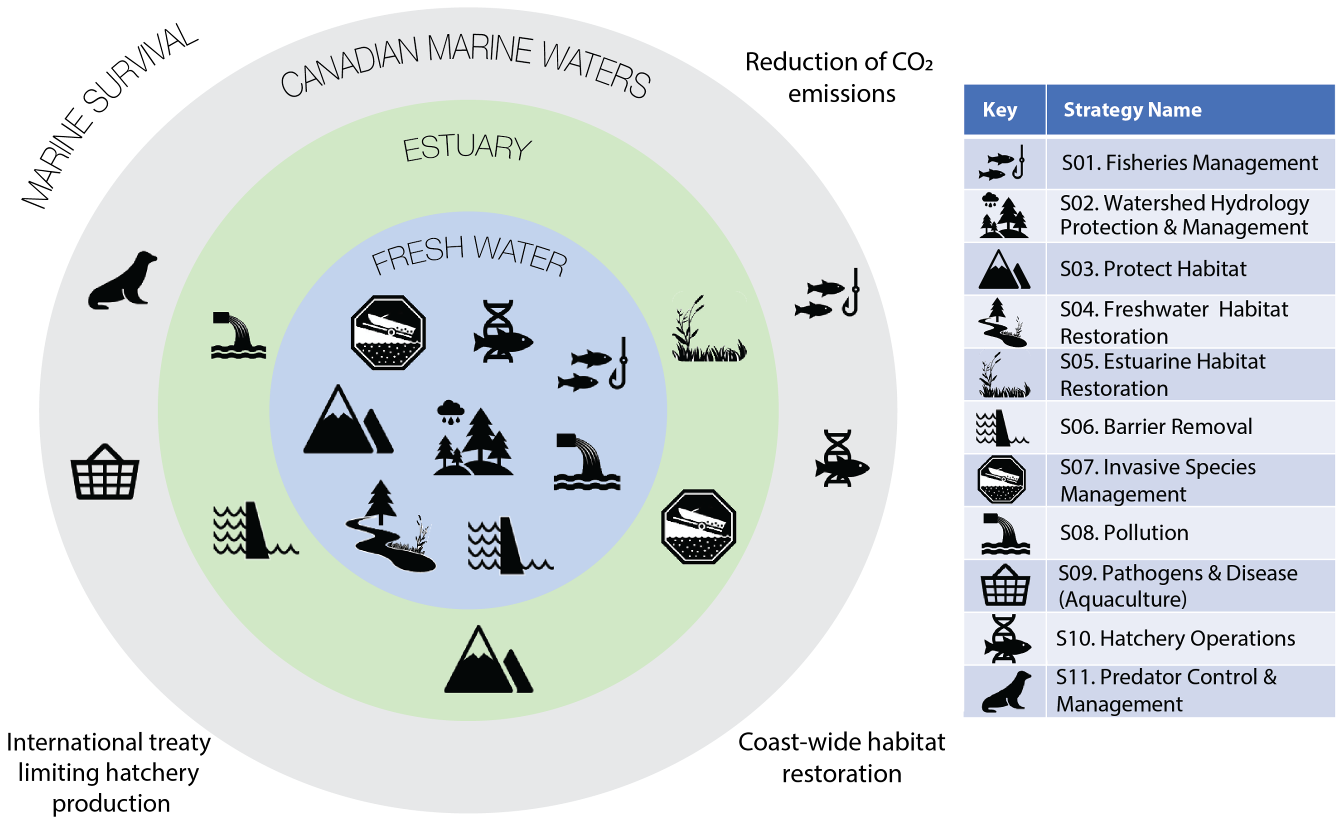


FIGURE 1 Schematic of threats and management tools for Pacific salmon in the lower Fraser River region by habitat. The inner circle (blue) represents available strategies within the realm of freshwater habitat. The next circle (green) represents strategies within the estuary realm, followed by strategies within the nearshore marine realm (grey). Icons represent 11 management strategies identified in this project (Table 1) and are repeated where they apply across realms. Several strategies which influence marine survival were not included in this study due to their international scope, including global reduction of greenhouse gas emissions to reduce the impacts of climate change, international treaty negotiations to minimize hatchery–wild interactions, and large-scale habitat restoration spanning the North American Pacific coastline.

strategies to guide strategic conservation investments is urgently needed.

Impacts to Pacific salmon can be addressed by identifying the actions that will lead to the greatest benefit to populations for the least cost to society. Priority threat management (PTM) is a conservation decision-science framework that enables prioritization of cost-effective conservation actions for species recovery (Carwardine et al., 2019). By structuring the problem and designing actions to meet clear objectives, it can facilitate discussion and engagement among diverse user groups under a shared goal (Carwardine et al., 2019). The process also reveals the return on investment for conservation action, thus providing a decision aid for decision-makers, and facilitating more rapid uptake (Martin et al., 2018). In this study, we apply the PTM framework to identify and evaluate a suite of management strategies intended to support wild salmon populations that spawn in the lower Fraser River region. Our research integrates the expertise of Indigenous and local knowledge holders, fishers, fisheries scientists and managers, and conservation practitioners to identify the most cost-effective management alternatives to achieve recovery of wild Pacific salmon in the Fraser River. While this is not the first application of PTM to Pacific Salmon (Kehoe et al., 2020; Walsh et al., 2020), it demonstrates that PTM can be applied to complex systems involving migratory species affected by multiple stressors with complicated and evolving governance structures.

2 | MATERIALS AND METHODS

We identified management alternatives available to 19 Conservation Units—ecologically and genetically distinct groupings of salmon—(CUs) in the lower Fraser River and assessed their benefit, cost and feasibility following the PTM framework (Figure 2; Carwardine et al., 2019). PTM applies the steps of decision analysis, also called Structured Decision Making (PrOACT; Problem definition, Identifying Objectives, defining Alternatives, predicting Consequences, and evaluating Trade-offs; Hemming et al., 2022). We elaborate on each of these steps in the following sections. The process involved a 3-day workshop (held at the University of British Columbia November 13–15, 2019; see Appendix S1). Information required to inform each of the steps was collated prior to and after the workshop by the research team. We reached out to 104 knowledge holders with diverse perspectives and expertise in the ecology and management

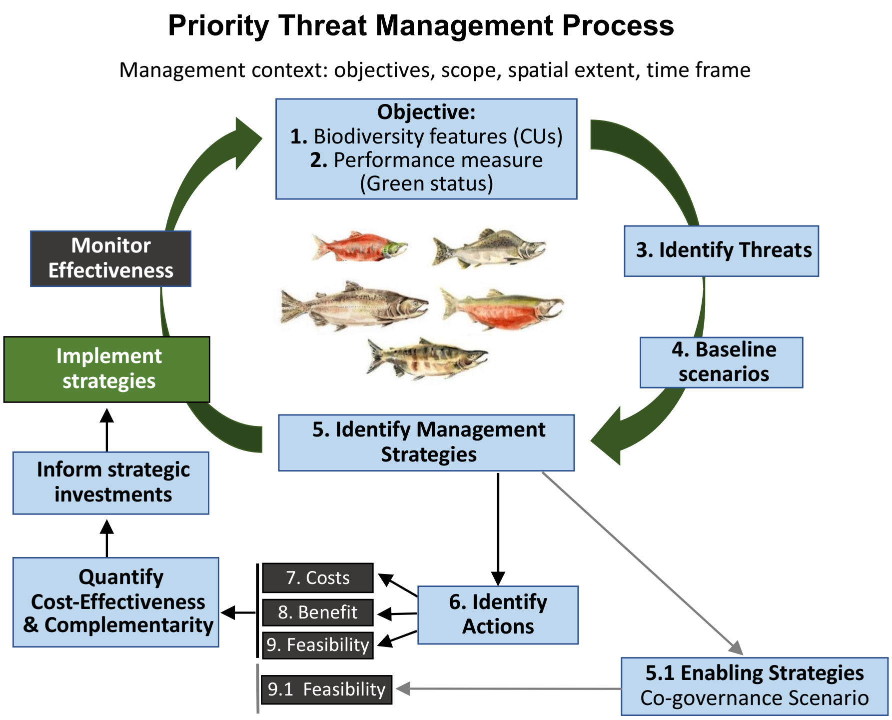


FIGURE 2 Overview of the key inputs for Priority Threat Management adapted from Carwardine et al. (2019). For a given objective and project scope (i.e. maximize the number of lower Fraser River salmon CUs that will achieve green status at the end of 25 years), threats are identified and the performance measure for each CU under baseline is assessed. Costs, benefits and feasibility are estimated for each strategy based on the component actions. In this study, a second feasibility estimate was elicited for a co-governance scenario. The costs, benefits and feasibility for each strategy are used to calculate the cost-effectiveness and complete the complementarity analysis, which provides the optimal management strategies to inform strategic investments for species recovery. Implementation should ideally follow an adaptive management process that monitors effectiveness according to the project objective. Illustrations of salmon species provided by the Pacific Salmon Foundation.

of salmon, of these 88 contributed to various aspects of knowledge gathering, 44 participants attended the workshop and 55 contributed to estimates of consequences (benefits, costs and feasibility) for each of the alternatives. The participants included First Nations, Canadian federal government, British Columbia provincial government, commercial fishing industry, recreational fishing industry, academic institutions, non-governmental organizations and independent experts.

Participation and data collection protocols followed in this study were approved by the University of British Columbia and University of Victoria and Human Research Ethics Board (permit H19-00267).

2.1 | Problem

The initial problem formulation was developed in consultation with knowledge holders prior to the workshop, and subsequently refined during the workshop. The problem was to identify the most cost-effective portfolios of actions to recover wild salmon in the lower Fraser River region, which we defined as the Fraser River mainstem and tributary watersheds west of Hope, BC (Figure 3). We included Boundary Bay CUs; although they use tributaries that are not part of the Fraser River basin, the identified actions will also impact salmon in this area. Together, these watersheds comprise the portion of the 230,400 km^2 Fraser River basin most heavily impacted by anthropogenic development (Birtwell et al., 1988; Boyle et al., 1997). The lower Fraser region supports 19 salmon CUs (Table S2): six Chinook *Oncorhynchus tshawytscha*, one chum *O. keta*, three coho *O. kisutch*, one pink *O. gorbuscha*, and eight sockeye *O. nerka*, comprising 35% of all Fraser basin salmon CUs (Holtby & Ciruna, 2007). The governance structures of this region are diverse and complex, and there is no single decision-maker responsible for achieving this objective. The timeframe of 25 years was chosen as it encompassed multiple generation times for each species, allows for results of implemented actions to be detected, can be divided into time periods that align with regional management plans, and was within the realm of experience and reasonable prediction by the expert participants.

As part of the problem formulation, project leads (LC, CH and TM) prepared a summary of key threats to wild salmon CUs based on status assessments from the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), the Canadian Science Advisory Secretariat (CSAS) and other appropriate federal, provincial and local reports (see Appendices S1 and S2). We also used biological status assessments and evaluations of freshwater habitat threats for each CU provided by the Pacific Salmon Foundation via the Pacific Salmon Explorer tool (Figure S1; www.salmonexplorer.ca).

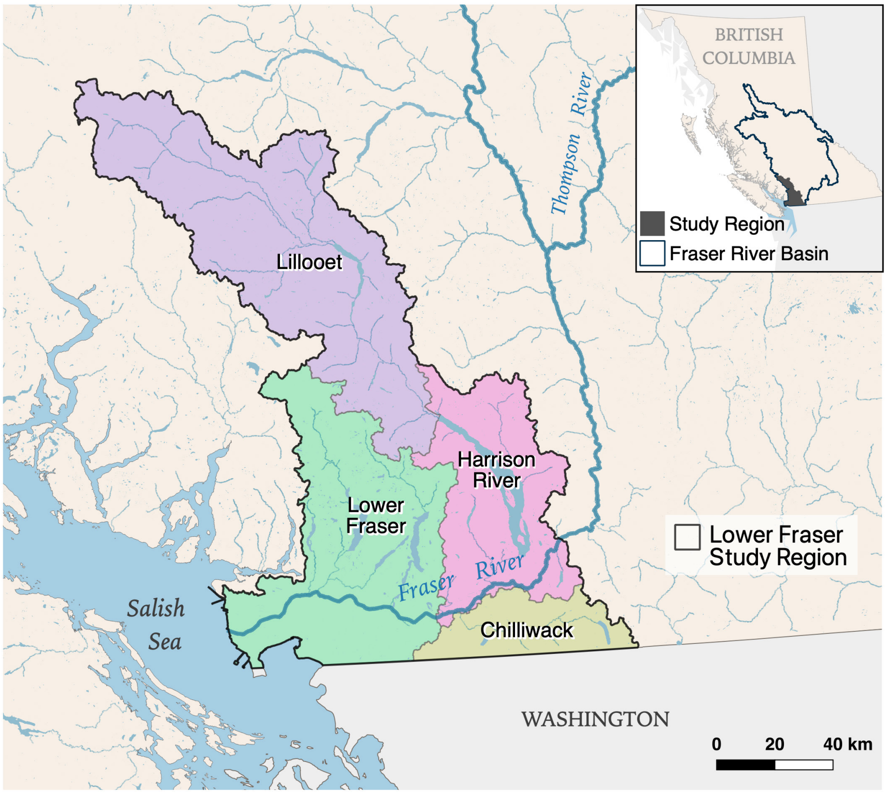


FIGURE 3 Map of the lower Fraser study region, including the Lillooet, Harrison River, Lower Fraser and Chilliwack River watershed groups in British Columbia, Canada. Inset map shows the boundary of the Fraser River basin, with the study area highlighted in dark grey. Data for watershed groupings obtained from the Freshwater Atlas (https://www2.gov.bc.ca/gov/content/data/geographic-data-services/topographic-data/freshwater).

We undertook a literature review to develop an initial set of actions that could be used to recover wild salmon in the lower Fraser. This list was circulated to workshop participants prior to the workshop, and subsequently refined during the workshop.

2.2 | Objectives

The primary objective of the assessment was to 'maximize the number of thriving lower Fraser salmon CUs', over a 25-year timeframe. A 'thriving' CU was defined as one in a state of relatively high abundance that fulfils its ecological function and role and provides livelihood opportunities for present and future generations. We assumed a thriving CU would be the equivalent of being assessed in the 'green status' zone under Canada's Wild Salmon Policy, where the need for conservation intervention is low and fishing is possible (Figure S2; DFO, 2005). Project objectives also included 'minimizing financial costs' (CAD) and 'maximizing feasibility' (a proxy objective that takes the product of probability of social acceptance and probability of technical success).

2.3 | Alternatives (management strategies)

The PTM assessment explores potential portfolios of actions and identifies the best portfolio(s) that can achieve the objectives for increasing levels of investment and increasing levels of certainty in the recovery of salmon. Prior to and during the workshop, participants identified a suite of 11 management strategies (portfolios of actions) that could abate threats to the salmon CUs in the lower Fraser region (Table 1; detailed in Appendix S1). Experts selected groups of strategies that if combined would likely have greater benefits than if implemented individually (combination strategies; Chadés et al., 2015). Two combination strategies were identified, the first, S12, combines fisheries management (S01), pathogens and disease (aquaculture; S09) and hatchery operations (S10). The second, S13 combines all habitat strategies (S02, S03, S04, S05 and S06), and a third combination strategy was assessed for all available management strategies combined (ALL). Two enabling strategies were also identified, which represent management strategies that have not been fully implemented to date, but which were considered to underpin the success of other strategies (detailed in Appendix S1). These were: improvements to salmon monitoring and assessment (ES1), and the formal establishment of co-governance structures between Indigenous and Crown governments (ES2). Enabling strategies were considered necessary to the future management of wild salmon in the region and were therefore not included in the prioritization. However, ES2 (co-governance) was predicted to impact the feasibility of implementing the strategies, and so feasibility was reassessed for each strategy under a scenario in which co-governance was implemented, and the complementarity analysis was run an additional time with these estimates (Table S5). Finally, to quantify the potential impacts from a suite of current major development proposals which were not included in the baseline (BSL), our analysis explored a second baseline scenario under which all these development projects are approved and completed (DEV BSL; Appendix S1).

2.4 | Consequences

We used structured expert elicitation to estimate benefits, feasibility and costs for the proposed management strategies (Hemming et al., 2018). Additional information for costs was gathered from published literature. Not all experts completed each stage of the elicitation process, however, 34/55 initiated the feasibility and cost estimates and 26/55 completed the benefits estimates. The number of expert benefits estimates ranged from a minimum of 13 to a maximum of 22 for each CU response to each strategy (Table S1). An additional 33 experts provided validations of cost estimates and resources that were not otherwise accessible. All analyses of the estimates were conducted in R version 3.6.2.

2.4.1 | Benefits

Experts used the background information provided including biological status, habitat pressures, trends in spawner abundance, harvest rates and hatchery releases, as applicable (CU background example Figure S1), as well as their own expertise to estimate the probability of each CU achieving green status at the end of 25 years (Appendix S2). They first estimated this under business as usual, including predicted pressures from ongoing human population growth, habitat loss and climate impacts to establish a baseline trajectory for each CU. Then they estimated the probability of green status assuming baseline conditions plus the implementation of each management strategy independently as well as the combination strategies. Finally, experts estimated the probability of achieving green status for the development baseline scenario, under which all proposed development projects are completed.

For each strategy, we calculated the expected benefit as the difference between the experts' best estimates of achieving green status with the strategy and the baseline, averaged across experts for each CU:

$$B_{ij} = \frac{\sum_{k=1}^{K_{ij}} \left(p_{ijk} - p_{0jk}\right)}{K_{ij}}, \quad (1)$$

where p_{ijk} is the probability of CU j being assessed as green status under strategy i as estimated by expert k, p_{0jk} is the probability of CU j being assessed as green status at baseline estimated by expert k, K_{ij} is the number of experts who provided estimates for CU j under strategy i and B_{ij} is the average benefit of strategy i for CU j. Benefit estimates were then weighted by the feasibility of each strategy to give the expected performance for each CU and strategy.

2.4.2 | Feasibility

For each action (h) identified within a strategy (i), experts provided an estimate of the probability that the action would have social-political support and be implemented, assuming funding was not a barrier ('uptake', U_{hi}) and the probability that, if implemented, the action would be technically successful (S_{hi}). The product of these two estimates created a feasibility score for each action:

$$F_{hi} = U_{hi} \times S_{hi}, \quad (2)$$

where F_{hi} is the feasibility of action h in strategy i. Feasibility estimates were then averaged across all actions for a given strategy. Combination strategy feasibility was calculated as the mean of all component strategy feasibilities. Experts then re-estimated the feasibility of each strategy with the establishment of an Indigenous-led co-governance framework (ES2, Appendix S1). The cost-effectiveness was then recalculated with the new feasibility estimates to quantify the potential effects of co-governance on salmon conservation.

2.4.3 | Costs

Initial annual costs of implementing each action over the 25-year period were estimated by the experts by asking them to consider the materials, equipment, labour, overhead or costs associated with planning, consultations or monitoring. Working through these cost details encouraged experts to consider all elements of implementation for a given strategy and helped to refine actions where necessary. We conducted follow-up research to validate these data, then converted the annual costs of each action to present day values using a discount rate of 4%, in line with recommendations on social discounting rates in Canada (Boardman et al., 2010). These estimates were then summed to determine the total cost of implementing each management strategy over 25 years (Table S4). Combination strategy costs were calculated by summing the costs of each component strategy.

2.5 | Trade-offs

We used multi-objective optimization to explore the best portfolio of management strategies that would maximize the conservation benefits of management across the populations of interest for incremental investment scenarios (Chadés et al., 2015). This approach accounts for the complementarity of alternative management strategies by considering the number of CUs that achieve our objective of green status with a given probability. We defined the minimum conservation threshold as >50% chance of achieving green status and explored threshold values of >60% and >70% based on the range of performance estimates. We performed the complementarity analysis (Chadés et al., 2015) for each threshold by solving the linear programming problem:

$$\max \sum_{i=1}^{S} \sum_{j=1}^{CU} P_{ij} x_i, \text{ subject to } \min \sum_{i=1}^{S} C_i x_i, \quad (3)$$

where $P_{ij} = 1$ if CU j exceeds the conservation threshold under strategy i, and $P_{ij} = 0$ otherwise; C_i is the total cost of implementing

TABLE 1 Overview of strategies considered in the prioritization for threat management of 19 Pacific salmon conservation units in the lower Fraser region. The complete list of actions and supporting details can be found in the SI. Benefits assessments assumed all actions were completed for each strategy. Strategies were assumed to be implemented within the 25-year project timeline, although estimated start and completion years varied

Strategy name	Key	Abridged summary of actions
Fisheries Management	S01	• Conduct assessments of salmon vulnerability to the impacts of climate change for all CUs and incorporate these into management procedures • Identify, develop and enforce best practices that reduce bycatch and incidental mortality of non-target CUs to minimize collateral mortality in fisheries • Support the development of Tier 1 (Nation to Nation) and Tier 2 [First Nations to Fisheries and Oceans Canada (DFO)] forums for exploring how food, social and ceremonial fisheries allocations can be distributed within First Nations communities
Watershed Hydrology Protection and Management	S02	• Develop and implement strategic watershed plans, including updated regulations, to maintain natural hydrological processes and patterns
Protect Habitat	S03	• Identify habitat requirements needed to support thriving salmon CUs and designate priority habitats for conservation/protection • Prevent the expansion of footprints of known habitat stressors into moderate- to high-quality habitat
Freshwater Habitat Restoration	S04	• Develop a central database of salmon restoration projects to highlight gaps and overlaps in the region • Identify and restore priority freshwater sites that support, or directly or indirectly impact, salmon and their spawning, rearing and migration habitats
Estuarine Habitat Restoration	S05	• Identify and restore priority estuarine sites
Barrier Removal	S06	• Upgrade flood control infrastructure at key access points to be salmon friendly • Upgrade and restore connectivity to culverts, sloughs and estuarine jetties prioritized to benefit fish passage
Invasive Species Management	S07	• Implement applied research findings into ongoing surveillance and management of invasive species to reduce impacts to juvenile salmon and their habitats
Pollution	S08	• Implement planned wastewater treatment upgrades to Iona Island and Annacis Island facilities • Revise and implement legislation to incorporate total amount limits as well as timing restrictions to reduce pollutants. Implement targeted legislation to ban copper and other heavy metals in brake pads in British Columbia
Pathogens and Disease (Aquaculture)	S09	• Phase out open-net pen salmon aquaculture • Increase the frequency and scope of pathogen screening on fish farms and implement proactive sea louse treatment regimes to better control sea lice populations and pathogens in farmed finfish • Increase surveillance of wild salmon in both freshwater and marine environments to better understand harmful pathogen loads, and potential links of these to aquaculture and hatchery fish
Hatchery Operations	S10	• Develop a revised lower Fraser regional hatchery strategy in an adaptive management framework to manage hatchery–wild interactions in conjunction with CU-specific enhancement targets • Evaluate the fisheries interactions, biological and ecological risks to wild lower Fraser salmon from Fraser River and Salish Sea hatchery production • Develop robust evaluation criteria for the implementation of conservation enhancement of at-risk CUs in the lower Fraser River
Predator Control and Management	S11	• Conduct experimental fishery (or traditional First Nations harvest) of pinnipeds in an adaptive management framework to assess the impacts of pinniped predation on salmon populations
Fisheries and Aquaculture and Hatchery Combined	S12	• All actions under S01, S09 and S10 implemented in concert
All Habitat Strategies Combined	S13	• All actions under S02, S03, S04, S05 and S06 implemented in concert
All Strategies Combined	ALL	• All actions under all strategies implemented in concert

strategy i; x_i is a binary decision variable that indicates whether a strategy i is selected (1) or not (0); S is the total number of strategies and CU is the total number of Conservation Units. The complementarity analysis assumes that the benefit of implementing two individual strategies, that is, the number of CUs secured, is equivalent to the maximum of the two values (and not the sum). For each addition of funding, the strategy or combination of strategies that secured the maximum number of CUs above the conservation threshold was selected, such that the optimal strategy or set of strategies secures the most CUs per dollar invested (Table 2). This analysis was conducted using the consOpt package in development (Nicolai Cryer, n.d.) and validated manually in Microsoft Excel.

2.5.1 | Uncertainty

We examined the effect of uncertainty in the benefit, feasibility and cost estimates on the resulting optimal strategies (Appendix S3; Table S3; Figures S3–S7). To further examine the effect of uncertainty in benefit estimates, we performed the complementarity analysis using the most optimistic and pessimistic estimates, which represent the most extreme outcomes within the realm of possibility predicted by the experts in this study (Table S3; Figure S3; Figure S4). The high capital costs of two wastewater treatment facility upgrades, which have been under consideration for over a decade, led us to assess two scenarios for the pollution strategy (S08): one with the capital costs of these projects assumed by municipal budgets (Figure S7), and one with them included in our assessment (primary results).

3 | RESULTS

Under 'business as usual' (i.e. baseline) all 19 salmon CUs in the lower Fraser study region were predicted to have <0.5 probability – or <50% chance—of achieving green status in 25 years (maximum 45%; BSL in Table 2). If all proposed development projects for the region were approved (development baseline scenario), these predictions declined further by 3%–9% to a maximum of 39% chance (DEV BSL in Table 2). In contrast, implementing all identified management strategies would bring most salmon Conservation Units, 16 of 19 CUs, above a 50% chance of green status for an estimated cost between 45 and 110 million Canadian dollars per year (Table 2; Figure 4). The combination of all habitat strategies (i.e. S02, S03, S04, S05 and S06) resulted in 14 of 19 CUs surpassing the 50% threshold (with three >60%) for an investment of 20M CAD per year (S13, Figure 4). For a smaller budget of 2.5M CAD per year, improved fisheries management (S01) brought half of these salmon CUs that were secured via S13 ($n = 7$) above the 50% threshold. Below 10M CAD annually several strategies had similar conservation outcomes at a higher cost, so were not identified as optimal strategies by the complementarity analysis (e.g. S10 hatchery operations, Table 2).

Out of the 19 CUs assessed, Fraser River (odd year) pink salmon and Pitt early summer sockeye salmon most easily surpassed the 50% conservation threshold with the implementation of a given strategy (Table 2). Conversely, Lillooet/Harrison late sockeye salmon and Lower Fraser Upper Pitt summer 1.3 Chinook salmon only surpassed the threshold with all strategies implemented (ALL, Table 2). Coho salmon had the largest improvements from implementation of all strategies (28% increase from baseline in the likelihood of achieving green status for Boundary Bay and 26% increase for Lower Fraser and Lillooet CUs, Table 2).

When each strategy was assessed with an Indigenous-led co-governance framework in place (ES2), the predicted feasibility of successful implementation increased by an average of 14% per strategy (Table S5). This improved the expected performance of the strategies, so an additional CU (Harrison upstream late (Weaver) sockeye salmon) achieved >50% chance of green status and 12 CUs achieved >60% chance of green status with all strategies implemented, as compared to seven CUs >60% without co-governance (Figure 5; Table S5).

Considering the most pessimistic and most optimistic benefit estimates in the complementarity analysis emphasized similar optimal strategies to the best estimates (Table S3). In the optimistic scenario an additional strategy was selected (hatchery operations, S10) and the number of CUs at each conservation threshold increased, such that a total of 18 CUs achieved >50% chance of green status with most >60% (six CUs between 60% and 70% and 11 CUs >70%) when all strategies were implemented (Figure S3). Conversely, under the most pessimistic scenario no salmon CUs achieved >50% chance of green status even with all management strategies implemented (Figure S4). The priority strategies identified by the complementarity analysis were unaffected by estimated changes to benefit, feasibility and cost estimates, despite some sensitivity in cost-effectiveness scores (Figures S5 and S6). The results were affected by an alternative scenario in which we assumed that the costs of improving wastewater facilities (pollution control, S08) would be borne by municipalities (Table S4 values in parentheses; Figure S7); however, the top two strategies (combined habitat strategy S13 and ALL) remained the same.

4 | DISCUSSION

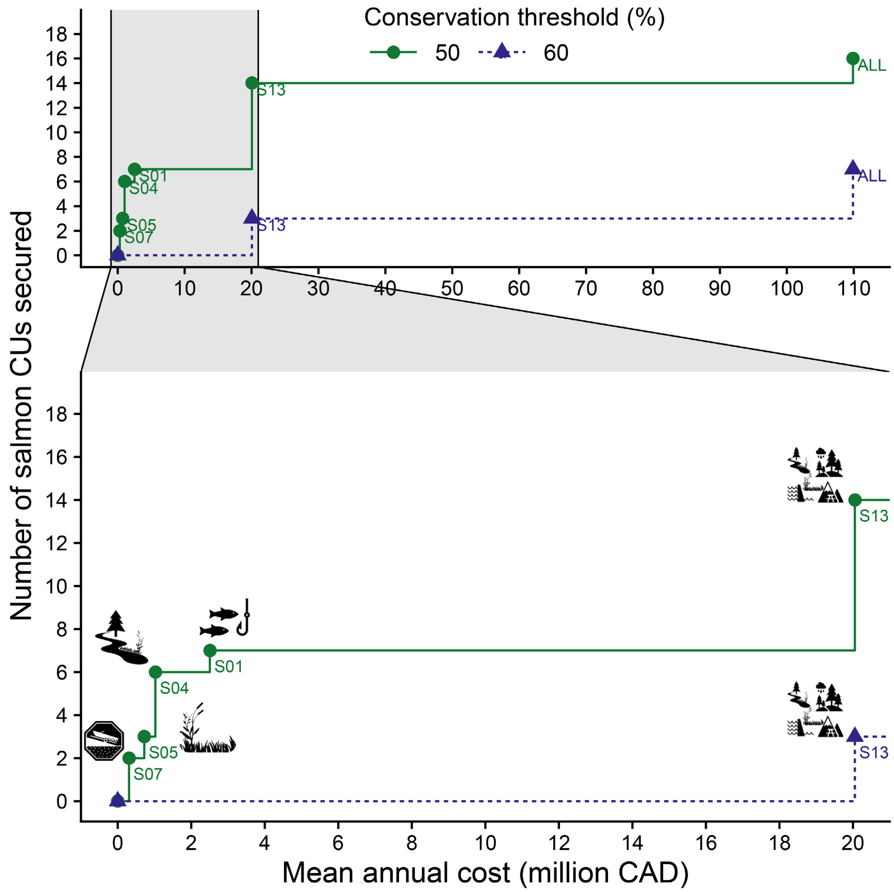
Our study provides support, and a pathway forward, for the comprehensive management of wild salmon ecosystems at a watershed scale, which has been increasingly called for (Atlas et al., 2021; Connors et al., 2020; Gayeski et al., 2018). Despite two CUs currently doing well (Harrison (River type) and Pitt early summer sockeye salmon CUs were assessed as green status (DFO) and not at risk (COSEWIC) in 2018; Table S2), none of the 19 CUs in this study were predicted to be in green status in 25 years if we continue the trajectory of 'business as usual'. If a 'development baseline' scenario is realized, involving the approval and completion of several major development proposals in the lower Fraser, the likelihood of

TABLE 2 Conservation optimization showing the expected chance of each CU[a] achieving green status at the end of 25 years under each strategy (>49% light grey, >50% medium grey, >60% dark grey). Cut-off for threshold (and shading) applied prior to rounding. BSL, baseline; DEV BSL, development baseline scenario

Conservation unit	BSL	DEV BSL	S07 *Inva*	S05 Est	S10 *Hatc*	S04 *Frsh*	S02 *Hydr*	S01 *Mgmt*	S11 *Pred*	S06 *Barr*	S03 *Prot*	S09 *aqua*	S13 *Hab*	S12 *mgt*+	S08 poll	ALL
			Strategy (sorted by annual cost, low to high)													
Chinook																
Boundary Bay Fall 0.3	27	22	38	39	37	42	39	38	37	42	38	36	53	46	42	53
Lower Fraser Fall 0.3	41	37	46	53	50	52	49	50	51	52	51	49	62	59	54	64
Lower Fraser Spring 1.3	37	33	42	46	45	47	46	48	46	47	46	43	58	54	47	59
Lower Fraser Summer 1.3	39	34	43	46	47	48	47	50	47	47	46	45	57	54	46	59
Lower Fraser Upper Pitt Summer 1.3	28	24	32	35	37	39	37	37	38	36	36	34	49	44	36	51
Maria Slough Summer 0.3	32	28	37	42	40	43	42	43	41	41	42	38	54	48	43	56
Chum																
Lower Fraser	40	32	47	49	49	53	50	50	48	53	50	47	59	54	51	61
Coho																
Boundary Bay	25	18	37	38	40	43	38	35	37	43	37	36	50	42	42	53
Lower Fraser	33	25	39	41	44	48	45	42	45	48	44	40	56	49	46	59
Lillooet	33	28	39	44	45	47	45	45	45	48	47	43	56	51	47	59
Pink																
Fraser River	45	39	50	52	52	54	51	53	51	54	54	51	63	59	55	64
Sockeye																
Chilliwack Early Summer	41	33	46	46	47	50	47	50	48	49	48	46	54	55	51	61
Cultus Late	14	11	20	17	19	22	18	23	19	19	20	17	25	25	24	30
Harrison Down Late (Big Silver)	42	33	46	46	48	51	48	51	50	49	50	48	56	54	50	61
Harrison (River type)	43	36	48	50	50	53	50	52	51	51	51	49	57	56	54	62
Harrison Up Late (Weaver)	26	23	31	32	34	36	34	38	34	36	35	33	43	42	36	48
Lillooet/Harrison Late (Birkenhead)	31	26	36	38	40	41	37	41	41	41	39	38	45	46	41	51
Pitt Early Summer	45	37	50	54	54	53	52	53	55	53	52	54	61	58	56	64
Widgeon (River type)	23	17	28	29	28	29	27	31	28	29	29	28	35	35	32	40
Feasibility	NA	NA	0.71	0.70	0.67	0.69	0.68	0.70	0.70	0.73	0.64	0.57	0.69	0.64	0.81	0.69
Annual Cost (million CAD) *(values with costs of facilities excluded)*	NA	NA	0.31	0.72	0.76	1.02	2.08	2.51	3.62	6.19	10.0	18.5	20.1	21.7	64.2 (*0.14*)	109.9 (*45.8*)

[a]CU nomenclature uses unique geographic location and as needed, other distinguishing characteristics such as run timing, depending on the species. For Chinook salmon, which have the most detailed CU names, the format is 'geographic location - season of adult return - dominant age of returning adults' using the European age designation system (Koo, 1962), for example, 'Lower Fraser - Fall - 0.3'.

FIGURE 4 The number of lower Fraser River salmon Conservation Units (CUs) that were predicted to achieve >50% (solid dark green line) or >60% (dashed dark blue line) chance of green status by implementing the optimal set of strategies for a given budget. Top: all optimal strategies. Bottom: optimal strategies between 0 and 20 million CAD magnified for clarity. ALL indicates all management strategies combined. Note that no CUs achieved a greater than 70% chance of being assessed as green status at the end of 25 years.



achieving green status further declines. Conversely, investment in a suite of management strategies at a cost of 45M annually (and up to 110M if wastewater treatment upgrades are included) improves the outlook for lower Fraser salmon, with >50% chance for 16 of 19 CUs to be assessed as green status in 25 years. Developing and implementing an Indigenous-led co-governance framework for wild salmon improved the likelihood of achieving green status for all CUs and brought one additional CU above the 50% threshold. Our results illustrate the plight of wild Pacific salmon in this region, the challenges posed by cross-realm ecosystem management (Camaclang et al., 2021), and the limitations of regional management to fully abate the myriad threats to these CUs.

Of the regional strategies examined, investment in a combination of five habitat strategies consistently benefitted the most CUs. Fourteen CUs, including all three coho salmon CUs, had >50% chance of achieving green status with extensive habitat conservation costing an estimated 20M CAD annually. Recent estimates of habitat loss for salmon in the lower Fraser indicate that up to 85% of the floodplain and 64% of the stream habitat has been lost entirely or is no longer accessible (Finn et al., 2021; Groulx et al., 2004). While significant restoration efforts have been made in the lower Fraser, most of these projects have been on a scale insufficient to achieve desired outcomes (Levings, 2004).

To achieve the full potential of these combined habitat strategies would require a system-wide change in habitat management for the lower Fraser, including implementing stringent watershed hydrology management plans, protecting remaining salmon habitat via a combination of land acquisition and restriction of industrial footprints, and strategically restoring riparian areas, instream habitat, wetlands and tidal marsh, including significant barrier removal. These strategies are complex and some, such as watershed hydrology management plans, are emerging practices with few regional examples. However, numerous watershed governance projects have been initiated in BC and both funding sources and guidance documents to support these projects are increasing (Hunter et al., 2014; Okanagan Basin Water Board, 2010; Polis Project on Ecological Governance, 2019; Tawaw Strategies, 2021). To avoid common pitfalls of failed restoration attempts practitioners must carefully consider the site-specific objectives, capacity and current and future conditions (Beechie et al., 2010; Beechie et al., 2013; Lievesley et al., 2017; Roni et al., 2011). Estimates of the probability of technical success of these restoration strategies ranged from 70% to 100%, however, incorrect procedure can easily result in complete failure to achieve the biological objectives (Lievesley et al., 2017). Improvements to connectivity are likely to have high efficacy and long-term benefits for multiple species, but freshwater habitat restoration projects including riparian and instream enhancements are far more variable in their effectiveness and longevity and should be carefully considered in the regional context prior to implementation (Beechie et al., 2013; Roni et al., 2011). While other studies have estimated higher costs for

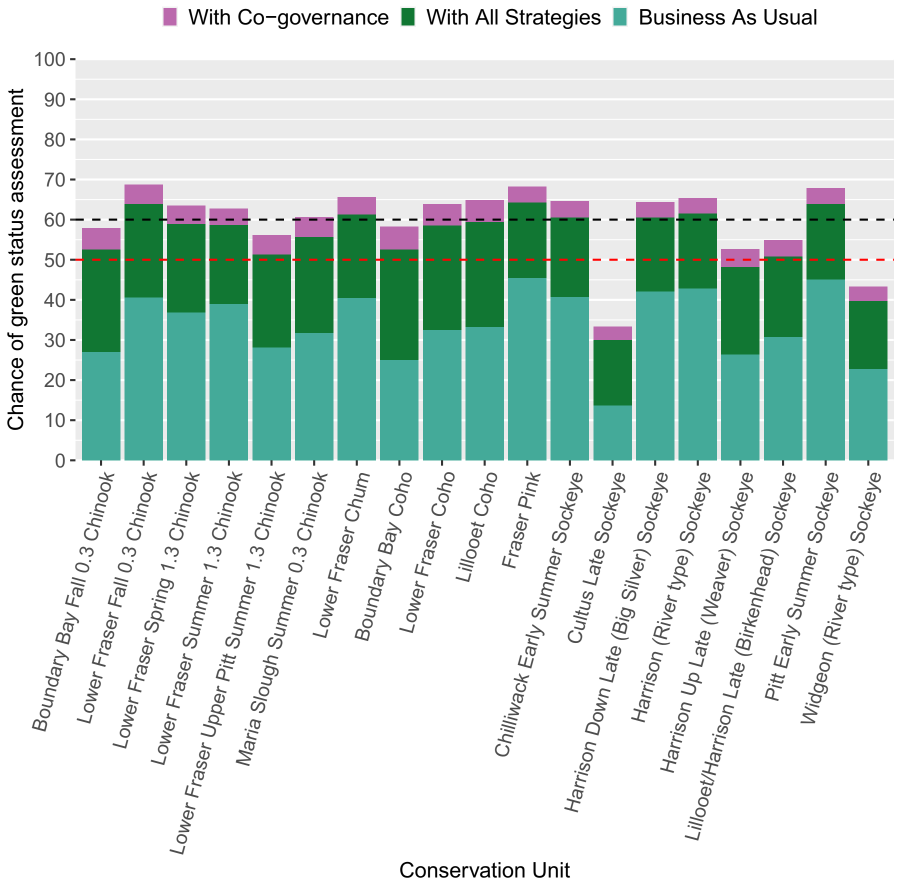


FIGURE 5 Estimated chance of achieving green status for each of 19 Conservation Units under increasing levels of investment over 25 years. The conservation thresholds of 50% (red) and 60% (black) are highlighted with dashed lines. Business as usual (turquoise, light) represents probabilities under no additional management; with all Strategies (green, dark): all management strategies implemented; with co-governance (magenta, medium): implementation of Indigenous-led co-governance (detailed in SI) in addition to all management strategies.

aquatic habitat restoration (i.e. Walsh et al., 2020), identification of habitat restoration as a priority strategy was robust to uncertainty in costs according to the sensitivity analyses. In addition, this study benefitted from cost and feasibility data provided by local restoration practitioners, who have successfully completed similar component projects, to inform the most likely scenario for this regional context. However, even if restoration costs were severely underestimated, applying costs such as those estimated by Walsh et al. still results in the combined habitat strategy (S13) remaining a priority due to its high estimated benefits to 14 CUs.

The costs of implementing these strategies do not account for the co-benefits they provide, which could offset the up-front economic costs (i.e. Barbier et al., 2011; Rees et al., 2020). Watershed management and restoration in BC provided an estimated 4200 jobs and contributed 432M CAD to the GDP in 2019, suggesting it can be an important contributor to the economy (Delphi Group, 2021). Additional co-benefits associated with regulating, provisioning and cultural services are also likely to arise. For example, extensive habitat restoration may alleviate some of the multiple threats faced by other Fraser River salmon (54 CUs), protecting existing diversity (Bottom et al., 2005), and in turn increase resilience to 'press and pulse' disturbances such as climate change and landslides (Hilborn et al., 2003; Moore et al., 2014; Schoen et al., 2017). In addition, 102 species at risk identified within the Fraser River estuary (Kehoe et al., 2020), including other aquatic species such as white sturgeon (*Acipenser transmontanus*), Nooksack dace (*Rhinichthys cataractae*) and Salish sucker (*Catostomus* sp. cf. *catostomus*), are likely to benefit from habitat conservation and restoration.

Three sockeye CUs are unlikely to achieve green status in 25 years, even if all strategies are implemented. One, Harrison River late (Weaver) sockeye, may achieve green status with the additional support of Indigenous-led co-governance. The Widgeon slough river type sockeye CU was determined unlikely to *ever* be assessed as green status under the Wild Salmon Policy due to its naturally small population size, which is limited by geographic constraints and therefore sensitive to stochastic events (DFO, 2018). Cultus Lake late sockeye also have naturally low relative abundance (~20,000 spawning adults) and were consistently caught in fisheries targeting larger runs, leading to regular incidences of overharvest (DFO, 2020b). This CU has been monitored longer than any other sockeye salmon CU in BC and has had dedicated stewardship and federal funding since it was assessed as endangered in 2002 (DFO, 2020b). Yet in the present study it was predicted to be the least likely CU to achieve green status even with all strategies implemented under the most optimistic scenario. Some of the lower Fraser's most stable and productive salmon populations have recently declined, such as the Lower Fraser fall 0.3 Chinook CU, which was assessed as Threatened (COSEWIC, 2018). Timely investment in priority strategies to support these more productive CUs may buffer these populations against future stressors while providing some benefit to CUs that are unlikely to achieve green status.

One of the most pervasive threats to wild Pacific salmon survival across life stages is climate change (Grant et al., 2019; Hertz et al., 2016; Hinch et al., 2012), which was not directly addressed by the management strategies in this project. However, experts were asked to assume climate impacts would continue over the next 25 years when developing alternatives and assessing the potential benefits of implementing each strategy. This context helped to identify strategies to mitigate the expected effects of climate change, for example, intensive restoration of lost and degraded rearing and spawning habitat was predicted to provide substantial conservation benefit to Fraser River salmon populations. This strategy can facilitate enhanced capacity for salmon to withstand stochastic climate events and adapt to future change (Atlas et al., 2021; Gayeski et al., 2018; Munsch et al., 2022).

PTM allows for the explicit and objective assessment of available strategies to determine optimal application of limited management resources for species recovery (Carwardine et al., 2012; Martin et al., 2018). This approach does not address the complex social and political ramifications of those strategies, apart from the requirement that all actions should be feasible to implement. Predator control (S11) had particularly divisive responses from experts with respect to feasibility, with some strong proponents and others voicing concerns that pinniped culls would be unethical and unlikely to achieve sufficient public support to be implemented in this region. However, the strategy was robust to changes in feasibility, which may alleviate concerns regarding the impact of the feasibility estimate on the priority ranking (Appendix S3). While predator control was not selected as an optimal strategy in this case, it did contribute to the overall success of the 'all strategies implemented' scenario.

The efficacy of each strategy hinges on successful implementation, monitoring and adaptation as needed (Carwardine et al., 2019). While PTM does not produce a detailed implementation plan, the inclusion of local decision-makers and practitioners in the PTM process provides a realistic pathway forward for complex resource allocation problems, which can help to facilitate support and uptake. This approach has been applied to diverse and complex set of conservation problems throughout Australia, Indonesia, Antarctica and Canada spanning multiple species, values and a wide range of budgets (Carwardine et al., 2019). In a world facing increasingly complex conservation problems requiring multiple trade-offs, we present this work as an example of the application of PTM to facilitate rapid and effective conservation decisions for migratory fishes.

5 | CONCLUSIONS

Our study highlights the urgent need for bold and sustained investment in strategic conservation strategies for wild salmon in the lower Fraser region, including improvements to monitoring and an Indigenous-led co-governance framework for managing salmon populations. PTM provides a framework to rapidly identify priority strategies for investment in species recovery compared to existing planning processes and may be useful to incorporate into wild salmon recovery planning. While the scope of our study was limited to actions within Canadian jurisdiction and focused within the lower Fraser region, additional strategies at an international scale are worth investigating, such as treaty negotiations to minimize hatchery–wild interactions. If the predicted benefits of these international strategies proved high, they could further improve the probability of Fraser salmon CUs achieving green status. Although the ability to recover lower Fraser River salmon remains uncertain, preventing further declines of wild salmon will almost certainly require a move away from 'business as usual' towards a restoration economy, with a shared vision among governing bodies.

AUTHORS' CONTRIBUTIONS

Authors L.C., J.K.B. and T.G.M designed the study; L.C., A.E.C., R.J.R.F., V.H. and C.H. carried out data collection; L.C. and A.E.C. conducted the data analysis; J.K.B., M.J.B., R.D., S.G.H., C.D.L., M.M., D.J.H.N., M.P., J.D.R., D.C.S., U.S., S.S. and J.S. participated as experts and contributed the data; L.C. and T.G.M. led the writing of the manuscript and all authors provided critical contributions to writing or editing the manuscript and gave final approval for publication.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All anonymized data and code used to prepare this manuscript is available via GitHub https://doi.org/10.5281/zenodo.6374510 (Chalifour, 2022).

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