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Application of a structured decision-making process in cryospheric hazard planning: Case study of Bering Glacier surges on local state planning in Alaska

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Abstract

Surging glaciers are glaciers that experience rapidly accelerated glacier flow over a comparatively short period of time. Though relatively rare worldwide, Alaska is home to the largest number of surge-type glaciers globally. However, their impact on the broader socioecological system in the state is both poorly understood and under-researched, which poses a challenge in developing appropriate sustainability decisions in Alaska. We investigated how the surge patterns of the Bering Glacier in Alaska have potentially devastating effects on the local ecological biodiversity of its watershed via a structured decision-making analysis of the different possible consequences. Specifically, this analysis was conducted to explore the various outcomes of a Bering Glacier surge particularly if humans have an increased presence near the glacier due to the area potentially becoming a state park. This work explored the benefits of applying a risk and decision analytical framework in a cryosphere context, to better understand the socioeconomic impact of glacier surges. This is a novel approach in which a decision analysis tool was used to better understand an environmental sustainability challenge, offering an innovative method to support the achievement of the United Nations Sustainability Development Goals in Alaska. We therefore emphasise the need for integrated biophysical and socioeconomic analyses when it comes to understanding glacier hazards. Our research highlights the importance of understanding and researching biophysical changes as well as using a structured decision-making process for complicated hazard planning scenarios, exemplified via glaciated regions in Alaska, in order to create adaptation strategies that are sustainable and encompass the range of possible outcomes.

KEYWORDS

cryospheric hazard, decision analysis tool, sensitivity analyses, structured decision-making

1 | INTRODUCTION

This paper presents a methodological study of applying structured decision-making, a decision and risk analysis method and tool, to an example of a multi-stakeholder decision regarding the development of a state park in the Bering Glacier system in Alaska. The methodology and the case study application were developed to investigate the benefits of using a structured decision-making approach in a large structural uncertainty (e.g., system-wide uncertainty) cryospheric hazard context, which to our knowledge has not been done before. This is both timely and relevant, given the large focus on watershed management as part of the United Nations (UN) sustainability developmental goals (SDGs) efforts to improve environmental sustainability.

Given the success of structured decision-making in other environmental management settings (Gregory et al., 2012), we explore how the application of this process can be used in cryospheric hazard settings, in this case a glacier surge. Structured decision-making is a method that supports decision-makers to take an informed and evidence-based approach to review different alternatives and possible consequences, to find the best possible decision given the knowledge and information available to them. Structured decision-making can be operationalised using different methods and approaches but, in its essence, it seeks to systematically analyse different decision alternatives and their consequences (Raiffa, 1968). Utilising a structured decision-making approach can therefore also help meet the goals of the UN SDGs, in that decision-makers, as well as those impacted by decisions, come together to utilise the best possible set of information to make informed environmental decisions.

The structured decision-making process utilised in this paper includes the six steps of the PrOACT model from (Hammond et al., 2015): (1) clarify the decision context; (2) define objectives and measures; (3) develop alternatives; (4) estimate consequences; (5) evaluate trade-offs; and (6) implement, monitor, and review. The evaluations were carried out using the multi-criteria decision modelling and evaluation tool, DecideIT (Danielson et al., 2020).

Risk and decision analyses for cryospheric hazards is a novel field that has recently started to be explored in the risk and decision analysis literature (Kougkoulos et al., 2018). Alaska has one of the largest concentrations of glaciers in the world apart from the Greenland and Antarctic ice sheets (Pfeffer et al., 2014; Sevestre & Benn, 2015). This paper discusses how structured decision-making can support multi-stakeholder decision-making regarding potential socioecological hazards in a glacial context, focusing on a specific glacier type common in Alaska, surge-type glaciers, which periodically exhibit large flow acceleration often accompanied by significant advances, even with climate warming. Specifically, this paper looks at changes to the Bering Glacier, a surge-type glacier and one of the largest glaciers in Alaska. Results from our work hold implications for the broader socio-cryospheric system, which is the socioecological system in cold regions (Carey et al., 2015; Gregory & Long, 2009). We therefore also discuss the necessity, and suggest avenues, of further decision and risk analysis research regarding potential socio-cryospheric impacts of glacier hazards in Alaska.

1.1 | Bering Glacier case study

Decision-making regarding land areas and biodiversity management in watershed floodplains affected by glacier surges are cryospheric hazard situations that lend themselves well to the application of a structured decision-making approach. Carey et al. (2014) offer a 3-part approach to ensuring that adaptation to cryospheric hazards is ultimately successful. This approach requires (1) understanding cryospheric hazards from a biophysical basis; (2) preventing disasters from occurring through risk management; and (3) reducing vulnerability by addressing socioeconomic factors that increase susceptibility to these events.

The Bering Glacier case study is an interesting one to explore the application of structured decision-making since there are several unknown impacts, particularly regarding the timing of future glacier surges as well as the impact of increased human presence on the biodiversity of the area. Areas such as the Bering Glacier system are of high scenic value. Trail systems and recreational areas—whether developed by city, state, or federal authorities—can therefore be present in the glacier surge forefield and subsequently can be impacted or destroyed during a surge event. In addition to eventually presenting a ranking of preferred courses of action, a structured decision-making approach can be useful to help relevant decision-makers assess the following questions:

1. What are the uncertainties associated with a surge event and how do these uncertainties impact management decisions?
2. Which stakeholders are impacted by a surge event and to what extent?
3. What are the impacts of human activity on the local biodiversity?
4. What are the various management decisions that can be undertaken, despite the uncertainties associated with a surge event and increased human presence in the area?

1.2 | Surging glaciers

During a surge, the glacier's flow is accelerated very rapidly over a comparatively short period of time, from a few months to years, and is often associated with considerable advances (several kilometres) of the glacier's terminus (Cogley et al., 2011; Harrison et al., 2018). Flow acceleration can reach 10–100 times normal ice velocity, which typically results in the fast transfer of large quantities of ice from the upper reaches of the glacier towards its terminus. Glacier surging is a quasi-periodic glacial phenomenon, with quiescent phases between surges characterised by 'normal' flow speeds and a thickening of the upper parts of the glacier, which typically last some decades at a time. Surging glaciers represent a small percentage of the world's glacier population (less than 1%) but constitute potential hazards, particularly if they advance and cut off valleys and/or trigger glacial lake outburst floods (Sevestre & Benn, 2015). Importantly, though glacial surge processes are not well understood, they present a unique opportunity to understand glacier dynamics due to surges being largely triggered by sub-glacier dynamics rather than by external factors, such as climate (Benn & Evans, 2014).

In Alaska, there are at least 300 identified surge-type glaciers—a glacier that has the propensity to surge (Sevestre & Benn, 2015). Furthermore, Alaska has one of the highest concentrations of surge-type glaciers in the world (Sevestre & Benn, 2015). Surge-type glaciers in Alaska typically experience surges that last between 2 and 3 years (Meier & Post, 1969) and therefore the surges themselves tend to be also quite rapid. The time period between surges, the quiescence phase, is also relatively short in Alaska, lasting anywhere between 20 and 30 years, compared to other regions (50–500 years) (Benn & Evans, 2014). Though most of Alaska's surging glaciers are far from human populations, glacier surges can impact human and physical systems as well as ecosystems, the latter particularly due to their impacts on surrounding biodiversity. A notable example of a surge-type glacier in Alaska is the Bering Glacier (Figure 1).

1.3 | Study site: Bering Glacier

The Bering Glacier system (3025 km^2, as of 2010) is the largest surge-type glacier, outside the ice sheets (Burgess et al., 2012; Windnagel et al., 2023). It is also the largest temperate surge-type glacier globally (Crossen & Noyles, 2010). Although Bering Glacier is retreating rapidly, five notable surges have been recorded for the glacier during the past century: ~1900, ~1920, ~1938–1940, 1957–1967, and 1993–1995 (Molnia & Post, 2010). A smaller surge was also recorded in 2008–2011 (Burgess et al., 2012). Data on the Bering Glacier's surges shows that the glacier's quiescence phase lasts about 20 years (Roush et al., 2003).

Bering Glacier's cycle of retreat and surging has significant implications for the area's surrounding hydrology. Vitus Lake, Bering Glacier's proglacial lake, was completely overrun by the Bering Glacier surge in 1993–1995, which totally destroyed the coho salmon population. The lake could possibly be overrun again in future Bering Glacier surges.

The Bering Glacier's surge advances and subsequent retreats dramatically affected the surrounding lakes and rivers during the glacier's surge in the early 1990s (Yakataga Area Plan, n.d.). Though Vitus Lake expanded to over 202 km^2 during Bering Glacier's post-surge retreat in the early 1990s, the 1994–1995 surge caused Bering Glacier to regain most of Vitus Lake (Yakataga Area Plan, n.d.). Due to high tides (approximately >2 m) entering via Seal River into Vitus Lake, it is expected that the lake will ultimately open up to the Gulf of Alaska. The increased tidal influx will not only create a fjord where Vitus Lake once was, but it is also projected to cause Bering Glacier to retreat up to 57 km in the next 50–100 years. However, recent models have shown that though Vitus Lake will continue to significantly expand in size and volume, the rapid retreat of Bering Glacier and its freshwater contribution to Vitus Lake as well as other factors make it more likely that tidal influxes will become less significant (Josberger et al., 2006, 2010).

1.4 | Socioecological impacts

Bering Glacier experiences rapid advances during its glacier surges and it has been experiencing rapid retreat since its last surge (2008–2011), which has a direct impact on its surrounding physical and ecological system. Although the glacier retreat and surges of Bering Glacier have been of notable interest from a glaciology perspective, there is comparatively little research done on how these changes affect the surrounding socioecological system. For example, Vitus Lake is becoming more and more saline due to tidal influxes from Seal River, creating potential research opportunities to study a freshwater-to-marine transition for salmon runs and bird rookeries (Yakataga Area Plan, n.d.). However, little research has been done to date on these ecological changes. Freshwater biogeography of newly deglaciated areas is still not well understood (Weigner & von Hippel, 2010).

What makes Bering Glacier particularly interesting to study in this regard is that Vitus Lake has a relatively high fish species richness, given its size and the fact it is tidally influenced. This is unique given that

FIGURE 1 Location of Bering Glacier in southern Alaska. Vitus Lake, the glacier's proglacial lake and the home to a coho salmon population, is connected to the Gulf of Alaska via the Seal River. *Source*: Google Earth.

most glacial lakes have typically low fish species (Weigner & von Hippel, 2010). If Vitus Lake continues to grow, as Bering Glacier retreats, it could potentially foster an even more vibrant fish community; older lakes and streams are more likely to have more fish and more fish species diversity. Vitus Lake can be an ideal environment for coho salmon runs as the stickleback species pair, a food source for coho salmon, is the only known species, to our current knowledge, that exists in a proglacial lake in the world (Weigner & von Hippel, 2010). However, as previously noted, the Bering Glacier surge in 1993–1995 completely destroyed the coho salmon runs in Vitus Lake (Weigner & von Hippel, 2010). Though the coho salmon have since returned, the full extent of the population recovery is not known.

According to the 1995 Yakataga Area Plan, the State of Alaska has considered opening the Bering Glacier area as a state park as the glacier continues to recede as well as potentially allowing for the continued use of the glacially fed rivers and streams for sport fishing. If this plan is approved, it is unclear at the moment how the state will take into account future surges of the glacier, especially if the area will be used for recreational use. Specifically, more research needs to be done on how Bering Glacier surges can potentially continue to destroy salmon and other fish populations each time they happen. Bering Glacier is due for another surge soon—its quiescence phase normally lasts 20 years and the last major surge was in 1993–1995. Although climate change may impact the timing and magnitude of surge activity (Bering Glacier has retreated considerably since its last surge), a risk analysis of surge-related lake draining would be necessary prior to the development of the area for recreational and, potentially, economic gain.

In addition to a glacial surge, fish populations in Vitus Lake may also be impacted by other human activities such as resource extraction and tourism. The US Bureau of Land Management oversees competing land interests, such as land rights in the area that have been sold to corporations interested in exploring the oil and coal potential as well as the increasing ecotourism the area has seen in recent decades; two public use cabins have been built along Vitus Lake (Josberger et al., 2006). The increase in human activity can potentially affect the stickleback species pair population—a food source for salmon—since it is particularly sensitive to human impacts on water quality and water withdrawals (Weigner & von Hippel, 2010).

Given the relatively young population of the fish colonies in Vitus Lake and the surrounding watershed as well as the sensitivity of the stickleback species pair to human presence, research is needed to shed light on whether increased human activity in the Bering Glacier system can negatively impact this ecosystem if a state park is indeed created as well as what are the risks to the human community if Bering Glacier surges again.

1.5 | Decision-making in environmental management

Structured decision-making is a collaborative, facilitated application for group decision-making (Gregory et al., 2012). Specifically, in the context of environmental management, structured decision-making allows for the utilisation of analytical methods from the fields of decision analysis and applied ecology, as well as cognitive psychology and group negotiation (Gregory et al., 2012). The decision-making is based on the five steps of the PrOACT process which aim to identify: (1) problems; (2) objectives; (3) alternatives; (4) consequences; and (5) trade-offs (Hammond et al., 2015). Each step of the structured process can have varying levels of both rigour and complexity, depending on the nature of the decision and the incentives, resources, and time available (Gregory et al., 2012). Structured decision-making is meant to be used as a methodological, iterative framework for decision-making. However, the process is meant to be flexible as it is iterative. From complex modelling to intensive, long-term data collection to elicitations and interviews conducted over the span of a few days, the resources and effort involved in a structured decision-making process are dependent on the questions being asked and the decisions being made. The essence therefore is to provide a transparent thinking process that helps to mitigate biases such that decision-making is undertaken in a consistent manner, in order to attain high-quality outcomes after careful consideration of the range of relevant concerns. Given that structured decision-making is meant to be a collaborative group process, the definition of what is a quality outcome as well as what are the relevant concerns for stakeholders are meant to be defined as part of the process. Each process and set of definitions will therefore be unique to the situation and individuals involved. As Brugha (2004) points out, while the process is not entirely formal, it is still well-structured and can thus be followed in an effective way.

In general, structured decision-making requires long-term institutional commitment—whether at the individual or organisational level—in order to ensure the process is maintained and built upon in future decision-making. There is consequently the risk that future stakeholders and managers will not uphold the process (Gregory et al., 2012). In addition, it can be challenging to implement a structured approach in institutional settings that are not already transparent and committed to transparency as an organisational value (Gregory et al., 2012). It is also important to ensure that participants and beneficiaries have realistic and appropriate expectations of what can and cannot be achieved from a structured approach. In addition, commitments must be made to sustain the longevity and proper application of the approach over time.

Ohlson et al. (2005) assessed how a structured decision-making approach supported forest managers in Canada in their development of climate change strategies at the local, regional, and national scales. A structured process in this context provided easy-to-understand guidance that decision-makers required to develop and evaluate climate change adaptation strategies. Importantly, the process helped to contextualise for decision-makers in this study that climate change is only one of several other issues that need to be addressed in planning, helping decision-makers realistically and actively evaluate various trade-offs. Ogden and Innes (2009) also applied a structured decision-making approach to the Canadian forestry sector, by assessing climate change vulnerabilities and adaptation options via eliciting knowledge from local forest practitioners. They found that though a focus on future decision-making—particularly related to climate change—is a part of planning, an understanding of current practices is important to ensure viable adaptation options are considered.

Martin et al. (2011) investigated how structured decision-making can be applied to decision-making in a different sector. At the time of their paper, though structured decision-making was gaining traction in the conservation management sector, it had not yet been applied to the sea-level rise sector. This is largely due to structured decision-making generally assuming that the systems and processes at play are fairly stationary whereas in the sea-level rise sector, the processes at play are non-stationary and continuously changing. They found that though many of the structured decision-making tools can be adapted to a non-stationary system, optimising solutions is more challenging, given the difficulty of capturing a problem with extreme dimensions.

Though the above examples and many others (Lienert et al., 2015; Wilson & McDaniels, 2007) highlight the benefit of structured decision-making in elucidating realistic solutions for decision-making, particularly in light of complex challenges related to climate change, gaps exist in the literature for developing concrete methods that actively take into account the multitude of uncertainties related to climate change (Martin et al., 2009). Specifically, challenges exist with how to capture unintended or unforeseen consequences in structured decision-making approaches regarding large structural (e.g., environmental) uncertainty contexts (Martin et al., 2009; Nichols et al., 2011). This paper aims to actively address this gap, by looking into how a structured decision-making framework can be developed for a large structural uncertainty context, specifically a glacier surge context.

2 | METHODS

We utilised the existing literature to inform our understanding of the Bering Glacier system and to develop our theorised structured decision-making application. To clarify the decision context step, we developed a problem statement in which we identified: the decision-makers who would make the decision, the reasons for the decision and why it mattered, the time period of the decision, as well as the constraints that need to be taken into consideration for the decision. We also identified the following decision-makers, hereafter referred to as stakeholders, by not only their involvement in the decision process, but also by the extent to which the decision would affect them: Alaska Department of Natural Resources, US Bureau of Land Management, US Geological Survey, commercial recreational guides, Alaska Department of Tourism, and Alaska Department of Fish and Game.[1] In structured decision-making, the goal is for all stakeholders to work together to reach a common decision. However, it is important to note the variability in each stakeholder's ability to affect the final decision, as well as how the decision can potentially impact each stakeholder. Given the small number of stakeholders, and the fact that most identified stakeholders are state or federal agencies, the ability of each stakeholder to affect the final decision was deemed as high for the purposes of this application. However, we identified that commercial recreational guides might not have as much impact to affect the final decision, given that the development of a state park and any other land management-related decision would need to ultimately be implemented from the state or federal level.

We defined the objectives for this structured decision-making application by identifying both fundamental and means objectives. Fundamental objectives are objectives that are essential to be met by any decision made while means objectives are those which help to achieve fundamental objectives. Measurable attributes were also developed to help quantify the achievement of an identified objective. We identified three possible decision outcomes, hereafter referred to as alternatives, which were considered in the case study (Figure 2).

We estimated the possible outcomes in relation to the objectives in Table 1. In order to evaluate the trade-offs between the alternatives, we first normalised the alternatives using a standard min-max normalisation score, $N_{Score}(A_i)$:

$$N_{Score}(A_i) = (s_{ij} - \min(s_j))/(\max(s_j) - \min(s_j)) \quad (1)$$

where s_{ij} represents a value in the set s_j and $\min(s_j)$ represents the lowest value in the set s_j and $\max(s_j)$ represents the highest value in the set s_j. This normalisation is done automatically in the DecideIT tool, see Table 4. That table shows $\max(s_j)$ and $\min(s_j)$ for all criteria considered. These are automatically kept track of by the tool and converted to [0, 1] scales prior to calculations by the user interface which converts each alternative's value to the corresponding N_{Score} before calling the inference and calculation engine (Danielson et al., 2003).

The higher the normalised score, the higher the alternative was ranked in the trade-off analysis (Tables 2–6). Since such a measure is quite rough, we supplemented it with a basic decision analysis (modelled in the decision tree in Figure 6). The actual evaluation principle was the ordinary expected mean of the respective alternatives,

$$E(A_i) = \Sigma w_j v_{ij} \quad (2)$$

where A_i is an alternative, v_{ij} is the estimated value of alternative A_i, under criterion j and w_j is the relative weight of that criterion. Thus, this employs the traditional multi-attribute value theory (MAVT) approach, which is then accompanied by the principle of maximising the expected value (PMEV) for ranking the alternatives under the totality of criteria.

More formally, the methodology applied rests on interval representations for both criteria weights and utilities/values. This enables the model to handle classes of value functions with infinitely many instantiations, which allows it to model different non-linear value functions without resorting to methods mostly associated with point-wise representations, such as, for example, the mid-value splitting procedure. Instead, the partial swing method is used for weight/scale elicitation, in which sub-ranges of the scales are compared via weights (Danielson & Ekenberg, 2019). Regarding normalisation of the value scales, this is done automatically in the decision-analytic software tool, in conjunction with the weight trade-off. Due to the scale/

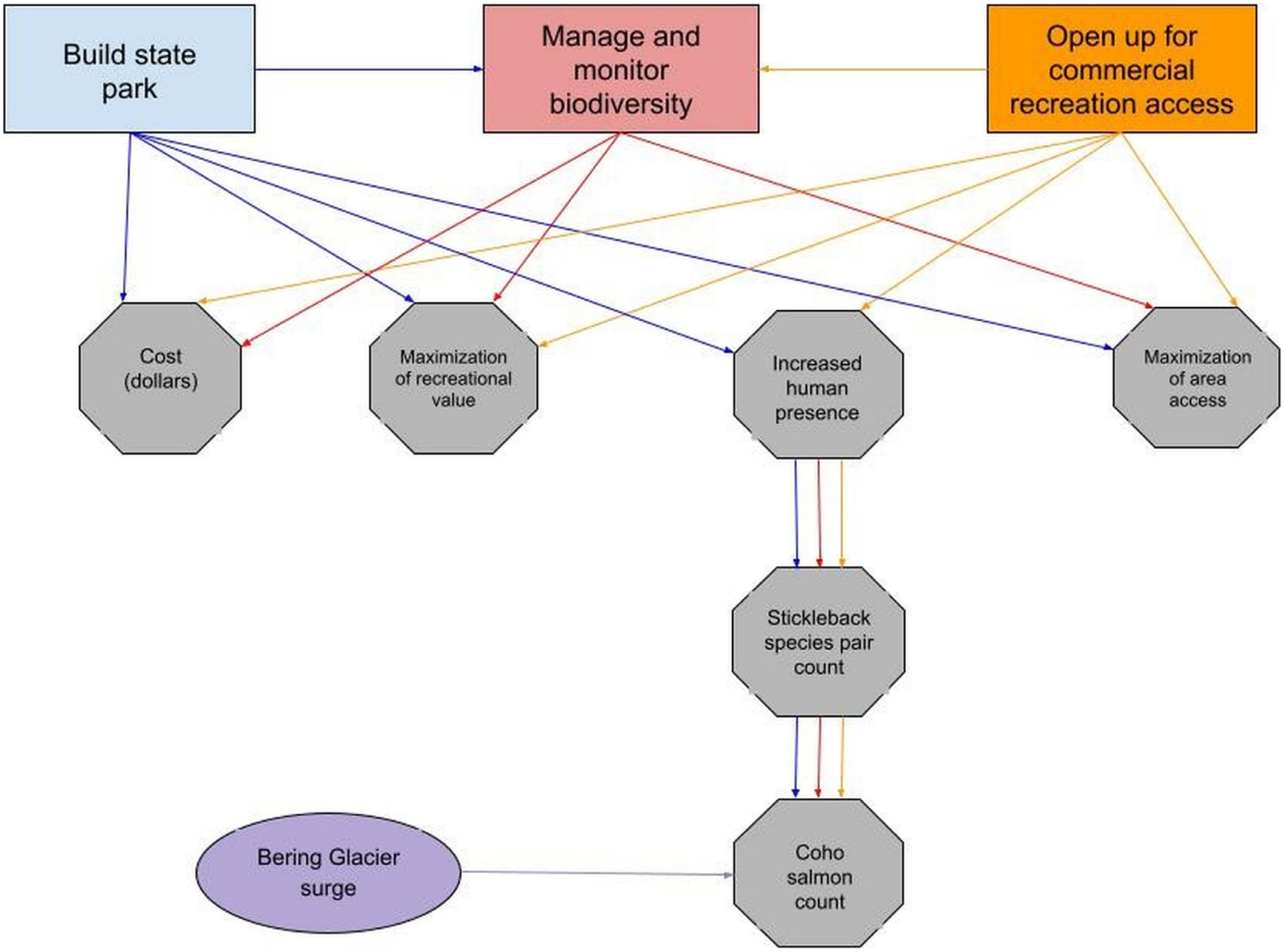

FIGURE 2 Influence diagram. Depicts the three alternatives considered in this study (boxes), the values considered to help achieve the identified objectives (hexagons), and the uncertainties associated with the decision-making process (oval). Corresponding arrows showing the relationship between the different alternatives and objectives are colour-coded accordingly. The uncertainty considered in this study, the Bering Glacier surge, predominantly affects the coho salmon count. We therefore considered it in the context of its potential impact on the coho salmon population.

TABLE 1 Objectives and measurable attributes of a decision.

Objective	Type of objective	Measurable attribute	Scale	Direction
Continue scientific research of the Bering Glacier area	Means	Number of field campaigns to Bering Glacier each year	Numerical	Maximise
Build scenic value of the Bering Glacier area	Means	Number of state parks or commercial recreational tours to Bering Glacier each year	Numerical	Maximise
Ensure local biodiversity of the Bering Glacier area	Fundamental	Population count of coho salmon and stickleback species pair	Low/medium/high	Maximise
Strive to better model the next surge(s) of the Bering Glacier	Fundamental	Determination or approximation of next Bering Glacier surge	Yes/no	Maximise

Note: The identified objectives were developed based off a review of the literature and state documents (see Introduction section). Each objective is classified as either a fundamental or a means objective. Fundamental objectives are objectives that are essential to be met by a decision while means objectives help to achieve fundamental objectives. Measurable attributes were also developed to help quantify the achievement of an identified objective. Scale describes how a measurable attribute is measured and direction refers to whether an objective is sought to be maximised or minimised. All the objectives identified for this study were sought to be maximised.

TABLE 2 Initial consequence table.

		Alternatives (decisions)		
Objective	**Goal**	**Build state park**	**Manage and monitor biodiversity**	**Open area for commercial access**
1. Continue scientific research of the Bering Glacier area *Measured by: number of field campaigns to Bering Glacier each year*	Maximise	[1, 2, 3]	[3, 4, 5]	[1, 2, 3]
2. Build scenic value of the Bering Glacier area *Measured by: number of state parks or commercial recreational tours to Bering Glacier each year*	Maximise	[8, 9, 10]	[0, 1, 2]	[6, 7, 8]
3. Ensure local biodiversity of the Bering Glacier area *Measured by: Population count of coho salmon and stickleback species pair*	Maximise	Medium	High	Low
4. Strive to better model the next surges of the Bering Glacier *Measured by: Strive to better model the next surge(s) of the Bering Glacier*	Maximise	Yes	Yes	Yes

Note: Each objective, as identified in Table 1, is listed along with its measurable attribute and its goal. All objectives were sought to be maximised in this analysis. Three alternatives (see Figure 2) were assessed. A value was determined for each objective, based off the alternative. It is important to note these values are theoretical, however, they are grounded in logical assumptions regarding how each alternative would potentially impact each objective. For example, we sought to measure the achievement of the continued scientific research of the Bering Glacier area objective via the number of field campaigns to the Bering Glacier area. If a state park was built or if the area was open for commercial access, we assumed no changes would occur to the number of field campaigns (2). However, for the manage and monitor biodiversity objective, we assumed we would see an increase in the number of field campaigns, due to the need to collect observational data for management and monitoring decisions, hence, the assignment of 4 versus 2 field campaigns. It is important to note the numbers chosen are not an indication of precise measurements but rather, an illustration of the relational differences between the values for each alternative.

TABLE 3 Consequence table with all valuations expressed as interval triplets. We converted the values for objectives 3 and 4 (see Table 2) to the same 10-point scale, with 10 being the maximal value.

		Alternatives (decisions)			
Objective	**Goal**	**Build state park**	**Manage and monitor biodiversity**	**Open area for commercial access**	**Notes**
1. Continue scientific research of the Bering Glacier area *Measured by: Number of field campaigns to Bering Glacier each year*	Maximise	[1, 2, 3]	[3, 4, 5]	[1, 2, 3]	
2. Build scenic value of the Bering Glacier area *Measured by: Number of state parks or commercial recreational tours to Bering Glacier each year*	Maximise	[8, 9, 10]	[0, 1, 2]	[6, 7, 8]	
3. Ensure local biodiversity of the Bering Glacier area *Measured by: Population count of coho salmon and stickleback species pair*	Maximise	[5, 6, 7]	[8, 9, 10]	[0, 1, 2]	
4. Strive to better model the next surges of the Bering Glacier *Measured by: Striving to better model the next surge(s) of the Bering Glacier*	Maximise	[4, 5, 6]	[4, 5, 6]	[4, 5, 6]	Same interval but not identical variables in calculations

weight duality, where changing the range of a scale implicitly alters the weight and vice versa, value scale normalisation is carried out in parallel to weight elicitation.

In this model, the alternatives are considered to be mutually exclusive and exhaustive. This modelling assumption can be justified by the nature of the exercise which is a theoretical exploratory investigation. The alternatives are broad and directed towards different kinds of measures available rather than very precise and clear-cut packages of action. Further, the criteria are assumed to be preferentially independent at this stage of the modelling since they are of such differing natures as to not interfere with each other in any substantial way. Other uncertainties in the model are expected to be higher and thus more important to try to keep under control. Based on a study with 100 decision-makers, where each one made

	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Output
Minimal value	1.0	0.0	0.0	4.0	0.0
Maximal value	5.0	10.0	10.0	6.0	10.0
Trade-off	0.625	0.25	0.25	1.25	

TABLE 4 Automatic scale function. The scale for each criterion (objective) can either be automatically determined or entered manually. The trade-off number indicates how much one unit under one criterion is worth on the output scale.

TABLE 5 Normalised consequence table. The normalisation of the values, based on their min–max range, from Table 3 using Equation (1). Normalising values ensures that they can be compared across different objectives.

		Alternatives (decisions)		
Objective	Goal	Normalised—build state park	Normalised—manage and monitor biodiversity	Normalised—open area for commercial access
1. Continue scientific research of the Bering Glacier area *Measured by: Number of field campaigns to Bering Glacier each year*	Maximise	[0.00, 0.25, 0.50]	[0.50, 0.75, 1.00]	[0.00, 0.25, 0.50]
2. Build scenic value of the Bering Glacier area *Measured by: Number of state parks or commercial recreational tours to Bering Glacier*	Maximise	[0.80, 0.90, 1.00]	[0.00, 0.10, 0.20]	[0.60, 0.70, 0.80]
3. Ensure local biodiversity of the Bering Glacier area *Measured by: Population count of coho salmon and stickleback species pair*	Maximise	[0.50, 0.60, 0.70]	[0.80, 0.90, 1.00]	[0.00, 0.10, 0.20]
4. Strive to better model the next surges of the Bering Glacier *Measured by: Striving to better model the next surge(s) of the Bering Glacier*	Maximise	[0.40, 0.50, 0.60]	[0.40, 0.50, 0.60]	[0.40, 0.50, 0.60]

TABLE 6 Criteria (objective) weight table.

		Relative weight intervals from the swing process		
Objective	Goal	Interval min-point (%)	Most likely weight (%)	Interval max-point (%)
1. Continue scientific research of the Bering Glacier area	Max	20	30	40
2. Build scenic value of the Bering Glacier area	Max	10	20	30
3. Ensure local biodiversity of the Bering Glacier area	Max	35	45	55
4. Strive to better model the next surges of the Bering Glacier	Max	3	5	7

Note: Based on our review of the literature and state documents, we found that the seemingly most important objective of land management in the Bering Glacier area is to ensure local biodiversity. We assumed a weight of 45% for this objective, to reflect our perceived stakeholder priority. We assumed, also based on our review of the literature and state documents, that the 'continue scientific research' and 'build scenic value' objectives were also of considerable importance, though with the research interest in the area, due to its glacier surge phenomenon, the 'continue scientific research' objective potentially carries more weight. We therefore assigned a 30% weight to continue scientific research and a 20% weight to 'build scenic value', while the remaining 5% went to the lowest-ranked criterion, 'strive to better model'.

one large decision over a 2–3-week period of time, the model refrains from pairwise comparisons of criteria weights other than in the swing stage (Danielson & Ekenberg, 2019). Although tempting from an information perspective (i.e., the more information, the more firmly based conclusions), in reality, it turned out that the increased elicitation complexity did outweigh the presumed advantages (Danielson & Ekenberg, 2016).

To sum up, the model uses interval extensions for the criteria weights and alternative values. This representation enables the model to capture uncertainty in model parameters and data. An interval can express both a set of specific values and, by its width, the current level of uncertainty for each variable (parameter). This is important when handling subjective information which invariably contains uncertainty. The decision information is stored in interval constraints, which is a shorter form for a pair of inequalities. For each kind of data (criteria weights, probabilities, values), the interval information forms a constraint set. By applying the principle of maximising the expected value, a ranking of alternatives can be obtained. Because of the intervals, different alternatives can dominate in different parts of the solution space. By comparing the hyper-volumes in which different alternatives are admissible, possibly convoluted by a belief mass function, a sensitivity analysis of the obtained preference order can be obtained. See (Danielson et al., 2020) for a formal discussion of the methodology.

The structured decision analysis in this paper was carried out using a method that allows for expressing second-order belief in intervals that each criterion (objective) weight and each value assessment under the criteria can take on. The weights and values are then represented by variables over which belief distributions are formed. The interval calculus and belief distributions stem from research conducted over a long period of time and have resulted in several decision analytic tools (Danielson, 1997; Danielson et al., 2003, 2020). A key observation is that imprecision and uncertainty over parameters and values are nearly always present. The DecideIT tool utilised in this paper enables built-in sensitivity analyses in the form of resulting beliefs in the obtained ranges of weighted expected values, see Section 3.4. Further, the process was divided into three distinguished steps: (a) identify criteria (Table 1); (b) identify alternatives and valuate them under each criterion (Tables 2–5); and (c) assess criteria weights relative to the available alternatives (Table 6).

The results from the decision tree analysis were then compared with the results from the consequence and trade-off analysis to evaluate whether the results were reproducible, such that the same alternative was deemed as the preferred decision in both analyses.

3 | RESULTS

3.1 | Clarify the decision context

Via our review of the literature on this topic as well as official state documents, we identified that the main goal of any decision regarding the Bering Glacier area is to maximise the scientific and scenic value of the area while minimising the impact on local biodiversity. For the purposes of this study, given the large uncertainty associated with when or if Bering Glacier will surge next, we consider the two cases of a surge and no surge with equal probabilities independent of the time frame within which a surge may occur. Thus, the aforementioned decision context was taken into consideration with the potential surge of Bering Glacier, the state's budget, the current health of the coho salmon population present in the area, as well as the ability of the area to serve as a scientific and recreational resource in mind, as outlined in Figure 2 (Yakataga Area Plan, n.d.).

As discussed in the Methods section, the stakeholders we considered for this study were based on their ability to not only affect the decision-making process, but also the extent to which a decision would affect them as well.[2] Given the remoteness of the Bering Glacier system, most of the stakeholders able to affect a decision in this context would be state and federal agencies mandated with overseeing or monitoring the area.

3.2 | Clarify objectives and measures

Table 1 outlines the fundamental and means objectives we identified as part of our structured decision-making exercise as well as the measurable attributes for each objective, based on indicators that could be collected and measured for each objective. It is also important to note that all of the objectives were sought to be maximised.

3.3 | Develop alternatives

Three alternatives (see the boxes in Figure 2) were identified as potential solutions to meet the fundamental and means objectives, based on our assumptions from a review of the literature. They were: build a state park, manage and monitor biodiversity, as well as open up the area for commercial recreation access. We were interested to see which alternative was the most preferred one considering the impacts (see the hexagons in Figure 2) and uncertainty (see the oval in Figure 2) of the decision, as informed by our review of the literature (see Section 1). It is important to note that the only notable uncertainty of outcome[3] in this study was whether Bering Glacier would surge during the next 5 years. Building a state park was the only alternative that influenced all the identified impacts.

3.4 | Estimate consequences

Tables 2–5 relay the process of consequence table analysis. We first provided values (see explanation in Table 2 caption) for each alternative for how they would contribute to the four identified objectives (Table 2). According to the measurable attributes and their scales as well as our understanding of the Bering Glacier system context, we provided values for each alternative. The values were expressed on a scale [0, 10] with an interval around each most likely value. This imprecision stems from two sources. First, each stakeholder group has slightly differing views on the merit of each alternative action under consideration. Second, there is an element of imprecision in any value estimate of this kind. Thus, we model the imprecision by an interval with a most likely value included. In Tables 2 and 3, this is represented as triplets [a, b, c] where a and c are the endpoints of the interval and b is the most likely value.

Next, we converted all the consequence values to a 10-point scale so that we could assess if any objectives were irrelevant; meaning for each alternative, each value for said objective was the same (Luo & Cheng, 2006). Even though we found that the 'striving to model the next surges of the Bering Glacier' objective was given the same assessment ('Yes'), there could still be a variation in how impactful it would be for the three alternative courses of action (Table 3).

Thus, we did not remove this objective from further analysis and consideration. Since the intervals are not variable identities, two values in the same range, for example [4, 5, 6], can, in the ensuing analysis by the DecideIT tool, take on different instantiations for different alternatives. This is automatically taken into account by the calculation engine of the tool (Danielson et al., 2020) and constitutes part of the sensitivity analyses.

The tool DecideIT automatically normalises the consequences using Equation (1), in order to compare them against one another. For clarity, we show the internal calculation values in Table 5. Table 4 shows how the automatic scale functions. While this is seldom necessary, if a decision analyst desires to do so, the scales can be manually changed.

3.5 | Evaluate trade-offs

Once the consequences are normalised, the next step is to assign weights to the different criteria (objectives), in order to ensure that the most preferred alternative elucidated after normalisation was not due, or sensitive, to an underlying dominant objective(s) (Table 6). We weighed each objective based on our perceived importance of each objective concerning how it would meet the fundamental objective assessed in this study, which was 'ensure local biodiversity of the Bering Glacier area'. It is very important to note that these weights are relative in the sense that they pertain only to the values expressed for the various alternatives under that criterion. There exists no such thing as absolute weights. Hence, statements like '"continue scientific research" is more important than "ensure local biodiversity"' are meaningless as standalone statements. They only make sense relative to the decision context, cf. (Danielson & Ekenberg, 2019) for a discussion on so-called swing weights. In the ensuing swing weighting process, the objective 'ensuring local biodiversity' was assigned the highest weight followed by 'continuing scientific research' and 'building scenic value' with 'strive to better model' in the last position; see Table 6 and the accompanying model in Figure 3.

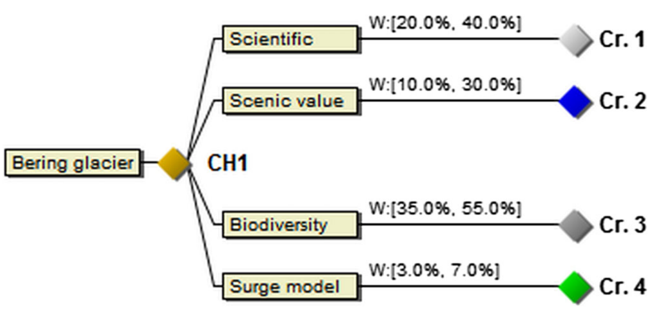

FIGURE 3 Final set of criteria (objectives). The final set of criteria (CH1) together with the relative (swing) weights (W) for each criterion (Cr.x, x ∈ {1,…,4}) in this particular problem model. For each criterion, the weight interval in percent is displayed after 'W:'. Note that if any value estimates are changed, the swing weights need to be revisited afterward.

After the weights were applied in DecideIT, we were able to gain a primary result, based on calculating all the distributions of second-order belief in the objectives' values for each alternative. The primary results are shown in Figure 4.

The primary results indicated with very high confidence (96% of the total belief) that the 'manage and monitor biodiversity' alternative was the most preferred, with a mean score of 0.675 on a [0, 1] result scale (i.e., reaching 67.5% fulfilment of a hypothetical optimal alternative), followed by 'build a state park' (0.550) and 'open area for commercial access' (0.285). The results in Figure 4 are also inherently a sensitivity analysis since the decision-maker's belief in all the ranges in Tables 3–6 are simultaneously taken into account. See Danielson et al. (2020) for an explanation of the details of belief calculations.

Nonetheless, as an extra sensitivity analysis, the interval ranges of either or both the criteria (objective) weights and assessed values were doubled in width, that is, all endpoints were set twice as far from the most likely points compared to Tables 3–6 and Figure 4. The results of widening (doubling) weights, values, and both were that the confidence shrunk to 90%, 83%, and 78%, respectively. The result of this extreme value analysis for weights is shown in Figure 5. The mean scores naturally stayed the same since it was the uncertainty intervals and the accompanying belief distributions that were widened. This extreme sensitivity analysis indicates very large stability in

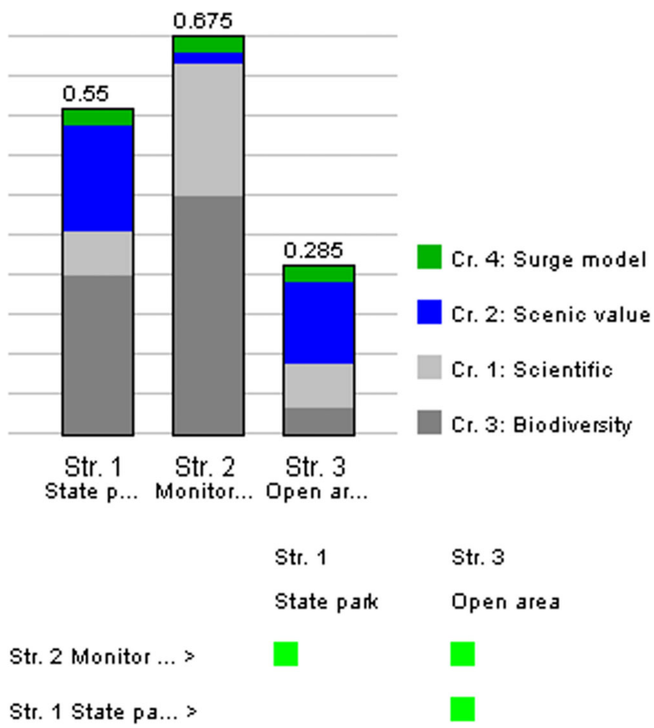

FIGURE 4 Results for the primary evaluation. The vertical bars show the weighted expected value of each alternative (here called strategy, Str.y, y ∈ {1,…,3}). The coloured parts show how much each criterion (Cr.x, x ∈ {1,…,4}) contributes to the total result. Further, the small squares show how confident the ranking is between two alternatives (green means very confident).

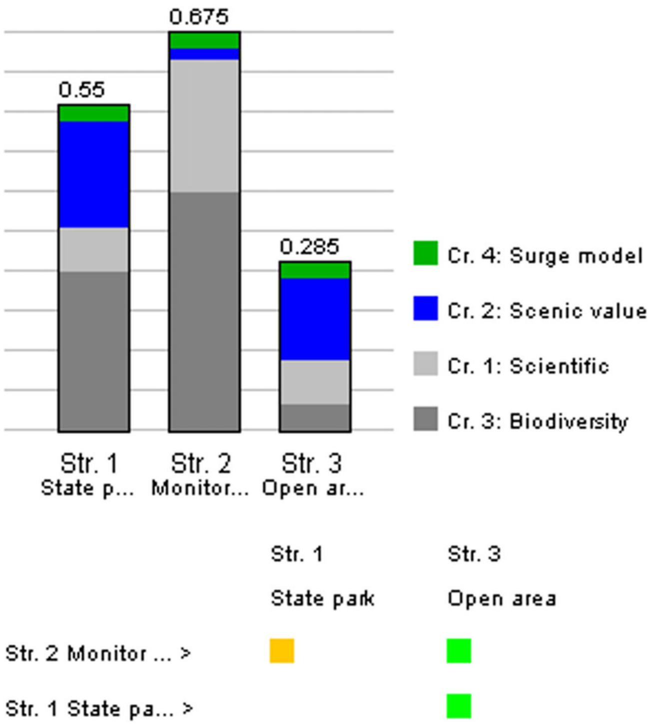

FIGURE 5 Result for the secondary, more extreme evaluation. Again, the coloured parts show how much each criterion (Cr.x, x ∈ {1,…,4}) contributes to the total result and the small squares show how confident the ranking is between two alternatives (green means very confident, yellow means moderately confident).

the result, even when taking the inherent imprecision of the input data into account.

3.6 | Implement, monitor, and review

Lastly, we checked if the results from our consequence table were reproducible by conducting a decision tree analysis (Figure 6). Given the complexity of the uncertainty of the Bering Glacier surge, we conducted a decision tree analysis primarily to see whether managing and monitoring biodiversity was worth the effort, given the potential of the area to experience another glacier surge soon. We assigned the theorised probabilities according to the range of possibilities based off our knowledge and understanding of the Bering Glacier context. The outcomes—the effect on stickleback species pair—were theorised based on the literature regarding their sensitivity to human impacts (Weigner & von Hippel, 2010) and did not include any observational data.

Each alternative is represented as a branch in the decision tree, and each decision node is given a probability of occurrence, terminating with an outcome. Once the decision tree was created, we calculated expected values based on Equation (2) for managing and monitoring biodiversity (E(yes)) and for not managing and monitoring biodiversity (E(no)) resulting in $E(yes) = 14.8$ and $E(no) = 28.9$.

Our goal was to minimise the expected value in this context—we wanted to see *less* of an effect on stickleback species pair. The expected value for managing and monitoring biodiversity was lower than that for not managing and monitoring biodiversity ($14.8 < 28.9$). Therefore, the decision tree analysis confirmed the same results of the consequence table analysis; that managing and monitoring biodiversity was the preferred solution. The formation of the criteria tree was thus a semi-structured process that was validated through comparisons with the consequence table, a procedure that helped align the criteria set with the problem formulation and its analysis. It is our observation that this process was both flexible but still reasonably structured and that a more structured process would not have added to the quality of the outcome of the modelling exercise. Using a systematic approach to create the criterion tree is advantageous for multi-criteria decision-making since it allows for organising the process. The decision-making process therefore resembles a dialogue between criteria and alternatives, a process of learning for the decision-makers, and a gradual reduction of the best options. Nevertheless, intervals of criteria weights and consequence values can be changed in that process through debates and discussions in an iterative way.

4 | DISCUSSION

Surging glaciers are a unique part of the Alaskan cryosphere. However, their impact on the broader socioecological system in the state is both poorly understood and under-researched. It is as important to understand the management frameworks as the biophysical changes that are taking place in glaciated regions, to create adaptation strategies that are both holistic and realistic of the actual situation in these regions.

This paper assessed several different scenarios regarding the potential surge patterns of Bering Glacier, which can have potentially devastating effects on the local ecological biodiversity of its watershed, particularly if humans have an increased presence near the glacier due to the area potentially becoming a state park. We utilised a structured decision-making theoretical exercise to explore the effect of three different management alternatives on the Bering Glacier area: build a state park, manage and monitor biodiversity, and open up the area for commercial recreation access.

Managing and monitoring biodiversity was the preferred solution that was derived from this exercise, which potentially suggests that the decision to build a state park or not is not necessarily a binary decision. Rather, ensuring the local biodiversity is well protected and monitored opens up the opportunity for decision-makers to explore other possibilities, such as the development of a state park, but within the confines of an established ecosystem preservation effort.

Although a structured decision-making approach can be advantageous to decision-makers in this Bering Glacier case study, there are factors associated with utilising such an approach that can nonetheless lead to a structured decision-making 'failure'. Namely, if there is no long-term institutional buy-in and commitment to utilising such an approach year after year in decision-making, the benefits of employing a structured decision-making approach will be short-lived and perhaps even non-existent. Furthermore, if there are stakeholders who deeply contest some, if not all, of the potential decision-making

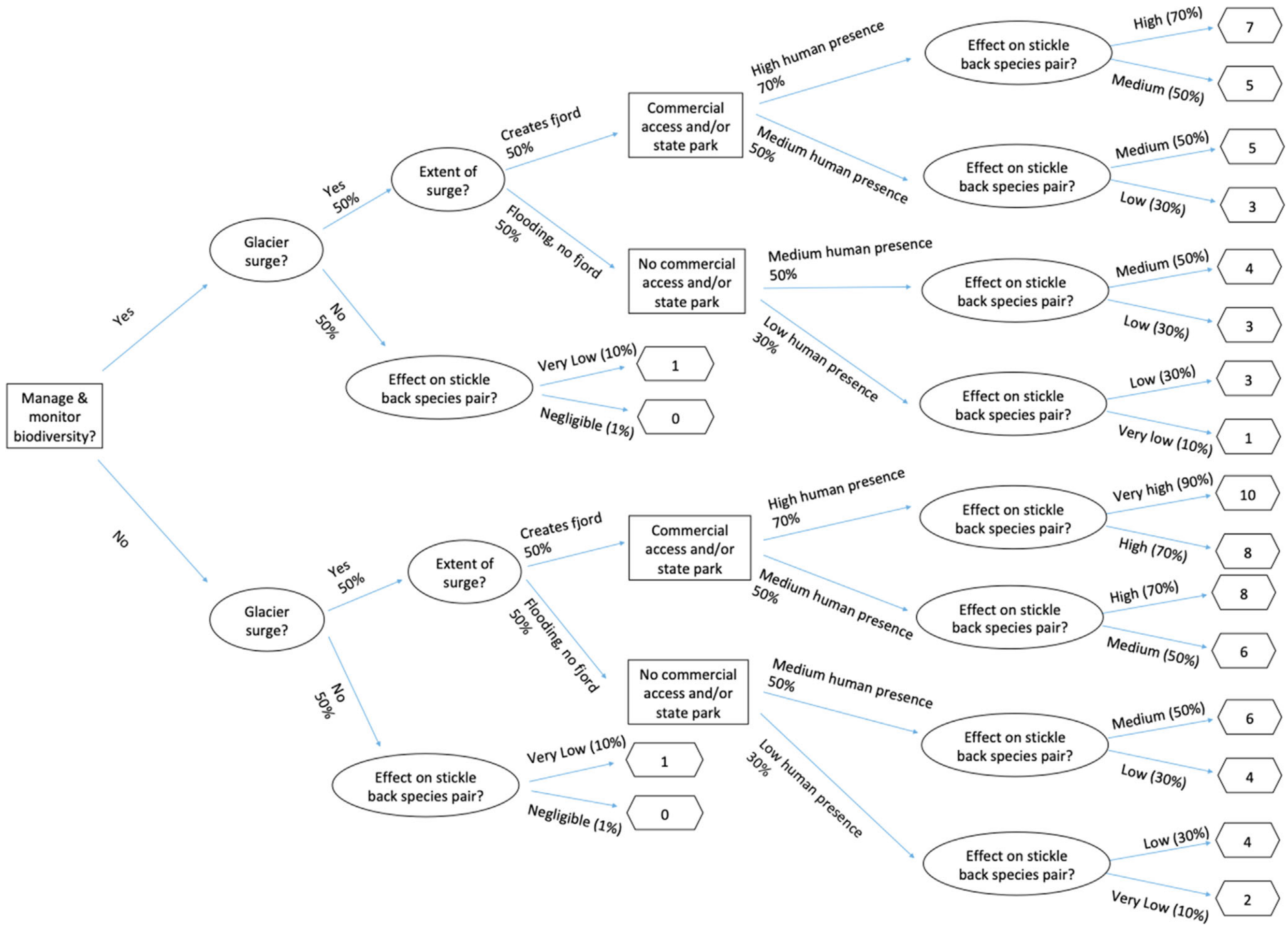

FIGURE 6 Decision tree analysis. Used to assess the expected value of undertaking and not undertaking the *manage and monitor biodiversity* decision. Decisions undertaken in this analysis are represented as boxes. Given that opening a state park and the area for commercial access would both increase the human presence in the Bering Glacier area, they were put into the same decision box to simplify the decision tree analysis. Uncertainties are represented as ovals. Each uncertainty has an upper bound (top arm) and a lower bound (bottom arm) associated with it. The probabilities (percentages) used for each bound were determined based off a review of the literature and state documents. They are meant to signify the potential range of possibilities rather than serve as precise estimates of chance occurrence. Lastly, the outcome assessed in this decision tree analysis, the effect on stickleback species pair, is represented as a hexagon. This is a 10-point scale, where 10 represents the highest negative impact on the stickleback species pair. The scale was determined via a review of the existing literature and state documents. Based on the decisions and upper and lower bounds associated with each set of uncertainties, each outcome reflects the extent to which the management decisions and the associated uncertainties affect the stickleback species pair.

alternatives, the ability to accurately carry out a structured decision-making decision will be greatly compromised and potentially completely blocked. Lastly, if decision-makers ultimately find the uncertainties associated with a surge event to be too large to optimise any, or all, potential alternative solutions, it will not be possible to use a structured decision-making approach to help elucidate viable alternatives given the large, and non-parameterisable, uncertainty.

4.1 | Review of the structured decision-making method in a cryospheric hazard context

Our methodology application suggests that structured decision-making can lend itself well to analysing stakeholder needs and objectives regarding cryospheric hazards. Importantly, the use of a structured process can potentially support stakeholders to arrive at well-informed decisions regarding cryospheric hazard management. Particularly in contexts where there is not an ample amount of scientific information or observational data available to assess the socioecological impacts of these types of hazards, such as in the Bering Glacier case study, our theoretical application of structured decision-making was conclusive and robust, in that the results were reproducible.

The results from this initial informal analysis, however, suggest the need to validate our findings with stakeholder inputs. The preferred alternative, to begin with, was ‘build a state park’. However, after conducting a more formal decision analysis including a sensitivity analysis, the preferred decision became ‘manage and monitor biodiversity’ by a wide margin. We were able to reproduce this result via the decision tree analysis, which supported the robustness of this result. Nonetheless, without utilising actual stakeholder inputs, we cannot ascertain that these findings are reflective of the preferred decision in a real-life setting. As with all quantitative decision analysis models, stakeholder elicitation is an important part of validating results from quantitative models. This being said, the goal of this paper was to demonstrate the analysis framework. A natural next step therefore would be to collect real-life data to be used as model inputs.

Nevertheless, the results of our study show the potential merits of employing structured decision-making to help empower stakeholders to arrive at a decision, despite limited information. The power of structured processes lies less in their quantitative modelling abilities and instead, in their ability to serve as a transparent and group-based process, where different stakeholders come together to find common goals, such that they use this commonality, despite limited information, to arrive at a decision together.

4.2 | Limitations

The framework is theoretically motivated, but not validated in terms of stakeholder engagement, limiting our ability to confirm our assumptions regarding the objectives, the weighting scheme for each objective, as well as the values asserted in the consequence tables and the decision tree. Importantly, we did not include Alaska Native perspectives in order to not portray perspectives that are not ours to portray. However, we recognise that by not including Alaska Native stakeholders in our hypothetical exercise, we are missing a critical and important group of stakeholders. Therefore, in our future research, we will work to ensure we discuss our work and gather perspectives from affected Alaska Native stakeholders.

The particular values and weight estimates are also hypothetical and the main concern in this paper is to demonstrate the usefulness of the actual framework rather than present conclusive particular results. In our future research, we will therefore investigate whether different weighting schemas could meaningfully be applied in real settings, such as P-swing weight elicitation (Danielson & Ekenberg, 2019), in addition to taking feasible sets of weight and probability distributions and aggregations into account (Danielson et al., 2020).

4.3 | Application to other glacier hazard scenarios and future research

More research is necessary from both a physical science and a decision and risk analysis perspective to understand the changes to glaciers in Alaska as well as how these changes affect and impact socioecological systems and communities. Researching surging glaciers and their socioeconomic impact in Alaska can support further research efforts and understanding regarding the combined socio-cryospheric systems. Longitudinal glacier data in Alaska, particularly for a large subset of glaciers, has been limited up until now due to the difficulty and demanding level of resources (i.e., time and money) that would be necessary to create a dataset like this. However, recent datasets that have been created regarding surging glaciers—such as the worldwide surging glaciers inventory via data from the Randolph Glacier Inventory[4] in addition to the glacier surface velocities map[5]—provide an opportunity to do more macro-level research on surging glaciers and their impacts on communities in Alaska and elsewhere. Datasets such as these can be combined with community-level data (infrastructure, natural resources, and salmon runs) to understand the potential areas of impact from glacier surges. For example, overlaying socioeconomic indicator maps against surging glacier information can provide insights to see which glaciers can potentially impact local communities, particularly from indirect effects. By identifying at a macro-level the target areas of concern, more localised research and projects can consequently be undertaken to understand the local socio-cryospheric context more deeply, helping to pave the pathway to relevant and feasible adaptation and resilience strategies.

Though the Bering Glacier case study discussed above focused on one ecological impact of the glacier's surging, cryospheric hazards can have an even more direct impact on communities. Glacial lake outburst floods, avalanches, landslides, and seasonal and long-term glacier runoff variability can greatly and potentially catastrophic impact downstream communities (Carey et al., 2015). Indirect impacts, such as what is shown in this case study, can also occur, particularly for communities that do not live near glaciers. Tourism economies, energy production, and food security can also be dependent on glacial run-off. This research therefore shows how structured decision-making can support decision-makers, helping them ensure that proposed adaptation strategies to address cryospheric hazards are considered from a biophysical understanding of these hazards as well as their socioecological impact (Carey et al., 2015). Furthermore, though this research focused on the application of structured decision-making in one specific type of cryospheric hazard, there is merit in trying to apply it in other cryospheric hazard contexts—such as glacial lake outburst floods, permafrost thaw, and sea ice hazards—where these hazards impact nearby communities, both directly and indirectly, on a variety of different scales.

5 | CONCLUSIONS

Structured decision-making can help to illuminate a variety of options for decision-makers faced with making decisions with little information or even large uncertainty. This paper shows how utilising a decision-making methodology and tool, despite very large uncertainty surrounding the Bering Glacier's potential next surge, does not need to immobilise decision-making processes. Rather, by considering options and consequences in a transparent and transdisciplinary manner, decisions can be made and amended, as part of the iterative process structured decision-making promotes. It should be noted that the decision analytical approach used in this paper was simplified in several aspects to demonstrate the general idea. However, this general framework can be adapted to considerably more elaborate methods and processes, such as the ones proposed in, for example, (Danielson et al., 2020; Danielson & Ekenberg, 2019). Nonetheless, it is the authors' experience that this structured approach has aided us in arriving at a decision model that is relatively easy to understand and employ across different disciplines. Furthermore, it was relatively simple to evaluate the model using a standard decision analytic software tool, which allows this approach to be utilised by non-multi-criteria decision analysis experts as well.

In conclusion, our proposed approach can be used as a model for similar environmental challenges, helping decision-makers to find appropriate solutions to highly uncertain and complex environmental challenges, with the aim to achieve sustainable solutions in line with the goals of the UN SDGs.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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ENDNOTES

[1] See section 4.2 for a discussion on why we did not include Alaska Native perspectives.

[2] See section 4.2 for a discussion on why we did not include Alaska Native perspectives.

[3] This should not be confused with uncertainty (imprecision) stemming from inaccuracy in criteria weights and value statements.

[4] See: https://www.glims.org/RGI/

[5] See: https://asf.alaska.edu/data-sets/derived-data-sets/glacier-speed/

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