# Measuring the degree of ‘fit’ within social-ecological systems to support local decision-making: The case of flood-risk in Truro, Nova Scotia

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# Abstract

Social-ecological fit is a promising approach to environmental governance. Its bottom-up, inclusive methodology is particularly needed in the wake of climate change, as decision-makers must consider the social consequences as well as the ecological. Social-ecological fit, however, is limited by (1) inconsistent terminology in the literature, and (2) a lack of quantitative methods to assess its effectiveness in decision-making. To address these knowledge gaps, I (1) conducted a comprehensive literature review on social-ecological fit, and (2) adapted the use of Bayesian methods to quantitatively assess the effectiveness of social-ecological fit. I found that social-ecological fit encompasses a broad range of fit types, and that not every type is appropriate or applicable to every social-ecological issue. I also found that Bayesian methods can be used successfully to quantitatively assess local social-ecological fit. In light of these results, I describe how to apply social-ecological fit to decision-making processes, and discuss potential areas of future research.

# Résumé

L'étude de l'adéquation socio-écologique (ASE) est une approche prometteuse pour la gouvernance des écosystèmes. Dans le contexte des changements climatiques, où les conséquences sociales aussi bien qu'écologiques des décisions doivent être prises en compte, la méthodologie ascendante et inclusive prônée par l'étude de l'ASE est des plus adéquate. Toutefois, la compréhension de l'ASE est limitée par (1) une terminologie décousue dans la littérature, et (2) un manque de méthodes quantitatives d'évaluation de son efficacité à aider le processus de prise de décision. Pour combler ces lacunes, nous avons (1) effectué une analyse complète de la littérature existante et (2) adapté une méthode statistique bayésienne pour évaluer quantitativement l'efficacité de l'ASE. Nous avons constaté que l'ASE englobe un large éventail de types d'adéquation, et que tous les types ne sont pas appropriés ou applicables à toutes les questions socio-écologiques. Nous avons également constaté que les méthodes bayésiennes peuvent être utilisées avec succès pour évaluer quantitativement l'ASE, et nous suggérons qu'elles représentent une méthode financièrement accessible à l'échelle locale. À la lumière de ces résultats, nous décrivons comment appliquer l'étude de l'ASE au processus décisionnel et discutons des avenues de recherches pour le futur.

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Finally, I am incredibly grateful and thankful for the support of my family. My grandfather was a constant source of inspiration for me throughout this journey, as he has started his own Masters as well! My parents and siblings have been my #1 cheerleaders throughout this degree, through the highs and the lows. Thank you for believing in me even when I lacked the confidence in myself. This degree would not have been possible without you.

# Thesis Style and Contribution of Authors

This is a manuscript-based thesis containing three main chapters. Chapter 1 provides a general introduction of the thesis, including a description of the research objectives and general methodology. Chapter 2 is a literature review defining environmental governance and social-ecological systems, and describes how social-ecological fit is used within the literature. Chapter 3 applies the concept of social-ecological fit to a case study on flood-risk in Truro, Nova Scotia, Canada. In Chapter 3, I introduce the use of Bayesian methods to quantitatively assess social-ecological fit. Chapter 3 will be submitted for publication as a standalone research article in an academic journal. Chapters 4 and 5 contain a general discussion and conclusion, respectively. There may be some unavoidable repetition to the manuscript-based format of this thesis in different chapters and references.

I am the lead author for all of the thesis chapters. Dr. Gordon Hickey, my supervisor, and Dr. Julia Baird and Dr. Jennifer Holzer are all co-authors on Chapters 2 and 3. Drs. Hickey, Baird, and Holzer all assisted with manuscript editing. Valentin Lucet, a collaborator, is also a co-author on Chapter 3, and assisted with data cleaning and interpretation.

# Chapter 1

# General Introduction

**Gökotta** (noun, n, Swedish)

lit. "*dawn picnic to hear the first birdsong*"; the act of rising in the early morning to watch the birds or to go outside to appreciate nature

- Mak and Garrity-Riley [2016]

## 1.1 The Need for Effective Environmental Governance

It is not uncommon to see the failings of human effort to solve ecological problems. Case studies highlight the importance of matching institutional action (the physical, temporal, symbolic, and/or social action performed by a social network or governing body [Abrutyn, 2012]) to ecological problems, from the famous Love Canal Superfund site in the United States, [Beck, 1979], to the outdated and inaccurate Tiger population survey methods in

India highlighted by [Karanth et al., 2003]. An extreme case of a mismatch between institutional action and ecological need can be seen with the introduction of cane toads (*Bufo Marius*) into Australia. The cane toad was introduced to Queensland, Australia in 1935 in attempt to address the persistent and devastating impact that crop pests, particularly the cane beetle (*Dermolepida albohirtum*) and the French beetle (*Lepidiota frenchi*) were having on sugar cane fields [Shine, 2018, 2010]. From a social perspective, little consultation with local farmers and other local actors was taken regarding the introduction of this species, and ecological considerations of potential environmental consequences were minimal [Shine, 2018, 2010, Urban et al., 2008]. The limited social-ecological considerations by the governing bodies involved contributed to the colossal failure of this introduction soon after. The cane toad did not prey upon the pest species, partially because these beetles resided at the top of the sugar cane crops, and the cane toads were not willing or able to reach them [Shine, 2010]. In addition to this ecological misstep, the cane toad largely had no predators in its new environment, which led to its rapid reproduction and spread throughout Australia and incredible damage to local biodiversity [Shine, 2018, Jolly et al., 2015, Shine, 2010]. In addition to the ecological problems, the cane toad's poisonous nature makes it a public health concern [Gowda, 2003], and an economic irritation, as efforts to reverse the cane toad's ecological destruction remain an expensive, unresolved endeavour [Shine, 2018]. The famous cane toad case highlights the importance of strong social-ecological fit (SEF).

Social-ecological fit is the matching of actions from a social network to the needs of the ecological components or issues assigned to that network [Bodin, 2017, Epstein et al., 2015, Folke et al., 2007]. A social network can be composed of governing bodies, as well as scientists, farmers, Indigenous, First Nations, and Metis communities, government officials, and any actor who has stake in a social-ecological system or issue [Nohrstedt and Bodin, 2019]. Social–ecological fit attempts to make institutional action effective and efficient by using a bottom-up approach that works with the actors affected by the ecological issue [Bodin, 2017, Epstein et al., 2015, Bergsten et al., 2014]. This approach to environmental governance is typically analysed by how well a social-network responds to its designated ecological issue [Bodin, 2017, Guerrero et al., 2018, Ekstrom and Young, 2009].

For the purposes of this thesis, I adhere to Castree et al. [2009]'s definition of environmental governance: "the manner, organisations, institutional arrangements and spatial scales by which formal and informal decisions are made regarding uses of nature" [475]. This definition provides a solid backbone for the use of 'environmental governance' throughout this thesis. However, for this study, I concentrate on the 'fit' of the most promising solutions being selected for social-ecological problems, rather than just the spatial fit and network focus described in Castree et al. [2009]'s definition.

The so-called 'problem of fit,' whereby institutional action does not match its respective social-ecological issue, has been described and analysed for decades in the literature [Bodin, 2017, Folke et al., 2007, 1998]. Issues of fit are described by Young [2008] as the "functions of fit between the institutions themselves and the biophysical and social domains in which they operate" (1). This idea of fit was first described in Folke et al. [1998]'s discussion paper on social-ecological fit for the International Human Dimensions Program of Global Environmental Change (IHDP), which covered then current perspectives on social–ecological fit. The updated Folke et al. [2007] provided further reflections on the field, as well as proposed areas of future SEF research. This area of research has now grown to include sub-classes of fit, but there is generally a lack of clarity between various SEF sub-class definitions and place within the SEF 'family tree.' Despite this, SEF remains a promising approach to environmental governance.

## 1.2 Research Question and Objectives

The overall objective of this research is to introduce a quantitative method to assess the effectiveness of the social-ecological fit approach to environmental governance. To reach this objective, I answered the following research question:

1. How can the effectiveness of social-ecological fit be assessed to inform environmental decision-making? (Chapter 3)

In Chapter 2, I present a literature review of social-ecological system governance and fit and identify the types of fit commonly associated with social-ecological fit, and create a social-ecological fit 'family tree' to visualise how these types of fit are relate to each other.

Using this information, I create a definition of social-ecological fit that encompasses the variety of types of fit present in the literature, and identify the need for decision support tools.

In Chapter 3, I use the social-ecological fit approach to environmental governance to trial a method to quantitatively assess its effectiveness: Bayesian Belief networks and Bayesian analysis. I apply this method to the case of the North Onslow saltmarsh region of Truro, Nova Scotia. Truro suffers from extreme flooding events several times a year and could benefit from decision-support tools to inform local environmental decision-making. Using Bayesian Belief networks and analysis, I quantitatively assessed the social-ecological fit of the region by creating flood-risk scenarios based on information gathered from the literature and local experts.

## 1.3 General Methodology

### 1.3.1 Case Study

In Chapter 3, I adopt a case study approach to assess the potential for Bayesian Belief networks and analysis to 'measure' social-ecological fit. The case study, which took place in the North Onslow Saltmarsh region of Truro, Nova Scotia, analyzed environmental decision-making surrounding the issue of flood-risk. This site was chosen because it was well- suited as a 'testing ground' for my concepts: there was a clear social-ecological issue (flood-risk), and a need for a decision-support to enhance local environmental governance.

I selected a case study approach for two primary reasons: (1) a case study would provide an ideal ‘testing ground’ for the use of Bayesian Belief networks to assess social-ecological fit, and (2) within the literature on Bayesian Belief networks, case studies are a frequently used method. Ridder [2017] describes four types of case study design, one of which is the ‘gaps and holes’ approach, which I used for this project’s case study. The ‘gaps and holes’ approach generally has a predefined research question (or questions) and relies on pre-existing theory [Ridder, 2017, Yin, 2009]. This approach also relies on purposeful sampling, which can be done through surveys and interviews with relevant experts [Ridder, 2017, Yin, 2009]. The selected case study used all of these elements.

Case studies, while an excellent tool for addressing a research problem of interest, are criticised for their potential bias [Guba and Lincoln, 1981]. Potential bias can result from a researcher cherry-picking a case study location, results, and/or variables so as to display the findings that most suit his or her research ideals [Guba and Lincoln, 1981]. However, it should be noted that this issue of bias is not isolated to just case studies alone, and can be present in almost all academic research [Flyvbjerg, 2006].

Researchers have also critiqued case studies for their lack of generalizability [Hamel et al., 1993]. A case study is not necessarily representative of other systems, even if they have similarities. However, in his defence of case studies, Flyvbjerg [2006] notes that formal generalization is“overvalued as a source of scientific development, whereas “the force of example" is underestimated" (228). Additionally, Flyvbjerg [2006] notes the near impossibility of finding 'universals' within human systems.

### 1.3.2 Bayesian Belief Networks and Analysis

In Chapter 3, I use Bayesian Belief networks and analysis to quantify local social-ecological fit. Bayesian analysis makes use of conditional probability to make predictions that can inform decision-making [Bromley, 2005]. The results of Bayesian analysis are numeric probabilities. For the purposes of the present study, I equate the probability of the target variable of interest to the social- ecological fit of the system. The closer the probability is to the desired state, the better the social-ecological fit.

Bayesian Belief networks inform Bayesian analysis. A Bayesian Belief network is visual illustration of each of the relevant factors and their relationship to each other and the target factor of interest [Scutari and Denis, 2015]. This information is gathered from a review of the literature and consultation with local experts [Castelletti and Soncini-Sessa, 2007b, Bromley, 2005]. A Bayesian Belief network includes Conditional Probability Tables (CPTs) that contain the possible states for a factor, and those states' probabilities [Castelletti and Soncini-Sessa, 2007b]. 'States' are the different possible outcomes a factor in the network can have. For example, in the case study in Chapter 3, the target factor (node) was flood-risk. The flood-risk factor has two states: above average and below average. The probability of above average flooding and below average flooding are each given in the CPT. There is a

CPT for each factor in the Bayesian Belief network; these CPTs inform the Bayesian analysis.

Bayesian Belief networks and analysis have been used to inform land-use decision-making [Celio, 2014], river-basin planning [Castelletti and Soncini-Sessa, 2007b], and water resource management [Castelletti and Soncini-Sessa, 2007a], among others. The use of Bayesian Belief networks to inform decision-making in ecology, therefore, is not new. Bayesian Belief networks and analysis have the benefit of seamlessly combining social and ecological factors and comparing them equally. This trait makes Bayesian Belief networks and analysis particularly useful for assessing social-ecological fit, where factors other than ecological must be considered to resolve an issue.

While Bayesian Belief networks and analysis have been previously used to inform decision-making, they have yet to be used as a metric to quantitatively assess environmental governance approaches. Quantitative assessment of environmental governance approaches remains a challenge, with several approaches proposed [Sayles et al., 2019]. Despite these approaches, however, there remains a disconnect between combining social and ecological factors to inform decision-making in a way that is accessible for local decision-makers. This is an objective of the case study presented in Chapter 3. Further details on how Bayesian Belief network and analysis methods were applied are presented in Chapter 3.

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# Preface to Chapter 2

Chapter 1 introduced the importance of effective environmental governance and the relevance of social-ecological fit to decision-making. In Chapter 2 I review the literature on governing social-ecological systems and expand upon the concept of social-ecological fit, describing the different types of fit, and their relationship to each other to identify knowledge gaps.

# Chapter 2

# Literature Review

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**Komorebi** (noun, Japanese)

the sunlight that filters through the leaves of trees

- Mak and Garrity-Riley [2016]

## 2.1 Abstract

Academics and researchers alike are recognising the importance of social-ecological systems within environmental governance. However, progress to include the social aspects of social-ecological systems in environmental governance remains limited. Social-ecological fit is an approach to environmental governance that offers this inclusive perspective to decision-making. While social-ecological fit is a promising approach to improve the efficiency and effectiveness of current environmental governance, its use and definition suffer from a lack of consistency within the academic literature. This chapter presents a literature review on the relationship between social-ecological fit, social-ecological systems, and environmental governance. A deeper understanding of the different types and complexities of social-ecological fit will help to enhance current theory and approaches to environmental governance. This review highlights selected types of fit, elucidates their relationships to one another, and explicates how each type of fit can be appropriately used as an analytical tool to facilitate effective environmental governance within social-ecological systems. Research needs are then identified.

## 2.2 Introduction

Effective environmental governance is essential for preserving the natural world we live in and depend on. Evans et al. [2020], in his book *Environmental Governance*, defines governance as "a commitment to collective action to enhance legitimacy and effectiveness, a recognition of the importance of rules to guide interaction, and acknowledgement that new ways of doing things are required that go beyond the state" (6). Attitudes towards this 'commitment to collective action' regarding the environment have been, and are still, constantly changing. While there have certainly been advances in environmental governance approaches and theory, there remains a notable absence of diverse perspectives in this field. These 'diverse perspectives' include the economic, cultural, and historical influences that affect the social-ecological issue of interest; these perspectives could come from local representatives, Indigenous communities, or non-profits, among others.

Historically, the study of environmental governance has largely focused on ecology and development [Sanwal, 2007]. Gradually, the concept of 'social-ecological systems,' which highlights the interplay between the social and ecological factors of a system [Berkes, 2017], has been introduced to environmental governance theory. This progress, however, remains slow. Approaches to environmental governance that consider social-ecological systems could, depending on the issue and/or needs of the system, better address environmental issues than approaches that focus just on the ecological aspects [Ostrom, 2009, Sanwal, 2007].

A general lack of the aforementioned 'diverse perspectives' in environmental governance scholarship limits the resolution of social-ecological problems. There is a significant need for an interdisciplinary governance approach [Bodin, 2017]. The social-ecological fit approach to environmental governance, which considers all social and ecological aspects of an environmental issue, could offer a potential solution to this problem [Epstein et al., 2015]. Challenges remain, however, in governing social-ecological systems, particularly in ways to assess the effectiveness of methods designed to identify the dynamics and patterns within social-ecological systems (see Section 2.3 for further details).

To identify knowledge gaps in the environmental governance and social-ecological system fields, I reviewed the literature to introduce and define the key concepts of environmental governance, social-ecological systems, and social-ecological fit. Social-ecological fit offers a unique perspective and union between the fields of environmental governance and social-ecological systems. In what follows I describe the most commonly referenced types of fit and distinguished how they are related to each other, social-ecological fit, and environmental governance. Based on this review, I identify knowledge gaps and associated research needs in the fields of environmental governance, social-ecological systems, and social-ecological fit.

## 2.3 Governing Social-Ecological Systems

The study of social-ecological systems is a growing field within ecology and environmental studies. Berkes [2017] defines social-ecological systems as the "integrated complex adaptive systems in which social and ecological subsystems are coupled and interdependent, each a function of the other, expressed in a series of mutual feedback relationships" (3). This definition builds upon earlier work by Berkes et al. [2003], Folke [2006], and Janssen and Ostrom [2006], who introduced the idea of social-ecological systems to a wider academic audience. Past researchers have devised a variety of frameworks to study the dynamics of social-ecological systems, including a framework for analysing the sustainability of social-ecological systems [Ostrom, 2009], and a framework to capture the interactions within social-ecological systems [Schlüter et al., 2019].

The applications of social-ecological systems to environmental governance are numerous and diverse. Fleischman et al. [2014] describes five different social-ecological systems, from the Great Barrier Reef in Australia to forests in Indonesia, and the lessons learned from the environmental governance practices in each. In their study, the authors found that large-scale environmental systems were heavily influenced by political dynamics; governance approaches only considering the ecological influences would likely be incomplete. Frantzeskaki et al. [2010], as another example, re-shapes ideas of flood management using the concept of social-ecological systems. Similar to one of the conclusions from the Fleischman et al. [2014] study, Frantzeskaki et al. [2020] highlighted the importance of including relevant social and ecological influences in governance approaches, as the absence of any key influence could disrupt the underlying governance "paradigm" [84]. These case studies highlight the importance of considering environmental systems as social-ecological systems due to the complex relationship between the social and ecological factors within a system.

Governing social-ecological systems remains a major challenge for society, and there are several knowledge gaps within the literature on this subject. Frequently discussed knowledge gaps include:

1. Approaches to analyse the inter-connectivity between social and ecological factors. [Schlüter et al., 2019, Bodin, 2017]

2. Approaches to quantitatively study social-ecological systems. [Sayles et al., 2019, Bodin and Tengö, 2012, Bergsten et al., 2014, Ekstrom and Young, 2009]

3. Approaches to analyse the dynamics and patterns within social-ecological systems. [Schlüter et al., 2019]

4. Identifying which components of a social-ecological system are the most important for resolving a social-ecological issue efficiently [Bergsten et al., 2014]

Each of these gaps calls for an inclusive perspective that considers issues such as the scale, social factors, and temporal factors to enhance governance outcomes [Bodin, 2017]. It is here that social-ecological fit has been proposed as a promising approach to govern social-ecological systems [Barnes et al., 2019, Bodin, 2017, Folke et al., 2007]. For example, knowledge gaps 1 and 3 both highlight the need for an interdisciplinary governance approach, which is explicitly stated by Schlüter et al. [2019]: "Analyses of [social-ecological systems] phenomena ... require approaches that can account for ... the intertwinedness of social and ecological processes." (1). These knowledge gaps could be resolved with the social-ecological fit approach, which is rooted in interdisciplinary governance.

Knowledge gaps 2 and 4 could also be addressed using the SEF approach, especially when used in conjunction with other decision-support tools. Knowledge gap 2 draws attention to the difficulty of quantitatively analysing social-ecological systems. Resolution of this knowledge gap would likely help to address knowledge gap 4. In Chapter 3, I combine the use of social-ecological fit and statistical analyses to address knowledge gaps 2 and 4.

## 2.4 The Importance of Social-Ecological Fit

To examine all aspects of a social-ecological issue, decision-makers and researchers alike must consider the social-ecological fit between the decision-making institution(s) and the social-ecological system. Social-ecological fit, as will be discussed later, is a broad term that encapsulates all aspects of a social-ecological system, including but not limited to: social, ecological, spatial, functional, temporal, horizontal, and vertical fit (Figure 2.1). Each of these different types of 'fit' offers a unique perspective on environmental governance.

The term 'fit' refers to the alignment of a governing institution's action with the needs of the social-ecological system [Folke et al., 2007, Young and Underal, 1997]. Young and Underal [1997] and Folke et al. [1998] first popularised the idea of fit, particularly SEF. In an updated publication of their 1997 manuscript, Folke et al. [2007] comment that, while research on the subject of 'fit' within social-ecological systems had grown significantly since their 1997 publication, social and ecological components of a system are still treated separately.

The importance of an inclusive approach to environmental governance (like social-ecological fit) is well documented in the literature. For example, Barnes et al. [2019], Sayles et al. [2019], Bodin [2017] and Olsson et al. [2007] all discuss the strengths of interdisciplinary governance approaches. These strengths can include better representation of the social-ecological system, and a more efficient use of resources than if other approaches were used.

In addition to a lack of quantitative methods to assess SEF, this promising approach is hindered by a lack of organisation within the literature. While past attempts have been made to provide structure to the social-ecological fit literature [Cox, 2012], the different definitions and overlapping terminology make the approach less accessible to decision-makers and other researchers. The following literature review classifies and defines the most commonly discussed types of fit, their relationship to each other, as well as highlight where there is overlap between the definitions to identify research needs.

## 2.5 The Various Types of Fit

### 2.5.1 Ecological Fit

Ecological fit is an aspect of environmental governance whereby the ecological mechanisms of an ecosystem are understood by a governing institution, which then makes informed decisions to manage aspects of the ecosystem. Definitions of ecological fit often make it sound synonymous with SEF. For example, Bodin [2017] defines SEF as the alignment of the social network with the ecological system under governance. A similar definition is given by Epstein et al. [2015] for ecological fit: "ecological fit...highlights the importance of matching governing bodies to the core features of the environmental problems they were meant to address" (34). The primary nuance between the two definitions is the role of governing bodies: how they interact (the social network) is an essential part of SEF, whereas this interaction is excluded from definitions of ecological fit.

### 2.5.2 Social Fit

Social fit is the matching of institutional action to the needs and interests of governed groups. In an ecological context, social fit is an understanding of the local population(s) that inhabit the ecological system under scrutiny. Beyond physical needs and interests, social fit also encompasses the psychological needs, cultural values, and beliefs of a group [Epstein et al., 2015, Meek, 2013]. Poor social fit will be reflected in a governing institution that has neglected these elements.

### 2.5.3 Scale Fit

Scale fit is the alignment of the scope of institutional action on functional, temporal, and spatial scales to the social-ecological system being governed [Wang et al., 2021, Epstein et al., 2015, Cumming et al., 2006]. The ability of governing bodies to appropriately respond to the scale of an issue within the social-ecological system is paramount; poorly-matched scale fit can result in significant financial, social, and ecological consequences [Epstein et al., 2015, Rawinski, 2008]. Cumming et al. [2006] highlight that ineffective scale fit generally results from the institutional misalignment with one or more of the three dimensions of scale fit (functional, temporal, and spatial), as well as inefficiencies within the system, or the loss of key components to the system.

### 2.5.4 Functional Fit

Functional fit is the understanding and correspondence of institutional action to the ecological linkages (e.g., food-webs, nutrient cycling, the water cycle, etc.) within a social-ecological system [Epstein et al., 2015, Cumming et al., 2006]. Functional fit is considered to be a sub-class of scale fit due to needed alignment of institutional action to the scale of ecological processes [Wang et al., 2019, Epstein et al., 2015], but its close ties to ecological mechanisms also make it a sub-class of ecological fit [Epstein et al., 2015].

Explicitly, ecological fit is the overarching concern of governing bodies addressing their designated environmental issues, whereas functional fit is concerned with the alignment of institutional action with natural systems so as these systems are not disrupted [Epstein et al., 2015]. The ability of governing bodies to recognize and consider these ecological linkages in their decision-making processes is considered essential for well-matched functional fit. Poor connectivity and communication between separately governed interconnected social-ecological systems (also known as weak horizontal fit) can contribute to ill-matched functional fit [Epstein et al., 2015].

### 2.5.5 Temporal Fit

Temporal fit is the timely formation of institutional action that corresponds to the present needs of a social-ecological system [Epstein et al., 2015, Munck af Rosenschöld et al., 2014]. The ability of governing bodies to rapidly respond to changing social-ecological dynamics is a key component of temporal fit. Well-matched temporal fit also includes sustainable institutional actions for long-term environmental governance; this need is often complicated by inconsistent funding and shifting governing networks over time [Bodin, 2017]. Munck af Rosenschöld et al. [2014] discuss at least four key aspects to consider for well-matched temporal fit: tempo, timing, time frame, and the sequence (or order) of institutional actions. These temporal features were explicitly derived from environmental governance research regarding the pollution and health concerns caused by endocrine-disrupting chemicals (EDC) [Munck af Rosenschöld et al., 2014]; however, they could be generalizable to other social-ecological systems, as well as be expanded or contracted depending on each unique situation.

### 2.5.6 Spatial Fit

Spatial fit is the alignment between institutional action and the geographical extent of an ecological system or issue [Epstein et al., 2015, Moss, 2012]. Well-matched spatial fit ensures that (1) an ecological system is governed by either one institution or a set of well-connected actors over the entire landscape, and (2) that local actors across these systems have efficient access to and communication with higher levels of government [Wang et al., 2018, Epstein et al., 2015]. Poorly matched spatial fit can lead to, for example, the over-exploitation of resources and inconsistent environmental regulations [Sayles and Baggio, 2017, Moss, 2012]. A mismatch of spatial fit could explain why otherwise socially- and ecologically-conscious governing bodies still struggle with effective environmental governance [Moss, 2012]. A lack of geographic scope or foresight into the conflicts and barriers that arise from socio-politically charged boundaries can hinder the effectiveness of institutional action [Dallimer and Strange, 2015].

### 2.5.7 Horizontal Fit

Horizontal fit is the pairing of interdependent ecological components with the different social networks that share them; it is a sub-group of spatial fit [Bodin, 2017, Alexander et al., 2017]. Collaboration with the different governing bodies or actors that share one or more ecological components is essential for effective horizontal fit and environmental governance. Poor horizontal fit can result in the exploitation of resources and environmental mismanagement [Wang et al., 2019, Bergsten et al., 2014, Ostrom et al., 1999]. Horizontal fit is enhanced by greater alignment between the social and ecological connectivity of a system [Bodin, 2017, Alexander et al., 2017].

### 2.5.8 Vertical Fit

Vertical fit is the degree of connectivity between levels of a governing network, as well as the connectivity between local actors and the ecosystems they manage [Bodin, 2017, Alexander et al., 2017]. For well-matched vertical-fit, one actor or governing institution works with the entirety of an ecosystem; the ecosystem is not broken-up into different sections operated by different actors or governing bodies [Bodin, 2017]. Poorly-matched vertical fit will likely result in an intensification of land and habitat fragmentation, and conflicting governance practices [Bodin, 2017, Dallimer and Strange, 2015]. The decline and mismanagement of the Amazon rainforest [Latrubesse et al., 2017] and Aral Sea [Micklin, 2007], among other environmental governance disasters, exemplify the danger of a landscape or ecosystem being managed by different governing bodies. Vertical fit, like horizontal fit, is a sub-group of spatial fit, given its potential to span geographical boundaries.

## 2.6 The Social-Ecological Fit 'Family Tree'

Through this literature review, I have identified various definitions and overlap between the different kinds of fit. I now organize these definitions to get a clearer picture of the social-ecological fit 'family tree' (Figure 2.1), and re-define these terms in the context of the literature. I also describe the overlap between the different types of fit, and provide examples of their use in environmental governance (Table 2.1). These findings suggest a need for environmental decision-makers and researchers to take a holistic view of any social-ecological problem by identifying and prioritizing the types of fit most applicable.

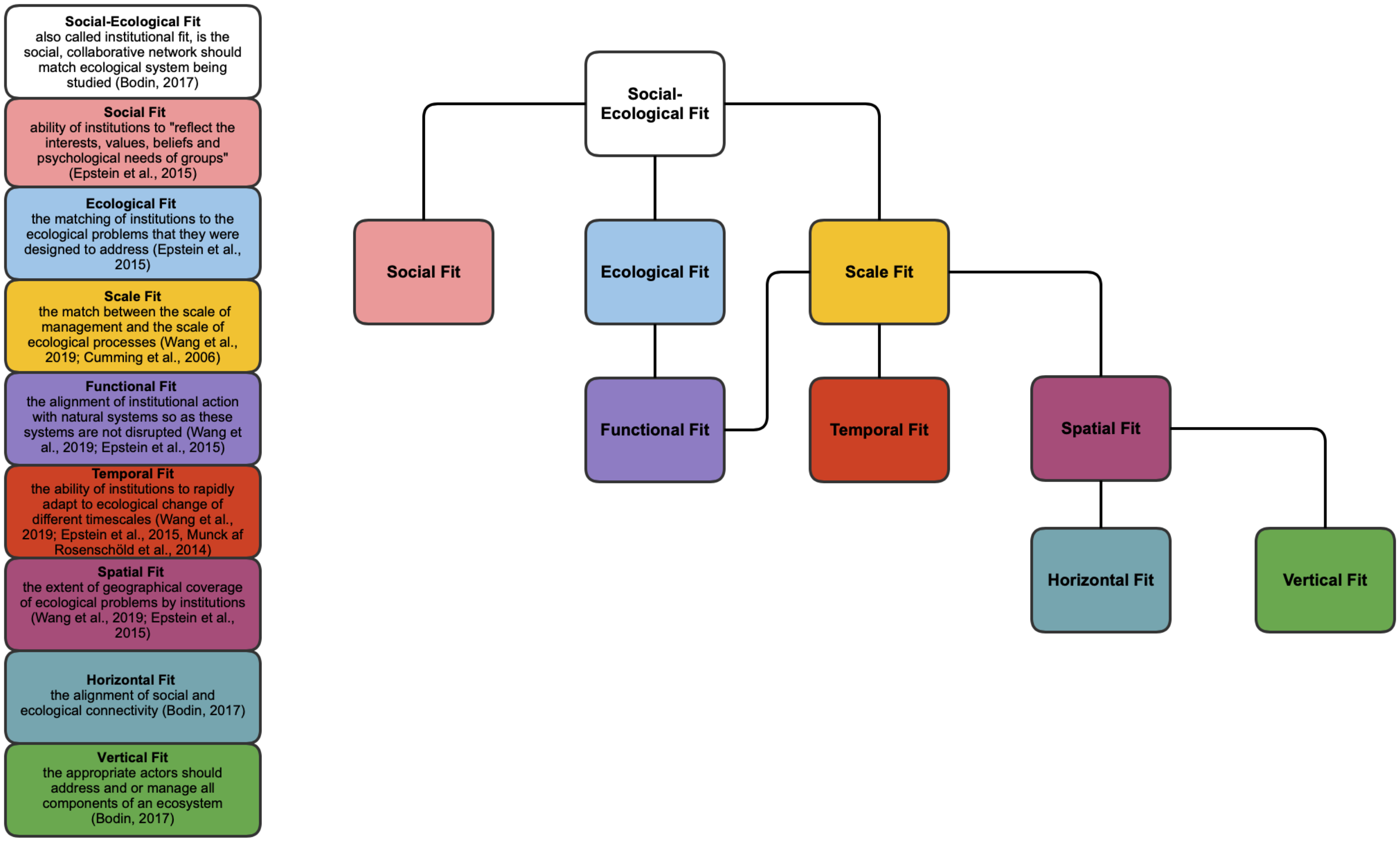


**Figure 2.1: Social-Ecological Fit 'Family Tree'**

A social-ecological fit 'family tree' visualising the relationship between the different types of fit

| | Social-Ecological Fit | Ecological Fit | Social Fit | Scale fit | Spatial Fit | Functional Fit | Temporal Fit | Horizontal Fit | Vertical Fit |
|---|---|---|---|---|---|---|---|---|---|
| **Social-Ecological Fit** | | X | X | X | X | X | X | X | X |
| **Ecological Fit** | X | | | X | | X | | | |
| **Social Fit** | X | | | | | | | | |
| **Scale Fit** | X | X | | | | X | | | |
| **Spatial Fit** | X | | | | | | | | |
| **Functional Fit** | X | X | | X | | | | | |
| **Temporal Fit** | X | | | | | | | | |
| **Horizontal Fit** | X | | | | | | | | |
| **Vertical Fit** | X | | | | | | | | |

**Table 2.1: Overlap Between Different Types of Fit**

A matrix detailing where there is overlap between the different types of fit, with overlap noted by a red X.

I recognize that other kinds of fit exist in the literature that are not included in Figure 2.1. The types of fit presented in this review are those that most appeared in the literature; those that were left out were either too obscure, or were synonymous with one or several of the types of fit described. Bergsten et al. [2014] for example, described institutional fit and its various sub-groups: geographical, jurisdictional, and functional. Based on the definition provided by Bergsten et al. [2014], I concluded that these types of fit were synonymous with the definition of scale fit and its own sub-groups of functional fit, temporal fit, and spatial fit. Similarly, Wang et al. [2021] described structural fit and dynamic fit, which I classified as sub-groups of scale fit. Different types of fit offer diverse perspectives on approaches to environmental governance; however, there is a need for greater consistency with terminology and definitions. Based on Figure 2.1, there is room for further 'pruning' or growth of the SEF 'family tree,' particularly as this approach to governance develops and evolves.

Despite the overlapping and occasionally conflicting definitions and terms within the SEF literature, the benefits of this interdisciplinary approach to environmental governance have been previously discussed [Barnes et al., 2019, Bodin, 2017, Rathwell and Peterson, 2012, Olsson et al., 2007, Brown, 2003]. These benefits emphasize the potential of SEF to improve environmental governance, and highlight why organizing and clearly defining it and the types of fit are essential.

Folke et al. [2007] defined social-ecological fit as: "the interplay between the human and ecosystem dimensions in social-ecological systems that are not just linked but truly integrated" (1). Based on the literature review, I believe that the Bodin, 2017 definition of social-ecological fit (that SEF is the matching of actions from a governing social network to the needs of the ecological components or issues assigned to that network) is the most inclusive of all of the 'dimensions' included within the literature on social-ecological fit. For this reason, I employ the social-ecological fit approach in the case study in Chapter 3.

## 2.7 The Need for SEF Decision-Support Tools

Building from the integrative definition of SEF presented in Section 2.6, there is a need for further research on operationalizing SEF in different contexts through novel decision-support tools [Enqvist et al., 2020, Guerrero et al., 2018]. Decision-support tools can be concepts, models, software packages, or frameworks [Bagstad et al., 2013] that "support decision making related to site selection from an environmental (e.g., potential loss of biodiversity, [essential fish habitat], and iconic feature) and socioeconomic (e.g., loss/gain of income and loss of other ecosystem service) perspective" [Baker and Harris, 2012] (1). These tools are considered essential to the governance of complex social-ecological systems because they can enable researchers to replicate or quantify social-ecological system analyses, and because they add integrity to decision-making processes [Bagstad et al., 2013]. They have been applied in a wide range of contexts such as ecosystem service analysis [Bagstad et al., 2013], natural resource management [Thiault et al., 2020], and policy analytics [Ekstrom et al., 2018]. However, there has been limited work on integrating social and ecological variables within decision-support tools to assess and enhance SEF [Gain et al., 2020]. This is an area that requires further research into the dynamics of social-ecological systems, and highlights the general struggle of relating social and ecological components within a social-ecological system [Gain et al., 2020].

Future research and experimentation in different contexts to operationalize decision-support tools for social-ecological fit would be beneficial. Such tools could help to fill the knowledge gaps outlined in Section 2.3 and enhance the outcomes of social-ecological system governance.

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# Preface to Chapter 3

Chapter 2 described and categorized the different types of social-ecological fit defined in the literature and identified research needs, including the need for novel decision-support tools. In Chapter 3, I combine the social-ecological fit approach to environmental governance with statistical analyses methods to inform decision-making on flood-risk in Truro, Nova Scotia, Canada.

# Chapter 3

# The Use of Bayesian Methods to Quantify Social-Ecological Fit

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**Offing** (noun, English)

the deep, distant stretch of the ocean that is still visible from the land; the foreseeable future

- Mak and Garrity-Riley [2016]

## 3.1 Abstract

Effective social-ecological fit is essential for properly managing social-ecological systems, especially in the wake of climate change. Despite this importance, the field of social-ecological fit lacks an accessible and practical quantitative method to assess governance effectiveness, and a method that equally assesses the social and ecological factors within the system being governed. To address these knowledge gaps, I used Bayesian Belief networks and analysis to quantitatively assess the social-ecological fit approach to environmental governance. For my study, I examined the North Onslow saltmarsh region of Truro, Nova Scotia, which suffers from extreme flooding. I used the North Onslow saltmarsh region to assess what decision-making choices would most likely reduce flood-risk in the region, and therefore achieve the best 'fit' possible. Using Bayesian Belief networks and analysis, I identified the relevant factors influencing flood-risk in the region, their relationship to each other, and their relationship to local flood-risk. I also generated the probability of occurrence for each of these factors, and how these changes in probability influenced local flood-risk. I found that the following factors influenced local flood-risk the most: ice jam frequency, high tide frequency, and dyke maintenance. This study can (1) be used to inform local flood-risk in

Truro, (2) act as a model for other communities facing social-ecological fit problems, and (3) be used as a model to quantitatively assess social-ecological fit.

## 3.2 Introduction

Effective social-ecological fit (SEF) is essential for properly mitigating the negative impacts of environmental change. Social-ecological fit is the matching of actions and/or decisions from a governing social network to the needs of the ecological components or issues assigned to that network [Bodin, 2017].This 'matching' can include the alignment between the governing actions and the temporal, spatial, and/or functional needs (among others) of the system. Social-ecological fit is a governance approach that considers all scales of a social-ecological issue.

Climate change issues, such as severe flooding or extreme weather, can be devastating for local communities from an ecological, social, and/or financial perspective. Poor social-ecological fit can exacerbate these issues; however, social-ecological fit theory has yet to describe methods to easily assess the effectiveness of local actions.

Present knowledge gaps in social-ecological fit literature include how to integratively analyze social and ecological aspects of social-ecological fit. Past attempts have been made by researchers to quantitatively analyze social-ecological fit [Sayles et al., 2019]; however, difficulties remain in combining social and ecological factors, as well as making this information accessible to local decision-makers. Additionally, less tangible, social aspects of social-ecological systems, such as financial constraints or decision-maker knowledge, have yet to be fully addressed by the literature in terms of how they impact social-ecological issues, such as flooding, which have social (e.g., financial, community-based) and ecological consequences.

These knowledge gaps can give way to sometimes extreme environmental consequences. Past studies have highlighted the impact that poor social-ecological fit can have from social and ecological perspectives [Karanth et al., 2003, Shine, 2018]. Shine [2010], for example, highlights the disastrous social and ecological impacts created by the introduction of the cane toad (*Bufo marinus*) to Australia in 1935. The species was introduced by local decision-makers in attempt to manage crop pests [Shine, 2010]. In addition to becoming an invasive species, the cane toad's introduction to Australia has resulted in severe financial costs in attempt to alleviate the ecological issues caused by the species [Bradshaw et al., 2021]. Case studies such as these highlight the importance of addressing knowledge gaps in social-ecological fit.

To support decision-makers in environmental decision-making processes, I propose the use of Bayesian Belief networks (BBNs) to quantitatively assess the social-ecological fit between governing bodies and the systems they govern. While BBNs have been used to make predictions on ecological phenomena [Celio, 2014, Castelletti and Soncini-Sessa, 2007a], they have yet to be implemented to quantify decision-making. Bayesian Belief networks make use of conditional probability, available scientific literature, and expert consultation to construct a network of relevant social and ecological variables surrounding the ecological issue of interest [Celio, 2014]. Using a BBN and associated variables, Bayesian Belief network analysis can be used to make predictions about how the social-ecological issue of interest is influenced by relevant social and ecological factors. The closer the probability of the desired social-ecological outcome, the better the SEF. This approach has the potential to (1) provide a quantitative assessment of relevant social and ecological factors, and (2) help to inform decision-making by providing a quantitative assessment of possible decisions for the system of interest.

In this study, I employ BBNs to assess possible social-ecological fit surrounding the issue of flood-risk in the North Onslow Saltmarsh region of Truro, Nova Scotia, Canada (Figure 3.1a & b). This region was chosen because it suffers from a clear social-ecological problem (flood-risk), and requires a decision-support tool. By introducing the use of BBNs to quantify social-ecological fit, I hope this method can be used as a decision-support tool by other communities suffering from complex social-ecological issues.

I collected data through surveys and interviews with local experts, as well as by reviewing relevant scientific literature on local flood-risk. The data were used to construct a network of relevant factors, establishing their probability of occurrence, and to conduct a Bayesian analysis of the system. The results of the Bayesian analysis included probabilities of flood-risk, which were influenced by the collected flood-risk variables. I found that, for the North Onslow Saltmarsh region, the frequency of ice jams, the status of dykes, and tide height had the most significant impact on local flood-risk. These results can be used by local decision-makers to inform their decision-making on flood-risk.

## 3.3 Methods

### 3.3.1 Bayesian Belief networks

A Bayesian Belief network (BBN) is a "decision support system" that relies on conditional probability to mathematically outline how "existing beliefs" of a system can be altered with the addition of new evidence [Bromley, 2005] (14). The use of Bayesian statistics enables researchers to make predictions about the network under "what-if?" scenarios (called 'belief propagation') that can be used to inform decision-making. The result of this analysis will be the probability of occurrence, in percentages, for each state in each node in the network. I propose the use of these percentages as a way to quantify social-ecological fit; the closer the percentage is to the desired social-ecological outcome, the better the social-ecological fit is.

In social-ecological systems, the 'existing belief' can be an ecological issue, and the 'new evidence' represents changes that alter the conditional probabilities of the social and/or ecological components of the system. These networks have been previously used in water resource management[Castelletti and Soncini-Sessa, 2007a,b] and land use decision-making [Celio, 2014], among other environmental fields.

### 3.3.2 Study Site

I used Bayesian Belief networks to analyze flood-risk in the North Onslow Saltmarsh region of Truro, Nova Scotia (Figure 3.1a&b). The North Onslow Saltmarsh boundaries will define the social-ecological system for the purposes of this case study, and was selected because flooding in this region is extremely common and severe. The Bay of Fundy, where the North Onslow Saltmarsh is located, experiences the highest tides in the world [Sherren et al., 2019]. This flooding has been particularly damaging to homes, schools, and senior residences in nearby Truro [CBCL-Limited, 2017]. The resulting damages from a single flooding event can incur millions of dollars, such as the flooding event in 2013 that cost $3.5 million in damages [CBC, 2013]. In addition to the high tides, flooding in this region is also exacerbated due to the municipality being built on the Salmon River floodplain, frequent ice jam events, high runoff flows, and river sedimentation [CBCL-Limited, 2017]. Proposed solutions (e.g., floodplain restoration, new infrastructure, etc.) are costly at best, and potentially ineffective at worst [Sherren et al., 2019], which requires local decision-makers to carefully pursue social and institutional action that has the best chance of mitigating flood-risk.

Dykes, which are embankments constructed to mitigate the impact of flooding, often for agricultural purposes, have been used for centuries in Atlantic Canada [Chen et al., 2020]. Historically, they have been instrumental in reducing flood-risk in this region, specifically in the Bay of Fundy [Chen et al., 2020, Sherren et al., 2019]. Beyond flood-risk mitigation, dykes provide nutrient rich soils that can be used for farming, while keeping saltwater out

out of agricultural fields [Chen et al., 2020]. Dykes offer unique ecological and economic ecosystem services by providing flood protection and by contributing to farmland production, respectively. These structures also have cultural importance, and offer ecosystem services in the form of tourism and recreation, among others [Sherren et al., 2016].

While dykes have been an important part of the Bay of Fundy landscape from historical, cultural, financial, and ecological perspectives, growing flood-risk due to climate change is instigating new talks about the role these structures play in flood-risk mitigation. In some regions, the severe flooding has proved overwhelming for local dykes, which were never designed to handle the severe inundation that has resulted from climate change [Sherren et al., 2019]. In an effort to reduce local flood-risk, some local dykes are being dismantled in order to restore local saltmarsh [Bowron et al., 2012]. Saltmarshes offer the key ecosystem service of flood-risk mitigation [zu Ermgassen et al., 2021], and could be more effective than dykes at preventing severe flooding in some areas [van Loon-Steensma and Vellinga, 2013].

The North Onslow Saltmarsh restoration project is a new attempt to reduce flooding in the Truro region. Local dykes have been breached as part of an effort to restore local saltmarsh. Through Bayesian Belief network analysis, I analyse the flood-risk factors in this region that contribute to local flooding to discover if dyke removal and restoration of local saltmarsh do reduce flood-risk. For this study, any discussion of dyke removal is also referring to saltmarsh restoration, not dyke removal alone. It should also be noted that the following observations and findings are specific to the North Onslow saltmarsh and Truro areas only, and are not meant to represent the entire province of Nova Scotia. Additionally, the removal of dykes and restoration of local saltmarsh remains controversial on both a local and provincial scale; agricultural farmland functions as a source of revenue for local farmers and the province, and the growing need for housing and development can be pitted against recommendations to restore local saltmarsh. Decision-makers are faced with the challenging task of trying to balance environmental needs and human needs. I hope that by introducing the use of Bayesian Belief network analysis as a tool to quantitatively assess decision-making, decision-makers can make more informed governance decisions that help to strike this delicate balance.


**(a)** A map of Canada showing the location of Truro, Nova Scotia (from MapTrouve.ca)


**(b)** A 'zoomed in' view of the North Onslow saltmarsh, circled in red

**Figure 3.1: Maps of Truro, Nova Scotia**

### 3.3.3 Data Collection

Following similar protocols to those outlined in Celio [2014] and Castelletti and Soncini-Sessa [2007a], my first step in the data collection process was to clearly define the social-ecological problem I wished to analyze, and identify the relevant variables that contribute to this problem. The North Onslow Saltmarsh region has a clear flooding problem. To identify the relevant social and ecological variables that influenced local flood-risk, I analyzed past flood-risk studies done in this region, and conducted several surveys and interviews with local experts. A copy of the surveys distributed can be found in Appendices B and C; the interview guide is available in Appendix D. These experts included local decision-makers, scientists, and nonprofit organizers (Table 3.1). While social scientists and members from the local Mi'kmaq community were contacted, none responded positively to a request to participate. Participating experts were consulted at each step of the data collection process.

Data collection was conducted in four steps (Figure 3.2). Experts were consulted at each step of the data collection process either through survey or interview form. These consultations were corroborated by a review of the literature.

1. A review of relevant literature and past local flood-risk analyses.

2. Creation of an electronic survey targeted to the experts. Experts (referred from here on as 'participants') were asked to identify factors that contributed to local flood-risk. For each factor, participants were also asked to provide possible states

(e.g., Low/High, Absent/Present). For each state, I asked the participants to identify what they believed to be the likelihood of that state occurring based on the present environmental circumstances. These states and probabilities become Conditional Probability Tables (CPTs). There is a CPT for each node within the network.

3. One-on-one interviews with survey participants to establish a pilot network of variables. This resulted in an first set of relationships between different relevant social and ecological factors related to flood-risk).

4. A final electronic survey designed to inform scenario-building. Participants were asked to describe what factor states were most likely to lead to high flood-risk, and what factors states would most likely lead to low flood-risk.

After each round of surveys and discussion with the participants, the data were updated. Outputs of data collection included listings of the relevant factors that contribute to local flood-risk in the North Onslow region, the possible states each of these factors could have, and the CPTs. The CPTs and Bayesian Belief network were finalised based on the data collected from the surveys, interviews, and relevant available literature, and discussions within the research team.

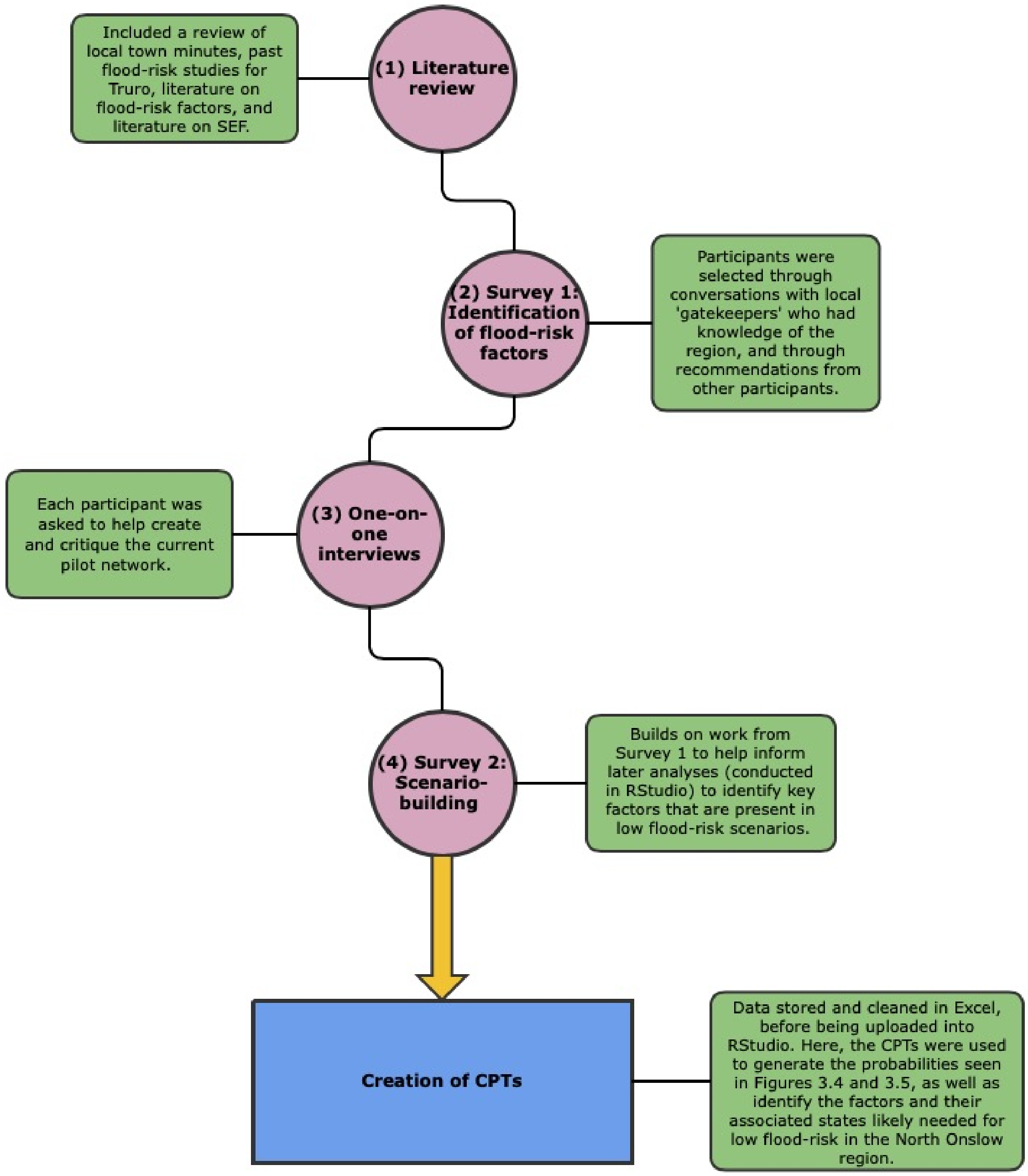


**Figure 3.2: Data Collection Flow Chart**

| **Types of Experts** | | | | | |
|---|---|---|---|---|---|
| | *Local Decision-makers* | *Natural Scientists* | *Non-profit Organizers* | *Social Scientists* | *Local First Nations Community Members* |
| **Number of Individuals Who Responded Positively to Study Participation** | 4 | 5 | 1 | 0 | 0 |

**Table 3.1: Classification of Consulted Experts**

**Table 3.1**: The classification and number of local experts consulted to discuss flood-risk factors for the North Onslow Saltmarsh

Outputs of data collection included listings of the relevant factors that contribute to local flood-risk in the North Onslow region, the possible outcomes each of these factors could have (called ‘states’), and the conditional probabilities of each of the states (called a Conditional Probability Table (CPT)).

### 3.3.4 Creation of the Bayesian Belief network and Bayesian Analysis in R

The flood-risk factors and their conditional probability tables were stored as matrices in Microsoft Excel 16.57. These matrices were uploaded to RStudio 1.3.1073 for BBN modeling. Once uploaded, I created a function to manipulate the CPTs into a usable format for the bnlearn package [Scutari and Denis, 2015]. I then used Rgraphviz to plot the pilot network from the re-formatted CPTs (Figure 3.2).

After the creation of the pilot network, I used the CPTs to predict future flood-risk (belief propagation). Belief propagation can be done using either Exact algorithms or Approximate algorithms; Exact algorithms use Bayesian analysis to obtain a more optimal solution to flood-risk prediction than Approximate algorithms, which rely on Monte Carlo simulations (repeated random sampling from the data set) [Scutari and Denis, 2015]. The North Onslow network and dataset are relatively small and simple, which enables us to more accurately use an Exact algorithm than if the dataset and network were very large and complex.

The Exact algorithm I used for this analysis is the Junction Tree Clustering algorithm.

This algorithm works by 'marrying' (called 'moralisation') every set of two variables (called 'parent nodes') in the network that share and precede another variable (a 'child node') [Scutari and Denis, 2015]. This unionization of nodes creates triangulated node clusters (cliques); each clique represents a 'branch' on the junction tree [Scutari and Denis, 2015]. The junction tree takes in the new evidence added to the network and modifies sequential cliques to produce an updated network that considers this new information [Smail, 2018].

Using this algorithm, I can set a specific state for a node to see how this would affect the probability of high flood-risk and low flood-risk (e.g., if Extreme Weather frequency is set to 'Above Average', how does this change impact flood-risk in comparison to when this state is set to 'Below Average'?). Results of this algorithm are then validated and discussed with local experts; data and network structure are updated accordingly.

## 3.4 Results

Following the above analysis, I drafted a pilot network where each factor's relationship to flood-risk and each other can be easily seen (Figure 3.3). Including flood-risk, this network has nine factors (also referred to as 'nodes'). The moralised Bayesian Belief network can be seen in Appendix A.

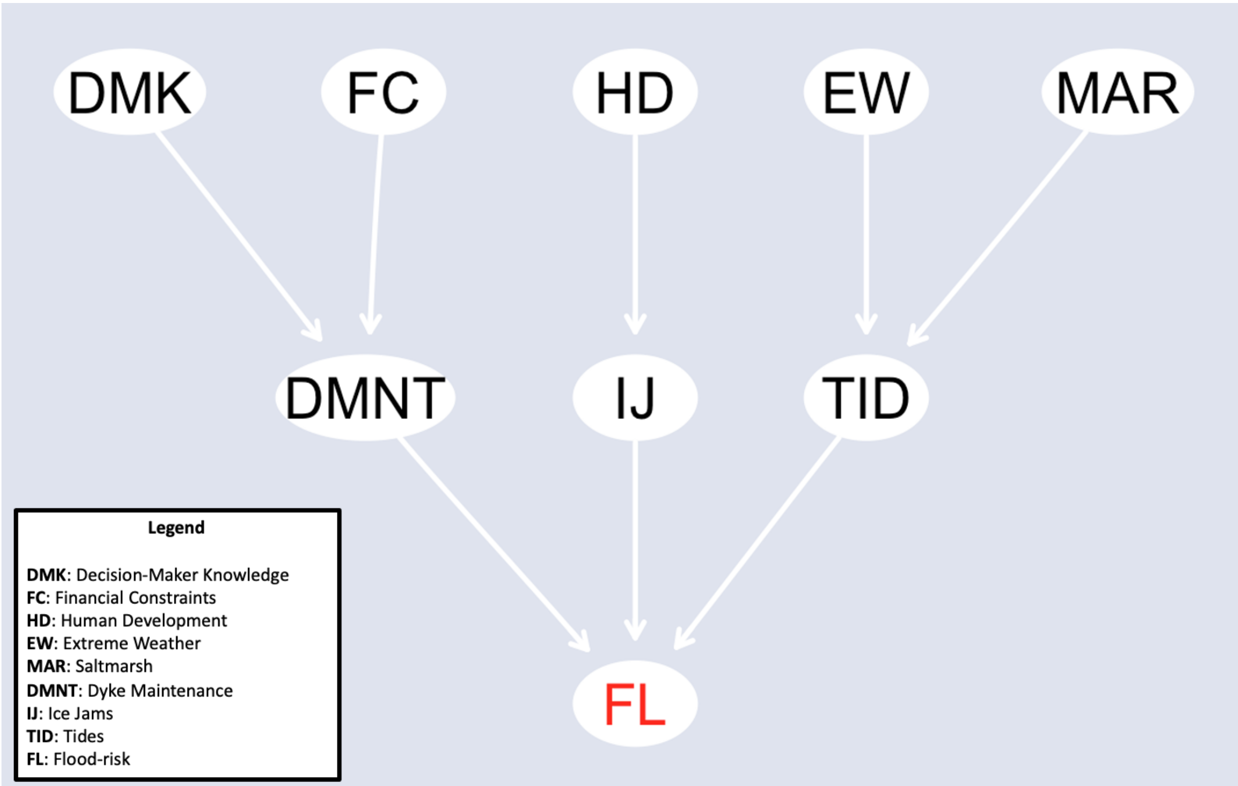


**Figure 3.3: The Bayesian Belief network for the North Onslow Saltmarsh**

**Figure 3.3**: The North Onslow Saltmarsh Bayesian Belief network. Each relevant flood-risk factor and their relationship to each other and the target node (FL, highlighted in red) is shown.

In addition to creating a visible network illustrating flood-risk in the North Onslow Saltmarsh, I used the data and CPTs to predict the degree to which each factor's change in state affected the probability of flood-risk. I divided factors into two categories: 'social' factors and 'ecological' factors. Social factors included financial constraints, human development projects, decision-maker knowledge, and dyke management (Figure 3.4). Ecological factors included tides, extreme weather, saltmarsh, and ice jams (Figure 3.5).

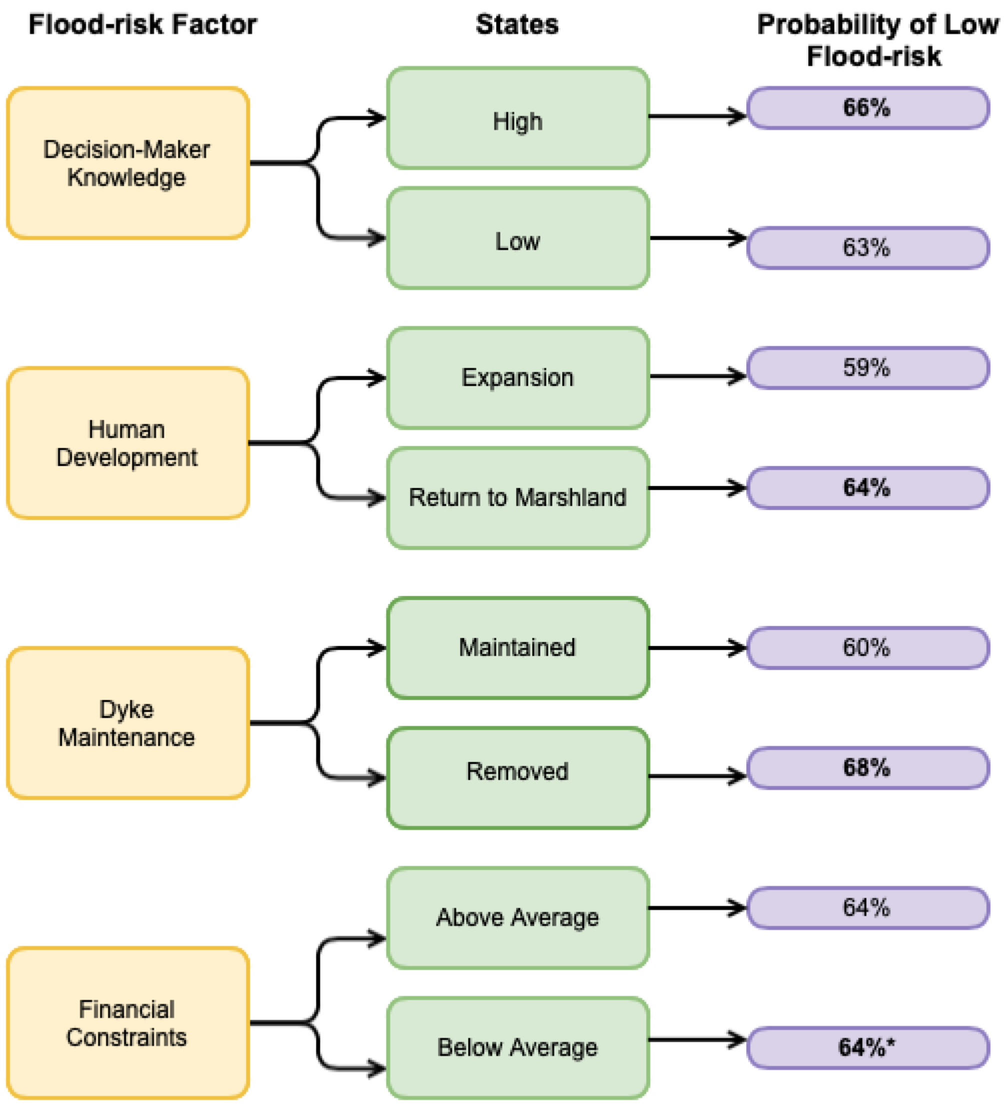


**Figure 3.4: Effect of Social Factors on Local Flood-risk**

**Figure 3.4**: Flood-risk decision-tree with social factors. The highest probability of low flood-risk is bolded.

*Probabilities are rounded to two significant figures, so the minute increased probability cannot be seen.

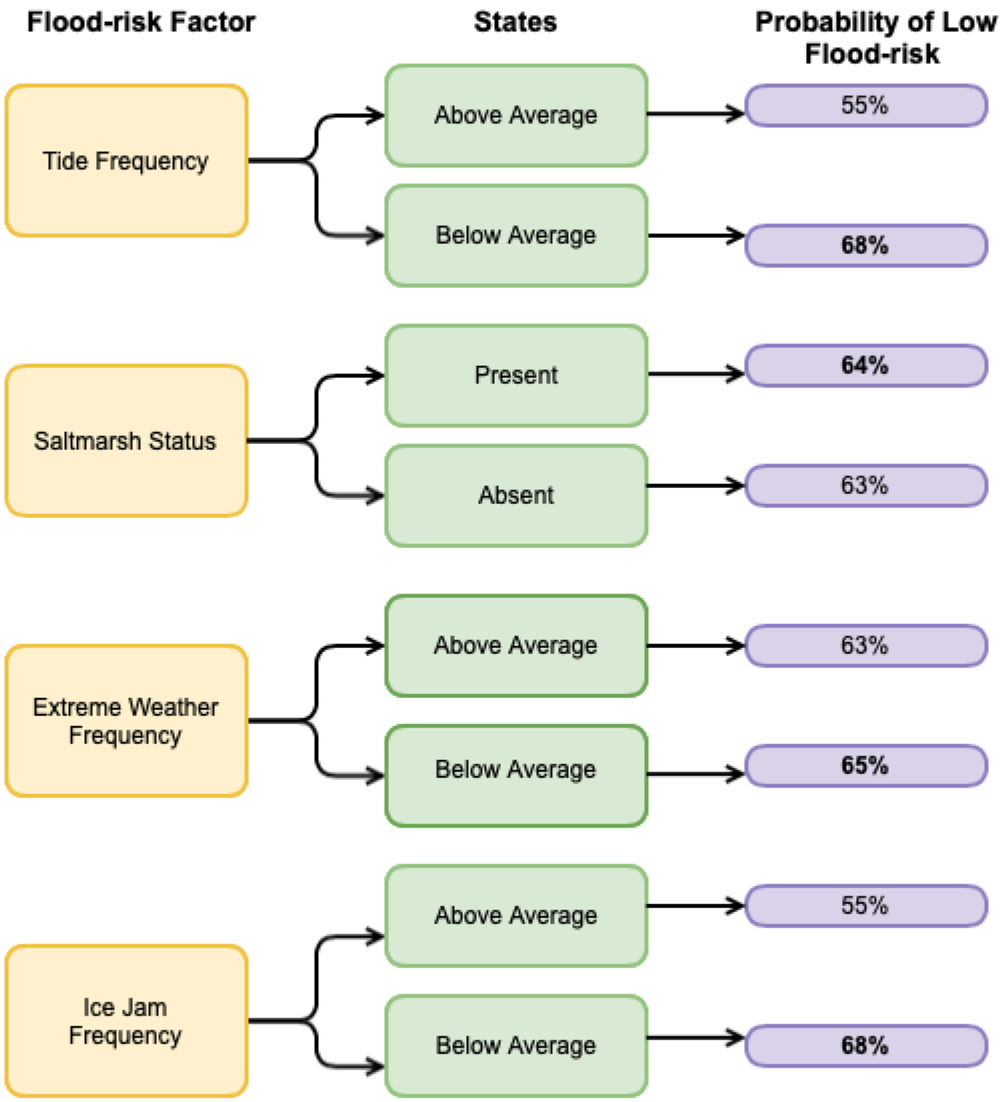


**Figure 3.5: Effect of Ecological Factors on Local Flood-risk**

**Figure 3.5**: Flood-risk decision-tree with ecological factors. The highest probability of low flood-risk is bolded.

For the social factors, removal of dykes (and restoration of local saltmarsh), cessation of human development projects, and high decision-maker knowledge all reduced flood-risk. Below average financial constraints also contributed to a reduction in flood-risk, though this change was less than 1%. For ecological factors, below average extreme weather, below average tide frequency, below average ice jam frequency, and the presence of saltmarshes resulted in a reduction in flood-risk probability.

Using these factors and their associated CPTs, I was able to mathematically conduct permutations in R to find the number of scenarios where flood-risk is low. I found 32 scenarios where there is low flood-risk. Each one of those scenarios had a below average frequency of ice jams, a below average frequency of high tides, and removed dykes (i.e., restoration of land to saltmarsh). Following these results, I conclude that ice jam frequency, high tides, and dyke status to be the most influential nodes in the network.

## 3.5 Discussion

My study produced two main results: (1) the organisation of a flood-risk network (the Bayesian Belief network) for the North Onslow Saltmarsh (Figure 3.3), and (2) the identification of 3 key factors that influenced flood-risk in the region. The key factors I identified were ice jams, high tide frequency, and dyke status. I identified these key factors by generating scenarios; I found there to be 32 possible scenarios for this community where flood-risk was low (out of 256). Each one of those scenarios had a below average frequency of ice jams, a below average frequency of high tides, and removed dykes (i.e., restoration of land to saltmarsh). By establishing the Bayesian Belief network (BBN) for the North Onslow region, I was able to identify the aforementioned key flood-risk factors, and quantitatively show the impact, in percentages, that each relevant factor had on flood-risk in the network (Figures 3.4 and 3.5). I propose the use of these percentages as a way to quantify social-ecological fit; the closer the percentage is to the desired social-ecological outcome, the better the social-ecological fit is.

In light of these results, I can quantify the decisions most likely to improve local social-ecological fit in Truro. As all the low flood-risk scenarios contained a below average frequency of ice jams, a below average frequency of high tides, and the restoration of local saltmarsh (i.e., removal of enough local dykes to restore the saltmarsh), it follows that decision-making that capitalizes on achieving these states will have a higher degree of fit than if governing bodies focused their resources elsewhere.

While ecological factors, such as ice jams and tides, can be difficult to control, their effects can be mitigated. This model can be used as a decision-support tool to help decision-makers know where to funnel resources to best improve local social-ecological fit (i.e., resolve the social-ecological issue at hand).

Despite these results, it is important to emphasize that these findings are specific to the North Onslow Saltmarsh and Truro areas only. While the model itself can be applied to a variety of situations, the results here are only referring to the study site. It is possible that in other parts of Nova Scotia, saltmarsh restoration is not the most feasible solution to flooding; the decision-making process for each municipality is influenced by a variety of cultural, financial, and ecological factors. Within this region, in addition to saltmarsh restoration, there are also dyke realignment projects taking place [Sherren et al., 2021], which again highlights both the complexity of the flooding problem as well as the individuality of each social-ecological system. Each system will require a different flood-risk mitigation approach.

I can also place the results in a broader context of social-ecological fit. As discussed in Chapter 2, a social-ecological issue may not contain all of the components of fit outlined in Figure 2.1; the social-ecological fit approach will be unique for each social-ecological issue. For Truro, this study highlights four 'fits' of interest: social fit (e.g., the social factors such as decision-maker knowledge), ecological fit (e.g., the ecological factors such as extreme weather), spatial fit (the geographic extent of the social-ecological issue, which was confined to the North Onslow Saltmarsh), and vertical fit (the discussions with local actors/experts who contribute to local flood-risk decision-making).

Through consultation with local experts and a thorough review of the literature, all relevant aspects of fit are assumed to be included in the network by association with the chosen factors (nodes). Each node is associated with a type (or types) of fit. For example, in the Truro case, the issue of ice jams is inherently connected to ecological fit, as it is an ecological issue that a local governing institution is designated to address. A missing node within the North Onslow BBN (Figure 3.3) would create an incomplete network that, in turn, would create inaccurate predictions on local flood-risk and poorly inform local decision-making.

In the context of the literature, these results help to address some present knowledge gaps. Quantitatively assessing social-ecological fit has remained a challenge for researchers, with several methods proposed, such as using similarity metrics [Ekstrom and Young, 2009] and ecosystem service bundle analysis [Raudsepp-Hearne et al., 2010], among others [Sayles et al., 2019, Bergsten et al., 2014]. This work is helpful and significant, but seamless analysis of social and ecological factors remains a challenge. Bayesian Belief networks and analysis could help fill this knowledge gap by assessing social and ecological factors equally. Papers such as Castelletti and Soncini-Sessa [2007b] and Celio [2014] have already successfully used BBN to assess social and ecological factors for water management land-use management, respectively. I have used this study to take the use of BBNs one-step further and adapted them to quantitatively assess governance strategies instead of just building scenarios.

In addition to the generalized significance of these results, this study adds to the current knowledge of flood-risk and social-ecological fit in Truro, Nova Scotia. In 2017, the consulting engineering firm CBCL Limited conducted a comprehensive flood-risk study of the ecological factors surrounding flood-risk in Truro [CBCL-Limited, 2017]. The findings from the CBCL Limited study, as well as from other local literature, partially informed the Bayesian Belief network I created for this study. In light of comprehensive studies such as the CBCL one, my research attempts to build upon and use their findings to better inform the presented model's relevance to local decision-making.

This study also builds on current research into the social factors influencing local flood-risk. Studies such as Sherren et al. [2016] highlight the importance of including the social and cultural factors in environmental decision-making in Truro. Social factors, such as the use of dykes and decision-maker knowledge, could influence local flood-risk to a similar degree that ecological factors influence flood-risk. However, these factors can often be excluded from ecological decision-making [Sanwal, 2007]. This study makes use of these factors to better inform local, social-ecological fit.

It is also important to note the limitations of this study. As with other studies utilising Bayesian Belief networks for environmental decision-making, my study relies heavily upon expert consultation, which could be biased. For example, none of the local social scientists nor members from the local Mi'kmaq community were able to participate, which limited the perspectives I was able to include in the study. Despite these limitations, I attempted to mitigate possible biases by consulting a variety of experts, each with a unique perspective on flood-risk, and by corroborating these discussions with the literature.

Additionally, the analysis would not have been possible without the extensive work done by previous researchers; a lack of substantial, pre-existing information on flood-risk in Truro would have significantly limited the findings. Consequently, I only recommend the use of Bayesian Belief Networks (BBNs) and analysis for quantitatively assessing social-ecological fit when there is already a large body of research available on the social-ecological issue of interest. ‘Data poor’ regions, or areas where there has been limited research on local ecological phenomena and/or local social networks, would not be good candidates for BBNs. Despite these limitations, however, this study has highlighted the potential benefits of the social-ecological fit approach. The use of Bayesian methods in conjunction with other environmental decision-making tools would help to mitigate these limitations, as well as better inform the Bayesian Belief networks and analyses.

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# Chapter 4

# General Discussion

**Smultronställe** (noun, c, Swedish)

lit. "*place of wild strawberries*"; a special place discovered, treasured, returned to for solace and relaxation; a personal idyll free from stress or sadness

- Mak and Garrity-Riley [2016]

## 4.1 General Discussion on Social-Ecological Fit

In Chapter 2, I provided a review of environmental governance, social-ecological systems, and social-ecological fit. In Chapter 3, I applied the concept of social-ecological fit to environmental decision-making. Based on this research, I identify the following future directions to better incorporate SEF in decision-making:

- The creation of a SEF systematic review that is written in an accessible language for local decision-makers.

- The establishment of a quantitative method to assess the SEF between governing bodies and the social-ecological problem of interest.

  - In Chapter 3, I introduce the use of Bayesian methods to assess SEF. I recommend that other researchers experiment with this approach and continually refine it.

- The introduction of the SEF concept to local decision-makers by academics through workshops and/or focus groups.

The social-ecological fit approach to environmental governance does, however, have its limitations. The types of fit, occasionally overlapping, could overwhelm and/or confuse potential decision-makers. It could be a challenge to distinguish between the different types of fit presented, and also to discern what types of fit should be focused on by local decision-makers to resolve a social-ecological problem. For this reason I again emphasize the importance of consistent terminology within the SEF literature.

Social-ecological fit is also limited in its feasibility. The success of this approach depends on the presence of enough knowledge on the different components of a social-ecological issue (e.g., temporal, spatial, social, ecological, etc.) to maximise its effectiveness. Knowledge gaps in these areas are inevitable, but this barrier limits the social-ecological fit approach to areas that have better established knowledge on the social-ecological issue of interest than those without.

Despite the limitations, the SEF approach to environmental governance has great potential to change how decision-makers and researchers approach environmental decision-making. It's bottom-up, inclusive approach allows for a diverse group of perspectives that could otherwise be excluded. This approach, coupled with BBNs, represents a new way to examine social-ecological systems by quantitatively assessing possible decision-making actions, a feat that has historically been a challenge within the literature.

# Chapter 5

# General Conclusion

**Nemophilist** (noun, English)

a haunter of the woods; one who loves the forest and its beauty and solitude

- Mak and Garrity-Riley [2016]

## 5.1 Key Findings

In this thesis, I have presented a detailed description of environmental governance, social-ecological systems, and social-ecological fit (Chapter 2), and an application of social-ecological fit in decision-making (Chapter 3). In Chapter 2, I reviewed the literature on SEF, described the various types, and organized this information into a social-ecological fit 'family tree' (Figure 2.1). My key findings from Chapter 2 are listed as follows:

- Social-ecological fit encompasses a broad range of fit types. Not every type is appropriate or applicable to every social-ecological issue. Social-ecological fit approaches must be tailored to the social-ecological system (i.e., no ‘one size fits all’ approach).

- The success of the social-ecological fit approach is dependent on the amount of information and/or knowledge available in a social-ecological system. Social-ecological systems that lack enough information on the relevant dimensions of a social-ecological issue (e.g., temporal, social, etc.) are not well suited to the SEF approach to environmental governance.

In Chapter 3, I applied the SEF approach to flood-risk decision-making in Truro, Nova Scotia, Canada. I quantitatively assessed the SEF of different flood-risk decisions using Bayesian methods. Based on the results of my analysis, and recognizing the limitations of this study, the key findings from Chapter 3 are listed as follows:

*For Truro*

- Local decision-makers should focus on reducing the frequency/ mitigating the impact of ice jams and high tides.

- Local decision-makers should consider restoring, where possible and applicable, local saltmarsh in the Truro region.

*For the use of Bayesian methods to measure SEF*

- Bayesian methods rely on pre-existing information in order to increase the accuracy and effectiveness of the results; social-ecological systems that lack substantive information on the relevant social-ecological factors and/or lack local experts are not well suited for these methods.

## 5.2 Future Directions

This thesis highlights the need for future work in two main areas: (1) further refining social-ecological fit to support decision-making, and (2) establishing Bayesian methods as a way to assess social-ecological fit and inform decision-making. For the first point, I identify the need for a systematic review on SEF and more consistent use of the definitions and types of SEF. For the second point, I recommend further case studies exploring the use of Bayesian methods as decision-support tools to assess SEF.

In addition to these areas of future research, I also want to highlight the need for more research and efforts on bridging the gap between local decision-makers and academics. The social-ecological fit approach to environmental governance will only be useful if fully adopted by decision-makers who understand its use and potential. In a similar vein, using Bayesian methods as a way to opertionalize social-ecological fit needs to be described to decision-makers in an accessible way. I hope this research has opened the door for future researchers to both engage with SEF and Bayesian methods, as well as promote collaboration.

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# Appendix A

# Moralised Bayesian Belief network

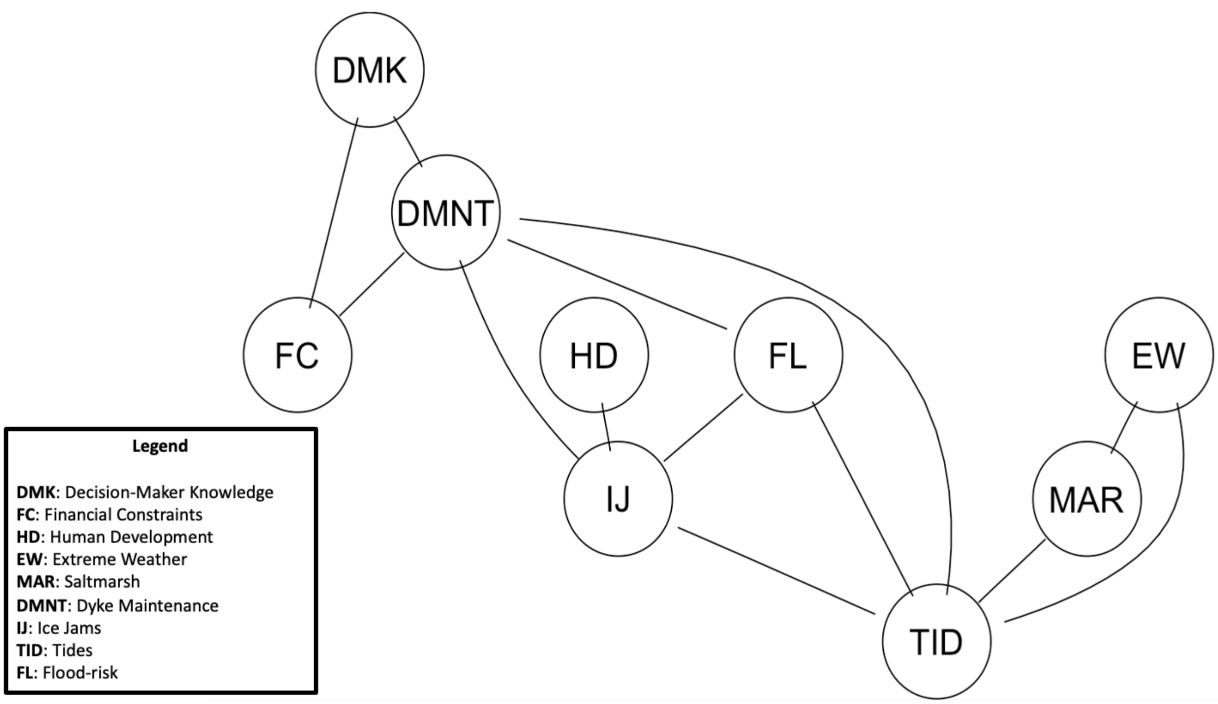


**Figure A.1: North Onslow Saltmarsh Moralised Bayesian Belief network**

# Appendix B

# Survey 1: Identification of flood-risk factors

# Flood-risk factors at the North Onslow Marsh

*This brief survey is designed to isolate the flood-risk factors most relevent to the Truro-Onslow Dyke Realignment and Tidal Wetland Restoration Project.*

This survey is being conducted at McGill University as part of a research project affiliated with Theme 1 of the NSERC ResNet network. The objectove of NSERC ResNet is to monitor, model, and manage Canada's ecosystem services. The Theme 1 division is tasked with developing decision-support systems for governance of ecosystem services in working landscapes.

Welcome! Thank you for your time and participation in this survey. The survey should take about 5 minutes to complete.
There are 4 questions in this survey.

## Consent

I understand that my participation in this study is entirely voluntary and that I may refuse to participate or withdraw at any time by closing the browser. Once the survey is submitted, withdrawal is not possible due to the anonymous nature of the survey. I understand that this survey is anonymous and that my name will not appear anywhere in the results of this survey. Responses will be coded and held in a secure database at McGill University, according to procedures that have been approved by McGill's research ethics board (REB File #: 21-03-090).

McGill University is committed to the ethical conduct of research; studies involving human subjects require the consent of participants. If you have any questions or concerns regarding your rights or welfare as a participant in this study, please contact the McGill Research Ethics Associate Director at 514-398-6831 or lynda.mcneil@mcgill.ca.

### 1 Do you consent to participate in this survey? *

☐ Check all that apply
Please choose **all** that apply:

☐ I agree

# Potential flood-risk factors at the North Onslow Marsh

Please rate the following potential flood-risk factors on a scale of **1** (not influential / not applicable) to **5** (extremely influential).

'Influence' can either be positive (e.g., increases flood-risk) or negative (e.g., decreases flood-risk). These factors can include both those that directly influence flood-risk **and those that influence flood-risk decision-making.**

## 2
## Rate the factors below:

*

Please choose the appropriate response for each item:

| | 1 - Not influential / Not applicable | 2 | 3 | 4 | 5 - Extremely influential |
|---|---|---|---|---|---|
| **Ice jams** | ○ | ○ | ○ | ○ | ○ |
| **Tides** | ○ | ○ | ○ | ○ | ○ |
| **Runoff flows** | ○ | ○ | ○ | ○ | ○ |
| **River sedimentation** | ○ | ○ | ○ | ○ | ○ |
| **Agricultural practices** | ○ | ○ | ○ | ○ | ○ |
| **Dyke maintenance** | ○ | ○ | ○ | ○ | ○ |
| **Citizen knowledge and understanding of flood-risk** | ○ | ○ | ○ | ○ | ○ |

| | | | | | |
|---|---|---|---|---|---|
| **Decision-maker and/or a local representative's knowledge of flood-risk** | ◯ | ◯ | ◯ | ◯ | ◯ |
| **Financial constraints** | ◯ | ◯ | ◯ | ◯ | ◯ |
| **Cultural significance of local farming, the agricultural landscape, and/or the dykeland infrastructure** | ◯ | ◯ | ◯ | ◯ | ◯ |

**3**

**If you believe there are factors that influence flood-risk that are not listed here, please add them in the textboxes below. You may add more than one factor.**

**One or more textboxes can be left blank if you believe there are no other factors to add.**

## 4

## If you added any factors to the textboxes in Question 2, please rate the factor in the corresponding row (e.g., if you added a factor to the 'Option 1' textbox, rate the factor in the 'Option 1' row).

## For any textboxes not filled in Question 2, please select 'No answer.'

Please choose the appropriate response for each item:

| | 1 - Not influential / Not applicable | 2 | 3 | 4 | 5 - Extremely influential |
|---|---|---|---|---|---|
| **Other 1** | ○ | ○ | ○ | ○ | ○ |
| **Other 2** | ○ | ○ | ○ | ○ | ○ |
| **Other 3** | ○ | ○ | ○ | ○ | ○ |

Thank you for completing the survey! A researcher from this project will be in contact with you soon.

Submit your survey.
Thank you for completing this survey.

# Appendix C

# Survey 2: Scenario-Building

# Flood-risk Scenario Building

This brief survey is designed to inform flood-risk scenario-modeling for the North Onslow Saltmarsh region. Specifically, the results from this survey will be used to predict, based on the variables present in this survey, the conditions needed to **maximize** flood-risk in this region, and **minimize** flood-risk in this region.

All responses to this survey will be automatically anonymized; your name will **not** appear in this survey, in past or present analyses, or in any media related to this project.

Welcome to the Flood-risk Sceanrio Building Survey!
There are 16 questions in this survey.

## Variable states most likely to maximize flood-risk in the North Onslow Saltmarsh region

The following flood-risk variables and their possible outcomes ('states') were collected from past suveys and interviews with local experts, as well as from relevant scientific literature. A variable's **state** are the different possible outcomes that variable can have; for example, the Extreme Weather variable has 2 states: above average frequency of occurance, and below average frequency of occurance.

For each variable, please select the state that you believe will most likely lead to a scenario that **maximizes** possible flood-risk for this region. Please consider each variable and state in the context of the present time (i.e., 2021-2022).

**Decision-Maker Knowledge (DMK): how knowledgable local decision-makers are about flood-risk in the North Onslow Saltmarsh region. This can include knowledge of flood-risk variables (such as tide height or extreme weather), finanical constraints related to local flood-risk, or knowledge of their local constituents' beliefs and opinions of flood-risk.**

**For DMK, please select the state that you believe will most likely lead to a scenario that maximizes possible flood-risk for this region.**

Please choose **only one** of the following:

- ◯ High / Significant amount of knowledge
- ◯ Low amount of knowledge

**Financial Constraints (FC): the degree to which finanical and economic concerns influence flood-risk decision-making.**

**For FC, please select the state that you believe will most likely lead to a scenario that maximizes possible flood-risk for this region.**

Please choose **only one** of the following:

- ◯ Above Average
- ◯ Below Average

**Human Development (HD): the degree to which humans are developing and urbanizing local saltmarsh.**

**For HD, please select the state that you believe will most likely lead to a scenario that maximizes possible flood-risk for this region.**

Please choose **only one** of the following:

- ◯ Expansion of HD into marshland
- ◯ Restoration of marshland

**Extreme Weather (EW): the frequency of occurance of extreme weather events (e.g., heavy rainfall).**

**For EW, please select the state that you believe will most likely lead to a scenario that maximizes possible flood-risk for this region.**

Please choose **only one** of the following:

- ◯ Above Average frequency
- ◯ Below Average frequency

## Dyke Maintenance (DMNT): the degree to which local dykes around the North Onslow Saltmarsh area are maintained

## For DMNT, please select the state that you believe will most likely lead to a scenario that maximizes possible flood-risk for this region.

Please choose **only one** of the following:

- ◯ Completely maintained
- ◯ Removed

## Ice Jam (IJ): the frequency of ice jams occuring in or around the North Onslow Saltmarsh area

## For IJ, please select the state that you believe will most likely lead to a scenario that maximizes possible flood-risk for this region.

Please choose **only one** of the following:

- ◯ Above Average frequency
- ◯ Below Average frequency

### Marshland Status (MAR): the presenece or absense of saltmarsh / marshland in the region

### For MAR, please select the state that you believe will most likely lead to a scenario that maximizes possible flood-risk for this region.

Please choose **only one** of the following:

- ◯ Present
- ◯ Absent

### Tide Levels (TID): the frequency of high tides in this region

### For TID, please select the state that you believe will most likely lead to a scenario that maximizes possible flood-risk for this region.

Please choose **only one** of the following:

- ◯ Above Average frequency
- ◯ Below Average frequency

## Variable states most likely to minimize flood-risk in the North Onslow Saltmarsh region

The following flood-risk variables and their possible outcomes ('states') were collected from past suveys and interviews with local experts, as well as from relevant scientific literature. A variable's **state** are the different possible outcomes that variable can have; for example, the Extreme Weather variable has 2 states: above average frequency of occurance, and below average frequency of occurance.

For each variable, please select the state that you believe will most likely lead to a scenario that **minimizes** possible flood-risk for this region. Please consider each variable and state in the context of the present time (i.e., 2021-2022).

**Decision-Maker Knowledge (DMK): how knowledgable local decision-makers are about flood-risk in the North Onslow Saltmarsh region. This can include knowledge of flood-risk variables (such as tide height or extreme weather), finanical constraints related to local flood-risk, or knowledge of their local constituents' beliefs and opinions of flood-risk.**

**For DMK, please select the state that you believe will most likely lead to a scenario that minimizes possible flood-risk for this region.**

Please choose **only one** of the following:

- ◯ High / Significant amount of knowledge
- ◯ Low amount of knowledge

**Financial Constraints (FC): the degree to which finanical and economic concerns influence flood-risk decision-making.**

**For FC, please select the state that you believe will most likely lead to a scenario that minimizes possible flood-risk for this region.**

Please choose **only one** of the following:

- ◯ Above Average
- ◯ Below Average

**Human Development (HD): the degree to which humans are developing and urbanizing local saltmarsh.**

**For HD, please select the state that you believe will most likely lead to a scenario that minimizes possible flood-risk for this region.**

Please choose **only one** of the following:

- ◯ Expansion of HD into marshland
- ◯ Restoration of marshland

## Extreme Weather (EW): the frequency of occurance of extreme weather events (e.g., heavy rainfall).

## For EW, please select the state that you believe will most likely lead to a scenario that minimizes possible flood-risk for this region.

Please choose **only one** of the following:

- ◯ Above Average frequency
- ◯ Below Average frequency

## Dyke Maintenance (DMNT): the degree to which local dykes around the North Onslow Saltmarsh area are maintained

## For DMNT, please select the state that you believe will most likely lead to a scenario that minimizes possible flood-risk for this region.

Please choose **only one** of the following:

- ◯ Completely maintained
- ◯ Removed

## Ice Jam (IJ): the frequency of ice jams occuring in or around the North Onslow Saltmarsh area

## For IJ, please select the state that you believe will most likely lead to a scenario that minimizes possible flood-risk for this region.

Please choose **only one** of the following:

- ◯ Above Average frequency
- ◯ Below Average frequency

## Marshland Status (MAR): the presenece or absense of saltmarsh / marshland in the region

## For MAR, please select the state that you believe will most likely lead to a scenario that minimizes possible flood-risk for this region.

Please choose **only one** of the following:

- ◯ Present
- ◯ Absent

## Tide Levels (TID): the frequency of high tides in this region

## For TID, please select the state that you believe will most likely lead to a scenario that minimizes possible flood-risk for this region.

Please choose **only one** of the following:

- ◯ Above Average frequency
- ◯ Below Average frequency

Thank you for completing this survey! We appreciate your time and expertise.
28.02.2022 – 14:28

Submit your survey.
Thank you for completing this survey.

# Appendix D

# Interview Guide

Interviews were recorded, and all included the following questions:

1. What factors do you think most influence flood-risk in the North Onlow Saltmarsh?
2. What parts of the North Onlow Saltmarsh pilot network, if any, would you change (alter, remove, etc.)?
3. What is your rationale for suggesting these changes? (if applicable)