Prioritizing threat management across terrestrial and freshwater realms for species conservation and recovery

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Abstract
The need to manage threats to biodiversity, and to do so cost-effectively, is urgent. Cross-realm conservation management is recognized as a cost-effective approach, but it requires collaboration between agencies and jurisdictions, and local knowledge of anthropogenic threats to biodiversity. With its emphasis on stakeholder engagement and use of structured expert elicitation, Priority Threat Management (PTM) facilitates rapid, cross-realm planning at the regional scale. We used PTM to identify cost-effective management strategies with the aim of securing nine ecological groups, comprised of 45 species and one ecological community of conservation concern, across terrestrial and freshwater realms within the Wolastoq/Saint John River watershed in Canada. Under business-as-usual, four of nine groups are expected to have >50% probability of persistence over the next 25 years. Investment of $141 million over 25 years in three management strategies could secure seven groups across both realms with >50% probability of persistence. Achieving higher levels of persistence comes at a cost—securing six groups with >60% probability of persistence requires investing $218 million over 25 years in seven strategies. Through a structured, iterative process, whereby stakeholders cooperate to clarify objectives, devise management strategies, and collate data, PTM can support timely and cost-effective management across multiple realms.

KEYWORDS
complementarity, cost-effectiveness, cross-realm planning, decision analysis, New Brunswick, priority threat management, structured decision-making, threatened species, watershed management, Wolastoq/Saint John River
1 | INTRODUCTION

Despite increased concern over recent decades, global biodiversity continues to decline while threats have increased (Burivalova, Butler, & Wilcove, 2018; Tittensor et al., 2014; WWF, 2018). Rapid management of threats and associated impacts is critical to prevent further biodiversity loss and expedite species recovery. However, for many species at risk of extinction, implementation of management actions can be significantly delayed (Martin et al., 2012). For example, the median length of time between listing of species under the U.S. Endangered Species Act or the Canadian Species at Risk Act and the publication of a species recovery plan is about 5 years (Ferreira et al., 2019; Malcom & Li, 2018), resulting in subsequent delays in their implementation. This may have significant consequences, ranging from increased costs of conservation (Drechsler, Eppink, & Wätzold, 2011; Fuller, Sánchez-Cordero, Illoldi-Rangel, Linaje, & Sarkar, 2007), to irreversible population declines and potential extinction (Grantham, Wilson, Moilanen, Rebelo, & Possingham, 2009; Lindenmayer, Piggott, & Wintle, 2013; Martin, Nally, et al., 2012).

Landscape-scale, threat-based conservation facilitates simultaneous management of threats to multiple biodiversity values, such as species or ecological communities that may be at risk of extinction, and therefore may help reduce delays in management action. By considering the impact of multiple threats, landscape-scale threat management can also help account for potential interactions and complementarity among proposed management actions when prioritizing for implementation (Auerbach, Tulloch, & Possingham, 2014; Chadès et al., 2014; Evans, Possingham, & Wilson, 2011). In particular, considering threats to biodiversity across terrestrial, freshwater, and marine realms can help account for cross-realm impacts of threats and benefits of actions (Adams et al., 2014; Álvarez-Romero et al., 2015; Giakoumi et al., 2019). Terrestrial land-use activities such as agriculture, forestry, or fire management also affect habitats and species in the freshwater and marine realms (e.g., Carignan & Steedman, 2000; Maina et al., 2013; Yoshimura, 2012), and vice-versa (e.g., Hazlitt, Martin, Sampson, & Arcese, 2010). Consequently, actions that address threats from one realm are likely to have benefits that extend beyond that realm. Integrated, cross-realm management may therefore improve the overall cost-effectiveness of conservation action and help maximize biodiversity benefits under limited resources.

Despite wide recognition of the advantages of cross-realm management, most conservation planning still occur within single realms, with some limited consideration of ecological links to other realms (Adams et al., 2014; Álvarez-Romero et al., 2015). Managing threats across large areas can be challenging, particularly when decision-making authority is divided among multiple jurisdictions with different mandates, priorities, and constraints (Ban et al., 2014; Beger et al., 2010; Dallimer & Strange, 2015), and actions may impact multiple stakeholders (Álvarez-Romero et al., 2015; Dallimer & Strange, 2015; Ruttenberg & Granek, 2011). Careful planning and coordination are needed to support knowledge and resource sharing that will enable strategic investments in more cost-effective conservation actions (Ban et al., 2014; Gordon, Bastin, Langford, Lechner, & Bekessy, 2013; Reuter, Juhn, & Grantham, 2016) and thus offset the potential costs of coordination (Bode, Protbert, Turner, Wilson, & Venter, 2011; Gordon et al., 2013).

Another key challenge in cross-realm planning and management is insufficient understanding of the links between realms and how the impact of threats and actions propagate across realms. When the level of threat is low and the risk of further population declines are minimal, these knowledge gaps may be the subject of additional research and data collection. However, in most cases, urgent action is required (Grantham et al., 2009; Lindenmayer et al., 2013; Martin, Nally, et al., 2012), and there is a need to rely on expert knowledge, including the observations and experience of traditional land holders, resource users and managers, and conservation practitioners.

Here, we demonstrate the use of Priority Threat Management (PTM) to identify priority strategies for managing multiple threats to species or ecological communities of conservation concern across the freshwater and terrestrial realms of the Wolastoq/Saint John River watershed region in New Brunswick (NB), Canada. PTM is a decision analysis framework that considers cost-effectiveness and complementarity of management actions to identify priority strategies at the landscape or regional scale (Carwardine et al., 2012; Chadès et al., 2014; Martin et al., 2018). It was developed to address resource allocation problems for biodiversity conservation (Carwardine et al., 2019) and is therefore most suitable when there is a clear fundamental objective of maximizing the conservation benefits for a given cost. However, the approach can also be adapted to address multiple objective problems that consider other values alongside biodiversity conservation and costs (Carwardine et al., 2019; Utami et al., 2020). Detailed descriptions of the steps of PTM, along with examples of the questions that it can address and comparisons with other decision tools, can be found in the review by Carwardine et al. (2019).

PTM provides a framework for working with stakeholders to develop a shared understanding of the
management context and to help define the scope of the project, identify the biodiversity values of concern, determine the conservation objectives and performance measures, and develop a list of actions or strategies to manage threats or impacts to biodiversity values (Carwardine et al., 2019). In the absence of such a framework, management recommendations risk being undermined by imperfect definitions of the objectives and scope of management, particularly when made within a rapid process (Canessa et al., 2020). PTM also provides guidance on the use of structured expert elicitation to obtain estimates of the potential costs, benefits, and feasibility of proposed management strategies (Carwardine et al., 2019). This emphasis on stakeholder engagement and participatory science facilitates stakeholder participation and coordination from the outset, enabling a more collaborative approach for the implementation of priority strategies and management actions identified through the PTM process.

2 | METHODS

2.1 | Case study

The WolastoqSaint John River (W|SJR) is approximately 673 km long, beginning in northern Maine (USA) and flowing through New Brunswick to the Bay of Fundy, with a total basin area of over 55,000 km² (Cunjak & Newbury, 2005). About 51% of the basin area (29,683 km²) is in New Brunswick (Figure 1), and the remainder in Maine and Quebec (Cunjak & Newbury, 2005). Within New Brunswick, the W|SJR watershed is comprised of seven different terrestrial ecoregions within the Atlantic Maritime Ecozone. It is home to a number of species that are endemic to the region, as well as various rare or threatened species and ecological communities (Kidd, Curry, & Munkittrick, 2011). It also has a long history of anthropogenic threats, from land clearing for agriculture and wood harvesting by European settlers to the more recent threats of industrialization and urbanization, that have led to the decline of many species’ populations within the region (Kidd et al., 2011; WWF-Canada, 2017).

Preventing further declines and recovering species or ecological communities of conservation concern within the region requires collaboration among multiple jurisdictions and stakeholders to address the multiple threats to those biodiversity values. To facilitate this, we used the PTM approach and worked with regional stakeholders and experts to identify strategies for managing threats within the portion of the W|SJR watershed region that occurs within New Brunswick (i.e., study area, Figure 1).

The objective was to identify the optimal set of management strategies that will maximize the number of ecological groups, each consisting of several species or communities of conservation concern, across the two realms that are likely to be secure over a given time period, while also minimizing the costs of management.

2.2 | Data collection

We used a rapid-prototyping approach to work through the steps of a PTM process. Within the context of conservation decision-making, rapid prototyping is an approach to structured decision-making that involves moving through the steps quickly and iteratively, with each iteration resulting in further revision or refinement of the key elements of the decision problem until the decision becomes clear (Garrard, Rumpff, Runge, & Converse, 2017). This allows decision makers to identify and work through any potential issues or obstacles to decision-making at an early stage, before too much time has been invested in the process (Garrard et al., 2017).

A total of 28 experts—individuals with expertise on the ecology and management of species of conservation concern in the W|SJR watershed—attended a 3-day
expert elicitation workshop held in May 2019 in Fredericton, NB. Experts were from scientific research institutions, federal and provincial government agencies, Indigenous groups, environmental non-governmental organizations (NGOs), and industry. During the workshop, experts identified 45 species and one forest community of conservation concern within the study region. These were grouped into nine ecological groups, based on potential similarity of responses to threats and management action (Table S1), to facilitate the elicitation of the benefits of proposed management strategies. Experts also agreed on a time period of 25 years over which to evaluate the costs and benefits of management strategies—long enough to detect the benefits of management, yet still within relevant management timeframes.

Using their expert judgment and information compiled from published literature and from species status assessments, recovery strategies, action plans, and/or management plans published on the Species at Risk Public Registry (Government of Canada, 2019), experts worked in small groups to identify key threats and develop conservation actions to recover species and communities of conservation concern. Actions were grouped into 16 high-level management strategies (Table 1) such that each strategy could be implemented independently, with the assumption that if a strategy is selected, all actions within that strategy would be implemented (Table S2). With the exception of actions in strategies S5 and S6 (Table S2), none of the other actions were included in more than one management strategy. In addition, experts identified five combinations of multiple strategies that are anticipated to have synergistic effects when implemented together (Table 1). We also asked experts to consider the scenario wherein all the individual strategies are implemented together (i.e., an “All Strategies” combination).

In small working groups, organized based on their knowledge and experience of a given strategy, we asked experts to estimate the total annual cost—inclusive of materials, equipment, labor, overheads, or costs associated with planning, consultations, or monitoring—of implementing each action in the strategy over the 25-year time period. Despite varying levels of experience among experts in making cost estimates, each working group had at least one expert with previous experience in estimating costs for actions similar to those found in the strategy. For actions with uncertain costs, we verified or revised the estimates from the workshop based on information from literature and consultations with additional experts. Experts also had the opportunity to review and provide feedback on the complete set of cost estimates.

To facilitate cost comparisons, we converted future costs to present values by applying a discount rate, which reduces the value of future costs relative to present ones to account for the societal preference for deferring costs and the potential investment returns earned by the capital before it is spent on an action (Goulder & Stavins, 2002). We used an annual discount rate of 4%, in line with recommendations on social discounting rates in Canada (Boardman, Moore, & Vining, 2010), and summed these values to determine the total cost of implementing the management strategy over the 25-year time period. For combination strategies, the total cost is the sum of the present value costs of the individual

### Table 1
List of threat management strategies for the W|SJR watershed

| Strategy |
|------------------|
| S1 Public land management |
| S2 Forestry land management |
| S3 Private land management |
| S4 Wetland and aquatic habitat management |
| S5 Dam discharge flow management for Mactaquac and other dams |
| S6 Removal of Mactaquac dam and discharge flow management for other dams |
| S7 Illegal and incidental take policy and regulations |
| S8 Wetland policy and regulation |
| S9 Water quality management |
| S10 Breeding, rearing and re-introduction of Atlantic salmon and yellow lampmussel |
| S11 Disease management for bat species |
| S12 Forest pest management |
| S13 Invasive species management |
| S14 Predator management |
| S15 Pollution reduction and management |
| S16 Climate change policies and actions |
| S17 Land management across tenures (S1 + S2 + S3) |
| S18 Riparian, wetland and aquatic habitat management and policy (S4 + S5 + S8 + S9) |
| S19 Policy development and implementation (S7 + S8 + S15 + S16) |
| S20 Dam discharge flow management and population enhancement (S5 + S10) |
| S21 Land and predator management (S1 + S3 + S14) |
| S22 All strategies except removal of Mactaquac dam and discharge flow management for other dams (S6) |
| S23 All strategies except dam discharge flow management for Mactaquac and other dams (S5) |
strategies in the combination. The undiscounted estimates of the costs of individual actions, and the total present value costs of each strategy can be found in the Supporting Information (Tables S2 and S3).

For each action \( h \) in management strategy \( i \), we also asked the expert groups to provide their estimate of the probability that the action will be implemented (i.e., uptake, \( U_{hi} \)), assuming that funds are available, and the probability that the action will be successful (\( S_{hi} \)) once implemented (Table S2). We used these values to estimate the feasibility of the action, as follows:

\[
F_{hi} = U_{hi}S_{hi},
\]

where \( F_{hi} \) is the feasibility of action \( h \) in strategy \( i \). We then calculated the total feasibility of a strategy (\( F_i \)) as the average feasibility of the individual actions under that strategy. To determine the feasibility for combination strategies, we averaged the feasibilities of individual strategies included in the combination.

We defined the performance of a strategy as the probability of functional persistence of ecological groups—that is, having viable, self-sustaining populations that continue to perform their ecological function—over a 25-year time period under that strategy. We used a modified Delphi elicitation protocol (Carwardine et al., 2019; Hemming, Burgman, Hanea, McBride, & Wintle, 2018) to elicit expert judgments of the performance of: (a) the baseline scenario of no additional management (i.e., business-as-usual) and (b) each individual and combination management strategy. This protocol provides a structured approach to expert elicitation by asking experts to provide their individual “best guess” estimate (i.e., the most likely value), the lowest and highest plausible estimates (i.e., estimate under the most pessimistic and the most optimistic scenarios, respectively), and their level of confidence (as a %) that the true value lies within the range bounded by their lowest and highest estimates (Hemming et al., 2018). We facilitated a group discussion among experts prior to the independent elicitation of estimates to ensure a common understanding of the questions and values being estimated. However, due to time and resource constraints, experts did not have the opportunity to review and discuss the initial estimates as a group before finalizing their estimates. Instead, we provided experts with summaries of the anonymized expert estimates (standardized to 80% confidence level) via email and allowed them to revise their own estimates, if desired, based on this new information. This approach allowed each expert to benefit from information about the diversity of responses among the wider group of experts (Burgman et al., 2011), while avoiding many of the pitfalls of unstructured group elicitation methods, such as “groupthink” (Martin et al., 2012). We used the finalized estimates to determine the benefit of implementing each strategy.

### 2.3 Analysis

For each individual or combination management strategy, we calculated the benefit for each ecological group as the difference between the experts’ best guess estimates of the performance of the strategy and of the performance of the baseline scenario, averaged over the number of experts who provided estimates for the strategy and ecological group:

\[
B_j = \frac{\sum_{k=1}^{K_j} (p_{ijk} - p_{0jk})}{K_j},
\]

where \( p_{ijk} \) is the best guess of the probability of persistence of group \( j \) under strategy \( i \) as estimated by expert \( k \), \( p_{0jk} \) is the best guess of the probability of persistence of group \( j \) under the baseline scenario estimated by expert \( k \), \( K_j \) is the number of experts who provided estimates for group \( j \) under strategy \( i \), and \( B_{ij} \) is the average benefit of strategy \( i \) for group \( j \).

To determine whether ecological groups exceed a minimum threshold probability of persistence under each individual or combination strategy, we estimated the expected probability of persistence of group \( j \) under strategy \( i \) (\( p_{ij} \)) by weighting the average benefit (\( B_{ij} \)) of strategy \( i \) for group \( j \) by the feasibility (\( F_i \)) of strategy \( i \), then adding this expected benefit value to the average estimate of the persistence of group \( j \) under the baseline scenario. That is,

\[
p_{ij} = \frac{\sum_{k=1}^{K_{ij}} p_{0jk}K_{0j}}{K_{ij}} + B_{ij}F_i,
\]

where \( K_{ij} \) is the number of experts who provided estimates of the probability of persistence of group \( j \) under the baseline scenario.

Two individual strategies—dam discharge flow management from Mactaquac and other dams (Strategy 5), and removal of Mactaquac Dam and flow discharge management for other dams (Strategy 6)—were designed to be mutually exclusive. To keep Strategies 5 and 6 separate, we created two new combination strategies to represent the original “All Strategies” combination described at the workshop: Strategy 22, which is a combination of all individual strategies except Strategy 6; and Strategy 23, which is a combination of all individual strategies...
except Strategy 5 (Table 1). The total cost and feasibility of the new combination strategies were calculated as described above. As Strategy 5 is primarily a subset of Strategy 6, we assumed that the benefit of the new Strategy 23 would be equal to that estimated by experts for the original “All Strategies” combination. We then estimated the benefit of the new Strategy 22 by subtracting the difference in expected benefit between Strategy 6 and Strategy 5 from the expected benefit of the “All Strategies” combination. That is, for each ecological group $j$:

$$B_{23j} = B_{\text{ALL,}j},$$

and

$$B_{22j} = \frac{B_{\text{ALL,}j}F_{\text{ALL}} - (B_{5j}F_6 - B_{5j}F_5)}{F_{\text{ALL}}},$$

where $B_{22j}$ and $B_{23j}$ are the benefits of the new combination Strategies 22 and 23 on ecological group $j$, respectively; $B_{5j}$, $B_{6j}$, and $B_{\text{ALL,}j}$ are the benefits of Strategy 5, Strategy 6, and the “All Strategies” combination elicited from experts at the workshop for ecological group $j$; and $F_5$, $F_6$, and $F_{\text{ALL}}$ are the corresponding feasibility estimates for Strategies 5 and 6, and the “All Strategies” combination. The expected performance of Strategies 22 and 23 was then calculated using Equation (3).

The cost-effectiveness of management strategies can be assessed using estimates of their benefits, costs, and feasibility, and the strategies ranked based on cost-effectiveness (see Supporting Information SI for the methods and results of cost-effectiveness ranking). However, using cost-effectiveness ranking to identify priority strategies does not necessarily maximize the conservation benefits of management, or ensure the long-term persistence of a species (Chadès et al., 2014; Firn et al., 2015). We therefore performed a complementarity analysis to determine the optimal combination of strategies that, when implemented together, will maximize the total number of ecological groups secured.

For the complementarity analysis, we considered ecological groups with a probability of persistence greater than the selected threshold to be “secure.” We considered two threshold values—50% and 60% probability of persistence over the 25-year time period—based on the range of expert-elicited benefit estimates and solved the following integer linear programming problem for each threshold and a range of budget amounts:

$$\max \sum_{i=1}^{S} \sum_{j=1}^{G} T_{ij}x_{ij},$$

subject to:

$$\sum_{i=1}^{S} x_{ij} \leq 1,$$

$$x_{ij} \leq y_{ij},$$

and

$$\sum_{i=1}^{S} C_{ij}y_{ij} \leq C_{\text{max}},$$

where $T_{ij} = 1$ and $x_{ij} = 1$ if group $j$ exceeds the threshold under strategy $i$, and 0 otherwise, $C_i$ is the total cost of implementing strategy $i$, $C_{\text{max}}$ is the total budget available, $y_{ij}$ is a decision variable that indicates whether strategy $i$ is selected (1) or not (0), $S$ is the total number of strategies, and $G$ is the total number of ecological groups. The first constraint ensures that a maximum of one strategy is counted towards group $j$, while the second constraint ensures that the contribution of strategy $i$ to each group $j$ is zero when strategy $i$ is not selected (i.e., when $y_{ij} = 0$). The final constraint ensures that the total cost of all selected strategies does not exceed the given budget.

To examine the effect of uncertainty in benefit estimates on the optimal sets of complementary strategies, we performed the complementarity analysis using the highest and lowest estimates elicited from experts. Detailed descriptions of the uncertainty analyses are provided in the Supporting Information SI.

### 3 RESULTS

Under the baseline, business-as-usual scenario, four of the nine ecological groups are expected to have >50% probability of persistence over the next 25 years (Table 2). With the implementation of all strategies, seven of the nine ecological groups can be secured above this threshold (Table 2). Overall, while management is anticipated to improve the probability of persistence of all ecological groups, expert estimates of the benefit of strategies tended to be pessimistic, with the probability of persistence for the majority of ecological groups remaining <70% even when all management strategies are implemented (Table 2).

Of the individual strategies, management of public land (Strategy 1), forestry land, which may be publicly or privately owned (Strategy 2), and private land (Strategy 3) have the greatest overall benefits across multiple ecological groups, as measured by the improvement in probability of persistence. However, the single most effective strategy varies for each group (Table 2). For example, for three ecological groups—the riparian and shoreline (“riparian”), the mature forest and peatland (“mature
| Ecological groups                     | # spp | Base line | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 | S11 | S12 | S13 | S14 | S15 | S16 | S17 | S18 | S19 | S20 | S21 | S22 | S23 |
|--------------------------------------|-------|-----------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Migratory fish                       | 6     | 37        | 41 | 40 | 41 | 45 | 45 | 52 | 40 | 39 | 42 | 49 | 37 | 37 | 42 | 39 | 40 | 47 | 44 | 47 | 46 | 52 | 42 | 55 | 62 |
| Riparian and shoreline               | 4     | 51        | 59 | 62 | 59 | 58 | 57 | 56 | 53 | 54 | 52 | 51 | 51 | 51 | 52 | 53 | 53 | 57 | 62 | 60 | 59 | 58 | 62 | 67 | 66 |
| Aquatic                              | 4     | 53        | 58 | 56 | 57 | 56 | 58 | 56 | 53 | 53 | 57 | 56 | 53 | 53 | 57 | 53 | 56 | 58 | 59 | 60 | 59 | 58 | 67 | 65 | 65 |
| Wetland                              | 5     | 57        | 64 | 61 | 61 | 63 | 59 | 58 | 58 | 63 | 60 | 57 | 57 | 57 | 58 | 59 | 57 | 58 | 67 | 65 | 63 | 60 | 64 | 71 | 70 |
| Grassland, open, or agricultural     | 9     | 45        | 50 | 46 | 57 | 48 | 45 | 45 | 46 | 46 | 45 | 45 | 48 | 46 | 51 | 53 | 62 | 49 | 54 | 45 | 57 | 63 | 63 | 65 |
| Mature forest and peatland           | 10    | 53        | 64 | 66 | 59 | 54 | 53 | 53 | 53 | 53 | 53 | 53 | 53 | 54 | 54 | 53 | 53 | 59 | 66 | 56 | 59 | 53 | 62 | 64 | 64 |
| Forest openings and young forest     | 2     | 46        | 56 | 64 | 52 | 46 | 46 | 46 | 46 | 46 | 46 | 47 | 46 | 46 | 46 | 50 | 62 | 47 | 51 | 46 | 55 | 60 | 59 | 60 |
| Bats                                 | 3     | 27        | 31 | 28 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 39 | 27 | 27 | 27 | 27 | 27 | 27 | 31 | 27 | 27 | 27 | 38 | 38 | 38 |
| Forest trees                         | 3     | 17        | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 32 | 17 | 17 | 17 | 17 | 17 | 18 | 22 | 17 | 18 | 22 | 18 | 28 | 28 |
| Feasibility                          | 1     | 0.85      | 0.92 | 0.62 | 0.53 | 0.54 | 0.41 | 0.45 | 0.52 | 0.52 | 0.75 | 0.81 | 0.97 | 0.64 | 0.50 | 0.56 | 0.64 | 0.80 | 0.53 | 0.54 | 0.64 | 0.66 | 0.65 | 0.65 |
| Cost (million CAD)                   | 0     | 1.5       | 2.9 | 26 | 30 | 137 | 498 | 15 | 7.7 | 13 | 3.3 | 1.0 | 0.4 | 24 | 4.6 | 6.6 | 11 | 30 | 187 | 41 | 140 | 32 | 284 | 645 |

Note: Values are based on the aggregated benefit estimates (calculated from individual best guess estimates) weighted by the estimated feasibility of each strategy, and rounded to the nearest whole number. Light yellow shading indicates probabilities of persistence >50%, while darker shading indicates values >60%; note that the shading is based on values before rounding.
..., and the forest openings and young forest habitat ("open forest") associates—Strategy 2 is predicted to be the most effective, whereas Strategy 3 is the most effective strategy for grassland/open habitat and agricultural ("grassland") associates (Table 2). The dam removal and dam discharge flow management strategy (strategy 6) is the most effective strategy for migratory fish species, while disease management (Strategy 11) and forest pest management (Strategy 12), respectively, are the most effective strategies for bat and forest tree species.

The expected benefit of each combination strategy (Strategies 17–23) is greater than for any individual component strategy alone, suggesting that combinations of multiple strategies are required to mitigate multiple threats. As expected, the highest probabilities of persistence could be achieved by implementing all individual strategies together (i.e., combination Strategy 22 or 23). Among the remaining combination strategies, land management across different tenures (combination strategy 17, which is comprised of Strategies 1, 2, and 3) yields the next highest benefit values on average (Table 2).

Of the five ecological groups with <50% probability of persistence under the baseline scenario, the grassland and open forest associates can be secured by implementing Strategy 1 for a minimum investment of about $1.5 million over 25 years (approximately $61,400 per year) (Figure 2, Table 3). This works out to about $768,000 per additional ecological group secured (Table 3). However, a larger budget of over $141 million over 25 years ($5.7 million per year) (Figure 2, Table 3) would be needed to secure a seventh group, migratory fish, with >50% probability of persistence by also implementing the combination strategy (Strategy 20) that includes dam discharge flow management (Strategy 5, $137 million over 25 years) and breeding, rearing, and reintroduction (Strategy 10, $3.3 million over 25 years).

Securing species with a higher probability of persistence would require higher levels of investment. Strategy 1, for instance, is predicted to increase the probability of persistence to >60% for only two ecological groups, the wetland and the mature forest associates (Table 3). Implementing Strategy 2 for a slightly higher investment of $2.9 million ($118,000 per year) would secure two more ecological groups, the riparian and the open forest associates, with >60% probability of persistence (Table 3). An additional $28 million over 25 years would be needed to secure a fifth group, grassland associates, with >60% probability of persistence through implementation of all three land management strategies (combination Strategy 17 or Strategies 1, 2, and 3 combined) (Figure 2 and Table 3). Finally, securing a sixth group, aquatic habitat associates, to the same threshold will require an extra $187 million over 25 years (for a total of over $218 million, or $8.7 million per year) to implement the combination of several riparian, wetland, and aquatic habitat strategies (combination Strategy 18; or Strategies 4, 5, 8, and 9 combined) along with combination Strategy 17 (Figure 2 and Table 3).

Performing the uncertainty analysis with the most pessimistic and most optimistic estimates highlighted only one new strategy, disease management for bats (Strategy 11), that was not already included in the optimal strategies identified under the best guess (most likely) estimates (Figure S3). Overall, the set of strategies that maximized the number of groups secured under the most likely scenario also performed well under the most pessimistic or most optimistic scenarios. Further details on the results of the uncertainty analyses are available in the Supporting Information SI.

4 | DISCUSSION

4.1 | Priority threat management strategies for the W/SJR watershed

We identified a set of cost-effective strategies to manage threats across terrestrial and freshwater realms within
**Table 3** Optimal sets of complementary management strategies that secure the greatest number of ecological groups or species for different total costs over 25 years. Cost values presented in the table are in present values, calculated using a discount rate of 4% over 25 years.

| Prob. of persistence (%) | Total cost (CAD) | Strategies | Migratory fish | Aquatic Riparian and shoreline Wetland Mature forest and peatland Forest openings and young forest Grassland/open habitat and agricultural Bats Forest trees | Number of groups secured | Marginal cost per additional group secured (CAD) | Number of species secured | Marginal cost per additional species secured (CAD) |
|--------------------------|------------------|------------|----------------|----------------|-------------------------------------------------|-------------------------|-----------------------------------------------|-----------------------------------------------|
| >50                      | 0                | Baseline   | ✓              | ✓              | ✓                                               | ✓                      | 4                                             | 0                                             | 23                                             | 0                                             |
|                          | 1,535,127        | S1         | ✓              | ✓              | ✓                                               | ✓                      | 6                                             | 767,564                                       | 34                                             | 139,557                                       |
|                          | 141,366,279      | S1 + S20   | ✓              | ✓              | ✓                                               | ✓                      | 7                                             | 139,831,152                                   | 40                                             | 23,305,192                                   |
| >60                      | 0                | Baseline   | ✓              | ✓              | ✓                                               | ✓                      | 2                                             | 767,564                                       | 15                                             | 102,342                                       |
|                          | 1,535,127        | S1         | ✓              | ✓              | ✓                                               | ✓                      | 2                                             | 705,019                                       | 21                                             | 235,007                                       |
|                          | 2,945,166        | S2         | ✓              | ✓              | ✓                                               | ✓                      | 4                                             | 705,019                                       | 21                                             | 235,007                                       |
|                          | 30,479,096       | S17        | ✓              | ✓              | ✓                                               | ✓                      | 5                                             | 27,533,930                                    | 30                                             | 3,059,326                                    |
|                          | 217,541,954      | S17 + S18  | ✓              | ✓              | ✓                                               | ✓                      | 6                                             | 187,062,858                                   | 34                                             | 46,765,715                                   |
|                          | 645,490,427      | S23        | ✓              | ✓              | ✓                                               | ✓                      | 6                                             | 187,062,858                                   | 34                                             | 106,987,118                                  |

*Note:* Tick (✓) marks indicate that the probability of persistence of the ecological group is expected to exceed the given threshold if the optimal strategies are implemented. The marginal costs of securing additional ecological groups or species were calculated as the increase in costs from the preceding set of complementary strategies, divided by the number of additional groups or species secured. Highlighted strategies (in light orange) secure the same number of ecological groups, but at a higher cost, than the preceding set of strategies; however, the ecological groups secured differ, resulting in a higher total number of species expected to be secure. For this analysis, the Appalachian hardwood forest community was counted as a single species.
the W|SJR watershed, and secure up to seven ecological groups, comprised of 40 species or communities of conservation concern from both realms, with >50% probability of functional persistence over 25 years. Doing so will require a conservation investment of around $141 million CAD over the 25-year time period, or approximately $5.7 million per year. With the exception of migratory fish, six of those groups can be secured to the same threshold for a fraction of that amount—a total cost of around $1.5 million over the same time period, or approximately $61,400 per year. The same six groups can be secured with >60% probability of persistence, at a cost of $218 million over 25 years, whereas excluding aquatic habitat associates, five of those groups can be secured to the higher threshold for only $30 million over 25 years. These include ecological groups that rely on both terrestrial and freshwater realms, such as the wetland and riparian habitat associates.

The optimal set of management strategies identified through the PTM process depends on the threshold probability of persistence used in the analysis. However, while higher probabilities of persistence are desirable, there are no universal standards that specify appropriate thresholds or criteria for defining a species or ecological community as endangered, threatened, or recovered (Doak et al., 2015; Wolf, Hartl, Carroll, Neel, & Greenwald, 2015). The selection of a threshold value is primarily a management or policy decision (Himes Boor, 2014) that depend on the values, goals, and risk preferences of the decision-maker, and therefore, is often subjective (Wolf et al., 2015). The PTM process therefore identifies optimal management strategies for multiple threshold levels of performance. In this case study, we identified optimal threat management strategies for two threshold values, 50% and 60% probability of persistence. We did not perform the analysis on a higher threshold as, with the exception of the wetland habitat associates, estimates of the probability of persistence for the other ecological groups remained below 70% regardless of the management strategy. Based on feedback from the experts, the low-expected probabilities of persistence under the management strategies are likely due to the low estimated feasibility for many of the strategies, particularly those with more innovative but potentially riskier actions, and the view that that the strategies proposed may be insufficient given the highly modified state of the W|SJR watershed region.

A cross-realm approach allowed for the development of strategies that apply to both realms simultaneously, and thus may have lower costs than if implemented independently in each realm. For example, the invasive species management strategy includes actions that focus on increasing public awareness of potential invasive species, and monitoring and preventing their introduction and spread. Implementing these actions to address terrestrial and freshwater invasive species simultaneously would likely cost less than if separate programs for the two realms were to be developed and implemented. Most importantly, the cross-realm approach allowed us to account for the benefits of strategies based in one realm, such as forestry land management or pollution reduction and management, on ecological groups that rely primarily on the other realm, such as migratory fish or aquatic habitat associates, and also the impact of both threats and actions in either realm on cross-realm species.

### 4.2 PTM encourages timely and collaborative management under uncertainty

The structured approach to expert elicitation used in the PTM helps minimize biases, quantify uncertainty, and improve the accuracy and transparency of expert elicitation (Hemming et al., 2018; Martin, Burgman, et al., 2012). Combining expert knowledge with empirical data allowed for more rapid management responses to address threats and their impacts. Where time and capacity allows, the elicitation process could be improved through the inclusion of conceptual model and results chain development (Margoluis et al., 2013; Margoluis, Stem, Salafsky, & Brown, 2009) to better capture and examine the mental models that experts use when estimating the benefits and feasibility of management strategies.

The PTM process also uses uncertainty analyses to assess whether, and how, uncertainties in expert elicited estimates might change the set of priority threat management strategies identified (Carwardine et al., 2019). In the W|SJR case study, uncertainties in the benefits of management strategies did not have a large influence on the set of management strategies identified as optimal. With the exception of disease management for bats (Strategy 11), the optimal strategies identified based on the most pessimistic or the most optimistic estimates were the same as those under the most likely, or best guess, estimates. This information can help decision-makers and managers assess whether investment in additional strategies is needed to ensure species persistence under anticipated best- or worst-case scenarios. Knowing whether the recommended priority management strategies are robust to uncertainties can also help improve stakeholder confidence and therefore the success of implementation.

Finally, through its emphasis on stakeholder engagement and participatory science, a PTM planning process
can facilitate collaboration and coordination among managers and other stakeholders. The workshop process encouraged the exchange of ideas and information among participants about recent research findings, effective management approaches, and new or planned conservation initiatives within the region, paving the way for future collaborations.

4.3 A role for single-species approaches

While integrated, cross-realm management of threats may help maximize the number of species protected or recovered, it is likely that there will be species or ecological groups that cannot be easily recovered and would require targeted, species-specific approaches that may not be cost-effective. In this PTM process, for example, none of the management strategies were expected to secure bats or forest trees with >50% probability of persistence. However, disease management (Strategy 11) improves the probability of persistence of bat species from 27% under the baseline scenario to 39%, while forest pest management (Strategy 12) can help improve the probability of persistence of forest trees from 17% under the baseline to 32%. As part of the PTM process, we can identify which species or groups may require targeted approaches, thus providing decision-makers the opportunity to consider the implementation of those strategies based on other factors, including cultural, institutional, or societal values and preferences.

The PTM approach also provides useful information on which management strategies have the greatest expected benefits for individual species or ecological groups, and the amount of investment needed to secure them. This may be of particular interest when considering targeted management of a single species or ecological group considered to be of higher cultural, social, or economic value. Here, we found that the combined implementation of all strategies, including the removal of Mactaquac Dam (i.e., Strategy 23), is needed to achieve the greatest benefit for migratory fish, an estimated 62% probability of persistence. The decision to invest in more expensive management strategies to secure migratory fish will depend on the relative value that decision-makers, and those they represent, place on this ecological group. By highlighting which species cannot be easily secured, or those that would require considerable resources to do so, PTM encourages greater transparency and accountability in the decision-making process. Alternatively, a weighting factor can be included in the problem formulation (Equation (4)) to account for the different relative values placed on species or ecological groups when identifying priority strategies (Joseph, Maloney, & Possingham, 2009). However, the weights assigned to different species or groups are subjective value judgments and will need to be elicited from the decision-makers that will be investing in conservation.

4.4 PTM as a rapid prototyping approach

In this case study, we applied the PTM process using a rapid prototyping approach to prioritize threat management strategies across freshwater and terrestrial realms of the W|SJR watershed in New Brunswick. Although we presented the PTM in a sequential manner here, in practice, the process was iterative, wherein experts were invited to review and revise the outputs of previous steps as needed. In particular, the list of species or communities of conservation concern and their grouping, and the management strategies and actions were revisited several times during the expert elicitation workshop. Experts were also provided opportunities to review and revise their individual estimates of the benefit of management strategies and to contribute to the refinement of cost estimates. The entire process took 12 months with one full-time post-doctoral fellow and approximately one additional full-time equivalent, spread across three individuals, along with the valuable contribution of 28 experts. In addition to the in-kind contributions of staff time and travel expenses from some of the participating organizations, approximately $25,000 CAD were spent on three separate workshops: a half-day meeting to introduce the project and invite participation from regional stakeholders, the 3-day expert elicitation workshop, and a full-day workshop to present preliminary results to experts and other stakeholders and obtain their feedback.

The rapid process meant it was possible that relatively novel or lesser known but potentially effective approaches were unintentionally excluded from the analysis. In addition, the full scope, extent, and location of implementation were not fully specified for some actions. Further iterations and the application of additional decision tools may help ensure a more thorough consideration of all feasible management actions, and a more detailed specification of each action.

The final steps of the PTM process is to communicate recommendations to stakeholders and work toward integrating the recommendations into new or existing conservation initiatives (Carwardine et al., 2019). Once implemented, the effectiveness of management strategies should also be monitored regularly to help inform subsequent iterations of the PTM (Carwardine et al., 2012; Ponce Reyes et al., 2019). In October 2019, we presented preliminary findings to regional stakeholders at a workshop to present preliminary results to experts and other stakeholders and obtain their feedback.
workshop. A summary report of the PTM recommendations, intended for the general public, is currently in preparation and will be used to help generate support for the implementation of priority strategies. In the spring/summer of 2020, with funding from the federal department of Fisheries and Oceans Canada, WWF-Canada began working with three local watershed groups to implement a number of priority actions identified through this PTM process. Funding for the following year has already been secured, and plans are underway to use the outputs of the PTM analysis to raise additional funds for the implementation of priority strategies.

5 | CONCLUSION

Rapid and cost-effective response is increasingly required to mitigate threats to biodiversity values. PTM provides a structured, iterative process, whereby experts and managers cooperate to clarify objectives and uncertainties, collate data, devise management strategies, and prioritize management action based on cost-effectiveness. Through the PTM process, we discovered that seven of the nine ecological groups, representing 40 species and ecological communities of conservation concern across terrestrial and freshwater realms, can be secured with an investment of $141 million over 25 years. The PTM process provided key information about priority management strategies across the terrestrial and freshwaters realms of the W/SJR watershed, estimates of the amount of investment needed to implement those strategies, and how the resulting set of priorities might change in response to uncertainties in the estimated benefits of management. By encouraging collaboration among stakeholders, improving cost-effectiveness, and accounting for uncertainty, PTM can be a highly useful framework for rapid threat management across multiple realms.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Abbey E. Camaclang led the data collection, analysis, and writing of the manuscript, and co-facilitated the expert elicitation workshop. Tara G. Martin and James Snider developed the initial project idea and provided critical input on the project scope and analysis. Tara G. Martin also co-facilitated the expert elicitation workshop and provided technical advice on data collection and analysis. Jessica Currie and Emily Giles managed stakeholder engagement and communications, organized workshops, contributed to data collection, and provided important feedback on the analysis. Graham J. Forbes, Christopher B. Edge, Wendy A. Monk, Joseph J. Nocera, Graeme Stewart-Robertson, Constance Browne, and Zoe G. O’Malley provided local knowledge about the regional conservation context, and contributed critical data used in the analysis. All authors reviewed and contributed to the manuscript and subsequent revisions.

Data Availability Statement

The anonymized estimates of the costs and feasibility of management strategies and the aggregated benefit estimates are available from https://github.com/aecamaclang/SaintJohnRiver_PTM.

ETHICS STATEMENT

This study was approved by the University of British Columbia’s Behavioral Research Ethics Board (Ethics ID#: H19-00973).

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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