

A Cumulative Effects Assessment approach to improving decision-making for freshwater resource
protection and restoration

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

Jessica Kidd was the sole author for Chapters 1 and 6, which were written under the supervision of Dr. Simon Courtenay and Dr. Heidi Swanson and were not written for publication.

This thesis consists in part of three manuscripts written for publication and one knowledge mobilization chapter. The knowledge mobilization chapter applies learnings from work completed by Jess Kidd throughout her PhD in a theoretical context, which is supported by the knowledge and experiences of the co-authors. A more rigorous review of the literature will be completed before the knowledge mobilization chapter will be prepared as a manuscript for publication. There are several co-authors on the manuscripts and knowledge mobilization chapter who have made the following contributions:

Chapter 2

Kidd, J., Brammer, J., Courtenay, S., Swanson, H., & Avery-Gomm, S. (2024). Pan-Canadian review of community-based monitoring projects and their capacity to enhance environmental monitoring programs for cumulative effects assessments. *FACETS*, 9, 1-19. <https://doi.org/10.1139/facets-2022-0192>

Jeremy Brammer, Stephanie Avery-Gomm, and I collaborated on the study conceptualization and design, which was reviewed by Simon Courtenay and Heidi Swanson. I collected, analyzed, interpreted the data, and wrote the manuscript. Jeremy Brammer and Stephanie Avery-Gomm cross-validated my data interpretation. All authors participated in the discussion of the results and review and editing of the manuscript.

Chapter 3

Kidd, J. A., Bergbusch, N. T., Epstein G. B., Swanson, H., Courtenay, S. C. A Fresh Perspective on freshwater data management and sharing: Exploring insights from the technology sector. Prepared to submit to *Canadian Water Resources Journal*.

I conceptualized the study and designed the methodology with Nathaneal Bergbusch, Graham Epstein, and Simon Courtenay. I collected the data, and collaborated on data analysis and interpretation with Nathaneal Bergbusch. I wrote the manuscript, and all authors reviewed and edited the manuscript.

Chapter 4

Kidd, J. A., Brekke, L., Courtenay, S. C., Swanson, H. Calculating the Natural Range of Variation for regional baseline surface water quality studies. Prepared to submit to *Journal of Environmental Management*.

This research was part of a larger study that was conceptualized and initiated by the Northwest Territories Cumulative Impact Monitoring Program (NWT CIMP), a division of the Government of Northwest Territories (GNWT). NWT CIMP scientists, including Anna Coles, Dion Kelly, and Lorraine Brekke, aimed to identify an appropriate method for calculating the natural range of variation (NRV) for surface water quality data to strengthen the ability of researchers and decision-makers to make informed inferences and develop evidence-based policies regarding the influence of anthropogenic effects on water quality in the Northwest Territories. As part of this study, the NWT CIMP collaborated with students and practitioners, including Dylan Deck, myself, and Jolie Gareis, to develop and apply methods for estimating NRVs for water quality parameters in the NWT. The outcome of this work was the selection of the Tukey's Inner Fence (TIF) and median 2 mean absolute deviation (M2MAD) methods (as described in Reimann et al., 2005) to calculate the NRV, and detailed methodology for the data treatment and analysis. The NWT CIMP supported my recommendation to build on this work and further test and refine the NRV methodology. Some of the work that followed is detailed in Chapter 4.

I designed the methodology used to test the NRV methods in this chapter in consultation with Lorraine Brekke, Heidi Swanson, and Simon Courtenay who reviewed and discussed the study methodology. I collected, analyzed, and interpreted the data, and wrote the manuscript. Heidi Swanson, Lorraine Brekke, and Simon Courtenay participated in the discussion of the results, and reviewed and edited the manuscript.

Chapter 5

Kidd, J. A., Courtenay, S. C., Annable, W., Epstein, G., Cott, P., Swanson, H. A Cumulative Effects Assessment approach to urban water body restoration. Prepared as a knowledge mobilization thesis chapter.

I conceptualized the study in collaboration with Heidi Swanson. Simon Courtenay, William Annable, Graham Epstein, and Heidi Swanson reviewed and discussed the study methodology. Pete Cott

provided information and insights that supported data interpretations and case study background. I collected, synthesized, and interpreted the data, and wrote the paper. All authors participated in the discussion of the results and review and editing of the chapter.

Abstract

This thesis investigated ways to gather, archive, share and use the knowledge needed to inform effective Cumulative Effects Assessment (CEA) for freshwater ecosystem protection and restoration. Specifically, this thesis focuses on methods for collecting, managing, and applying long-term regional data needed to characterize baseline conditions and monitor cumulative effects by addressing the following four questions: 1) Can community-based monitoring (CBM) collect long-term regional biophysical data needed for effective CEA; 2) How can long-term regional freshwater data be managed and shared so that it is reusable for CEAs; 3) How can long-term regional surface water data be analyzed to estimate baseline conditions and identify areas impacted by cumulative effects; and 4) Can the restoration of water bodies impacted by cumulative effects be improved with knowledge that is foundational for effective CEAs? Results of a pan-Canadian analysis of CBM projects confirmed that CBMs can contribute robust, valuable long-term regional biophysical data to CEA. As part of this analysis, project characteristics that should be considered when designing CBM projects for integration/use in CEA were identified. Insights gained from interviews with technology sector experts guided the development of recommendations that will make freshwater data open and reusable within the freshwater science sector. Natural Range of Variation (NRV) calculations (Tukey Inner Fence or median ± 2 median absolute deviation methods) were used to estimate surface water quality baselines which, when paired with Mann-Kendall trend analysis and spatial assessment of regional concentrations, provided a robust approach for assessing cumulative effects in freshwater ecosystems. Finally, known deficiencies in conventional approaches to urban water body restoration were addressed through application of the foundational elements of effective CEA to a case study of a degraded lake (Frame Lake) located in Yellowknife, Northwest Territories. This thesis defines the types of information that should inform freshwater ecosystem decision-making and articulates how that information can be obtained, managed and used.

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I would first like to thank my co-supervisors Dr. Simon Courtenay and Dr. Heidi Swanson for their support and guidance throughout my time as a PhD student. The prospect of working with these two researchers—my “dream team”—is partly what prompted me to embark on the PhD journey. I feel fortunate for having had two supervisors who have broad interests and skills and were supportive of me exploring a variety of research questions. I also appreciate their patience with my compulsion to turn everything into a consulting report.

I am grateful for the opportunity to have worked with my committee members Bill Annable and Graham Epstein. They both were generous with their time and offered valuable feedback and insights for my research projects. I think having an engineer and social scientist on the team really helped round out my research and make it more applied and pragmatic.

The Government of Northwest Territories Cumulative Impacts Monitoring Program funded part of my research. From the start of my PhD, I had the opportunity to work with their scientists, including Dion Kelly and Lorraine Brekke, who offered me the opportunity to work on their Natural Range of Variation project, and offered guidance and project direction.

Field work in the Northwest Territories was a highlight of my time as a PhD student. Andrea Lister gave me several opportunities to work with her in the field, which were all extremely fun adventures and helped keep me stay sane amongst all the office work.

I also had a wonderful time working with Mike Palmer and Nigel Rossouw from the Aurora Research Institute on a Sediment Oxygen Demand study of Frame Lake (not included in thesis). Mike offered advice and guidance on the Frame Lake project (Chapter 5) and life in general as a PhD student.

I thank Geoff Gunn from the Canada Water Agency who worked with us on the Freshwater Data Management and Sharing study (Chapter 3). Geoff reviewed and edited project documents, including the thesis chapter, and provided very useful sources of information for the study. He also gave me the opportunity to participate in the Canada Water Agency’s freshwater data workshop where I had the opportunity to learn more about the challenges and opportunities for open data sharing from the freshwater science community.

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My most supportive colleague and friend throughout my PhD was hands down my husband Andrew McGrath. Not only did Andrew give me the support one would typically expect of a partner, but he also helped me on several of my research projects. Andrew helped me design and build the device I used to measure sediment oxygen demand in cores I collected from a northern lake in collaboration with the Aurora Research Institute. Without him, I would not have had access to the highly skilled technology experts who I interviewed for my data management and sharing research project. Finally, after looking over my shoulder and proclaiming, “that is not sexy code,” he taught me how to create much more efficient functions in R that allow others to be able to reuse the statistical methods in the R package I created.

Finally, I would like to thank those who helped fund my PhD research. The Government of the Northwest Territories provided funding for the Natural Range of Variation project throughout my time as a PhD student. I also received funding from the Swanson and Courtenay labs. I was awarded an Ontario Graduate Scholarship from the Province of Ontario for the last two years of my studies.

Dedication

I would like to dedicate this thesis to my grandmother May Kidd. May knew how to love and was so easy to love in return. My favourite May catch phrase was “if you’re alright, then I’m alright.” Beyond a loving Grandmother, she was also a great research buddy. I would read journal articles while she napped. When she woke up, we would go for walks down the long hallways to get tea, coffee, and muffins. The frequent walks, snacks, and coffee mixed with writing breaks during naps gave me some of my most productive days as a PhD student.

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Chapter 1

Introduction

Freshwater ecosystem sustainability is a top priority for those living within Canada's jurisdictional boundaries (Environment and Climate Change Canada [ECCC], 2021; Gunn, 2021; McKittrick et al., 2018). With 20% of the world's freshwater resources, lakes and rivers cover much of the Canadian landscape (Hanrahan, 2017). These freshwater ecosystems offer abundant ecosystem services and hold significant subsistence and cultural value (ECCC, 2021). Yet, water security (i.e., water quality and quantity) is not universal in Canada (McKittrick et al., 2018), and water insecurity disproportionately affects Indigenous communities (Hanrahan, 2017). The safety and security of freshwater resources in Canada are increasingly at risk, with flooding, droughts, algal blooms, and drinking water advisories threatening ecological health and the well-being of people and the economy (Clark et al., 2023). Degraded freshwater ecosystems inhibit our ability to mitigate and adapt to climate change (United Nations Environment Programme, 2022). The cumulative effects of climate change and human development will continue to exacerbate water insecurity and threaten the sustainability of freshwater ecosystems (Gunn, 2021; Pomeroy et al., 2019; Seitz et al., 2011; Sheelanere et al., 2013) and the health and well-being of communities that they sustain. Nature-based solutions—natural areas that are managed or restored to address societal issues and simultaneously promote environmental and human health—are needed now more than ever, with 2024 officially being the hottest year on record globally (Lynch et al., 2023; Skidmore & Wheaton, 2022; Valença Pinto et al., 2023; World Meteorological Organization, 2024). With the climate crisis upon us (Intergovernmental Panel on Climate Change, 2021), Canada needs more effective tools and approaches to support improved governance and reform how we assess projects and land uses, and manage cumulative effects, such that safe water sources are secured for future generations (Ball et al., 2013; Miller et al., 2022; Sheelanere et al., 2013). Now is the time to enhance Canada's freshwater ecosystem protection and restoration practices.

This thesis explores how the protection and restoration of Canada's freshwater ecosystems could be enhanced with decision-making informed by a Cumulative Effects Assessment approach. Cumulative Effects Assessment (CEA), which can be practiced within and outside of formal Environmental Impact Assessment (EIA) practice, has the dual purposes of generating knowledge and understanding of ecosystem conditions and informing decision-makers (Jones, 2016). Cashmore (2004) described applied science and civic science as two broad EIA paradigms that overlap along a spectrum of the role of science in EIA. CEA can fall in the middle of this spectrum, as an information provision tool that is supported by systematic monitoring and quantitative methods and participatory approaches to inform environmental decision-making. The intended outcome of the practice of CEA

is to inform sustainable development decision-making that maximizes positive environmental and socio-economic benefits while avoiding harmful impacts. However, the effectiveness of CEA in practice is often limited by a lack of sufficient data collected through scientific and participatory processes. Thus, to achieve effective CEA, we need a paradigm shift that reestablishes how we fundamentally view data collection—not as a reactive process that simply informs assessment but a proactive process that defines assessments.

Below, I summarize the issues and recommendations identified in the literature for Cumulative Effects Assessment and environmental decision-making that form the foundation of this thesis. These include current approaches to Cumulative Effects Assessment, community-based environmental monitoring, open data, surface water quality baselines, and Cumulative Effects Assessments for freshwater ecosystem restoration. Finally, I outline the specific research objectives and questions addressed in this thesis.

1.1 Cumulative Effects Assessment for Freshwater Ecosystem Protection

Ensuring current and future sustainability of freshwater resources requires assessing and managing the cumulative effects of climate change and human activities (Gunn, 2021; Pomeroy et al., 2019; Seitz et al., 2011; Sheelanere et al., 2013). Due to the pervasive nature of cumulative effects, Cumulative Effects Assessment (CEA) has received considerable attention from researchers and government agencies in recent years (Blakley & Russell, 2022; Cronmiller & Noble, 2018; Sinclair et al., 2017). CEA is intended to be a planning and decision-making approach that promotes sustainable development through assessment of cumulative effects of multiple stressors over multiple temporal and spatial scales, and from both retrospective and predictive perspectives (Bristow et al., 2025; Dubé, 2003; Dubé et al., 2006; Duinker & Greig, 2006). CEA has the potential to improve decision-making for freshwater ecosystems (Ball et al., 2013; Chilima et al., 2013; Dubé et al., 2013; Sheelanere et al., 2013). The dual purposes of CEA are to generate knowledge and understanding of current ecosystem conditions and inform decision-makers with accurate predictions of future conditions, both of which are needed for sustainable watershed management and planning (Dubé et al., 2013; Jones, 2016). Unfortunately, it is widely acknowledged that current CEA practices in Canada—in both regulatory and non-regulatory contexts—are ineffective and consequently, CEA is falling short of supporting sustainable stewardship of freshwater resources (Ball et al., 2013; Chilima

et al., 2013; Dubé et al., 2006; Dubé et al., 2013; Duinker & Greig, 2006; Johnson et al., 2011; Noble, 2008; Seitz et al., 2011; Sinclair et al., 2017).

CEA scholars have described the necessary elements of effective project-level and watershed CEA for decades without witnessing substantive change (Arnold et al., 2022; Dubé et al., 2013; Duinker & Greig, 2006; Foley et al., 2017; Jones, 2016; Sinclair et al., 2017). Although the 2019 federal *Impact Assessment Act* was supposed to address the deficiencies of project-level CEA identified in the previous legislation, scholars suggest that it still falls short of ensuring sustainable outcomes (Eckert et al., 2020). For project-level and watershed CEA, decision-makers remain uncertain about defining and approaching cumulative effects as there remains a lack of standard approaches (Arnold et al., 2019; Ball et al., 2013). CEA issues need to be finally addressed if CEA is to realize its promise of supporting sustainable stewardship of freshwater resources (Duinker & Greig, 2006).

1.2 Community-based Monitoring in Support of Environmental Decision-Making

Community-based monitoring (CBM) offers an avenue for meaningful community engagement that is currently being advocated for in environmental decision-making (Arsenault et al., 2019; Gérin-Lajoie et al., 2018; Lawe et al., 2005; McKay & Johnson, 2017a; Wilson et al., 2018). CBM can foster relationships and trust between communities, industrial proponents, and government regulators (Arsenault et al., 2019; Gérin-Lajoie et al., 2018; Hunsberger et al., 2005; Lawe et al., 2005; McKay & Johnson, 2017a; Noble & Birk, 2011; Wilson et al., 2018). CBM has been described by Wilson et al. (2018) as “both a method for generating data useful for decision-making and an expression of governance itself, rooted in understandings of stewardship, kinship and responsibility.” CBM is one of the most common methods that bridge Western and Indigenous science in freshwater ecosystem research, monitoring, and management in Canada (Alexander et al., 2021). Not all CBM projects provide a meaningful level of participation as some are designed and executed by researchers from outside local communities with objectives that are irrelevant to the community (Danielsen et al., 2008; Kipp et al., 2019). CBM has been accused of advancing the economic interests of industries and governments while co-opting Indigenous participation and pacifying potential resistance to projects (Natcher & Brunet, 2020). Noble & Birk (2011) referred to CBM projects as “comfort monitoring” for their lack of efficacy in delivering on their promise of meaningful participation for

community members in environmental decision-making. To achieve a meaningful level of engagement, CBM programs need to be community-led, meaning the community co-designs the project, leads the data collection (perhaps with the guidance of third-party scientists), and uses the data (Mahoney et al., 2009; Wilson et al., 2018).

Alongside community engagement, CBM can also be a cost-effective way to fill critical data gaps in the understanding of freshwater resources in Canada (Gunn, 2021). CBM can expand the temporal and spatial scopes of environmental baseline data collection beyond traditional monitoring programs (Hunsberger et al., 2005; Lawe et al., 2005; McKay & Johnson, 2017a; Theobald et al., 2015). CBM also helps to include the knowledge of historical conditions from local community members and Indigenous peoples to establish a more complete understanding of baseline conditions (ECCC, 2016; Hobbs et al., 2014).

There is a growing interest in establishing CBM projects that can effectively detect environmental change. A review of CBM projects in Canada by Carlson and Cohen (2018) revealed that the number of such projects quadrupled in Canada between 2000 and 2016. However, not all CBM programs will produce data or knowledge that inform environmental decision-making. Some CBM programs are designed as stewardship initiatives without decision-making goals, and decision-makers can be reluctant to trust the credibility of CBM data (McKay & Johnson, 2017a). The ability of CBM programs to inform environmental decision-making hinges on rigorous, robust, and defensible methods (McKay & Johnson, 2017a). As such, much of the research in CBM has focused on evaluating the quality of CBM data. A number of studies have demonstrated that, when designed well, CBM can produce data that are of similar quality to professional scientists while being less expensive (Kidd et al., 2021; Thompson et al., 2020). While previous research has established an interest in the use of CBM to inform environmental decision-making, there is a need for research on developing protocols for CBM projects designed to inform environmental decision-making (Kouril et al., 2016; McKay & Johnson, 2017a).

1.3 Open Data for Environmental Decision-Making

There is growing acknowledgement that openly available data are needed to support freshwater resource protection and restoration (ECCC, 2021; Miller et al., 2022; Piczak et al., 2022). Freshwater resource protection and restoration requires sufficient data to understand current conditions and predict the impacts of cumulative effects (Arnold et al., 2019; ECCC, 2021; Miller et al., 2022). Data

collected for watershed and project-level CEAs should be openly shared to integrate the different levels of assessment as it has become apparent that individual project proponents and research groups do not have the capacity to collect the scope and scale of data needed for effective CEA (Ball et al., 2013; Chilima et al., 2013; Dubé, 2003; Duinker & Greig, 2006; Foley et al., 2017; Johnson et al., 2011; Jones, 2016; Seitz et al., 2011; Sheelanere et al., 2013; Sinclair et al., 2017). Effective CEA has sufficient data to characterize baseline conditions and understand how past and current disturbances have interacted to cause current conditions, and to predict future conditions under several development scenarios. This effective CEA practice can support sustainable development decision-making that achieves net positive environmental and socio-economic outcomes. Similarly, restoration projects should share their data to allow other projects to build on and improve on their work (Food and Agriculture Organization et al., 2023; Piczak et al., 2022). Yet, all data should not be by default publicly accessible—data sovereignty and privacy must be considered before data are considered for open access (Wilson et al., 2024; Zipper et al., 2019). Indigenous data sovereignty stipulates that Indigenous governments and communities have jurisdiction over the collection and sharing of data collected by or about their peoples and land (Carroll et al., 2020; Zipper et al., 2019). Therefore, to improve freshwater ecosystem protection and restoration, all levels of government, academia, industry, consultants, and communities need to work together to make freshwater data more openly available (Ball et al., 2013; ECCC, 2021; Foley et al., 2017; Johnson et al., 2011; Miller et al., 2022; Sheelanere et al., 2013).

Despite its importance, reviews of freshwater data availability have indicated that most Canadian watersheds are data-deficient, including the Great Lakes—one of Canada’s most populated watersheds (Goucher et al., 2021; Miller et al., 2022; Water Rangers, 2025). Freshwater scientists remain generally reluctant to share their data due to concerns about competition from other researchers, the time required to manage data for sharing, lack of recognition for data sharing, perceived liability concerns, and fears of others misinterpreting data or exposing errors (Goucher et al., 2021; Gunn & Stanley, 2018; Hahnel et al., 2023; Roche et al., 2015). Those who are willing to share their data may be unable to do so due to a lack of data literacy, lack of detailed guidance on data sharing, confusion over who owns the data, inadequate digital infrastructure, staff turnover, lack of time and/or support, and/or weak data management policies and procedures (Hahnel et al., 2023; Ho et al., 2021; Kroetsch, 2021; Roche et al., 2020). Even when datasets are available, they can be difficult to find as the various organizations that collect and manage freshwater data store them on

multiple platforms, resulting in a large, disparate, and fragmented network of data (Chilima et al., 2013; DataStream, 2024; ECCCC, 2021; Gunn & Stanley, 2018; Miller et al., 2022; Wrona & Munkittrick, 2024). Overall, inefficient, non-standardised data management and sharing practices in freshwater science continue to reduce the quality of studies and limit the applicability of data collected for decision-makers (Stanley & Gunn, 2018).

1.4 Surface Water Quality Baseline Studies for Cumulative Effects Assessment

The first step in a CEA is to establish baseline (i.e., reference, background, accumulated state) conditions to assess the current state of the watershed and cumulative impacts of anthropogenic activities (Ball et al., 2013; Dubé, 2003). For freshwater ecosystems, baseline conditions are typically established for water quality, water quantity, and the composition and abundance of aquatic organisms (Ball et al., 2013). Data are collected from reference sites to establish baseline conditions, which represent the condition of the environment without the contaminant or stressor being investigated (Ball et al., 2013). Baselines can be used to derive thresholds (i.e., benchmarks) that indicate when changes to an indicator are outside the natural range of variation and signal that a significant effect has occurred (Ball et al., 2013; Dubé et al., 2006; Dubé et al., 2013; Dung et al., 2013; Foley et al., 2017; Worrall et al., 2019). Researchers have argued that baseline estimates should be used as thresholds over water quality guidelines because they are more appropriate social thresholds (“the point at which the public becomes alarmed and demands action”; Duinker & Greig, 2006) and more scientifically defensible (Arnold et al., 2019; Dubé et al., 2013). Ecologically and socially relevant thresholds need to be developed for all indicators, and the methods for setting thresholds must be standardized for all CEAs (Dubé et al., 2013; Jones, 2016). Unfortunately, there are no standard methods for establishing and validating baseline conditions, and adequately defining baseline remains one of the main criticisms of CEA (Ball et al., 2013; Dubé, 2003; Dung et al., 2013; Foley et al., 2017).

Monitoring and assessing freshwater ecosystem health requires identifying when surface water quality parameters have changed beyond their natural range of variation (NRV), which signifies impacted conditions. Defining the NRV of surface water quality parameters is difficult due to widespread anthropogenic influences on water chemistry (Miller & Miller, 2007; Sahoo et al., 2019). While baseline characterizations based on samples collected before anthropogenic influences would be ideal, there is growing acknowledgement that areas unimpacted by anthropogenic activities are no

longer available (Jarva et al., 2010; Mali et al., 2015; Sahoo et al., 2019). With ongoing climate change, contemporary sampling may no longer serve as a useful baseline (Shackleford et al., 2021). Water quality parameters are also naturally dynamic and can vary widely from season to season and year to year based on varying local weather patterns (Sahoo et al., 2019). Thus, natural background water quality concentrations are a range rather than a single value (Dung et al., 2013; Miller & Miller, 2007; Reimann et al., 2005; Reimann & de Caritat, 2017). This range—referred to as the NRV—can be used to identify samples that may be impacted by human activities and require further investigation (Reimann & de Caritat, 2017; Sahoo et al., 2019). There are several methods that can be used to estimate the NRV, each with strengths and weaknesses that should be carefully weighed (e.g., Barrett et al., 2015; Reimann et al., 2005). Further study is needed to assess the applicability of NRV methods for surface water quality data (Sahoo et al., 2019).

1.5 Cumulative Effects Assessment for Freshwater Ecosystem Restoration

Restoration researchers and practitioners are increasingly recognizing the need to consider cumulative effects as water bodies are rarely subjected to a single pressure (Dey et al., 2021; Hughes et al., 2014; Poikane et al., 2024). The cumulative effects—including those from environmental and socio-economic influences—that led to the degradation of a water body and could impede the success of the restoration project need to be understood to select appropriate restoration measures (Hughes et al., 2014; Hychka & Druschke, 2017; Poikane et al., 2024). In the context of amplifying cumulative effects of climate change and human activities, effective restoration of freshwater ecosystems requires a new approach (Poikane et al., 2024). Globally, scientists are calling for immediate action to address the lack of progress towards effective restoration as restoring degraded freshwater ecosystems and other critical natural infrastructure is a vitally important component of climate change mitigation and adaptation (Abell et al., 2022; Poikane et al., 2024; Tammeorg et al., 2023; United Nations Environment Programme, 2022). A poor understanding of both anthropogenic and natural pressures and their interacting effects (both spatially and temporally) causes many restoration projects to fail (Poikane et al., 2024).

Similar to project-level CEA in Impact Assessment, cumulative effects are typically assessed for restoration projects in terms of the cumulative impact (negative and positive) of restoration projects (Gray et al., 2011; Thebaud et al., 2015; Theis et al., 2022). These cumulative effects assessments typically compare restoration sites to unimpacted reference sites (i.e., desirable

conditions) and impacted sites (i.e., undesirable conditions) to determine the relative success of restoration measures (Gray et al., 2011; Shackelford et al., 2021; Weber et al., 2018). Regional spatial scopes are also used to evaluate cumulative effects (and relative success) of multiple restoration projects (e.g., Beck et al., 2019; Gray et al., 2011; Weber et al., 2018). CEAs of restoration projects typically focus on biophysical results without considering the socio-economic components (Beck et al., 2019). Beck et al. (2019) recommended a more comprehensive approach that considers the human and social factors of restoration success.

Restoration scholars have independently identified similar elements recommended for effective CEA in Impact Assessment as necessary for effective freshwater ecosystem restoration. These elements include meaningful community engagement (e.g., Pradhananga et al., 2019), transdisciplinary collaboration (e.g., Hychka & Druschke, 2017), long-term monitoring (e.g., Poikane et al., 2024), regional spatial scope (Shackelford et al., 2021), open data (Piczak et al., 2022), a strategic approach to setting restoration objectives (e.g., Abell et al., 2022), and a sustainability assessment of restoration measures (Tammeorg et al., 2023). To our knowledge, however, no study has combined all of these elements into a comprehensive approach that can guide restoration efforts.

1.6 Research Objectives

The overarching goal of this thesis was to investigate ways to gather the knowledge needed to inform effective CEA and thus improve freshwater resource protection and restoration processes.

Specifically, the focus was on how to collect, manage, and apply long-term regional data needed to characterize baseline conditions and monitor cumulative effects. To achieve this goal, this thesis addressed four main questions: 1) How can we collect long-term regional monitoring data; 2) If we can collect long-term regional monitoring data, how do we effectively manage and store it in a way that can be publicly accessible and reusable; 3) Once we have access to long-term regional data, how do we analyze it to understand baseline conditions and identify areas impacted by cumulative effects; and 4) Once we have identified impacted areas, can we use a CEA approach to ensure sustainability and success of restoration measures? Each of these questions is addressed in individual chapters (Chapters 2–5):

Chapter 2: This chapter addresses the need for long-term regional environmental monitoring data to inform CEA. While it is widely understood that long-term regional data are needed to understand natural variability and inform impact predictions, baseline studies remain short (<3 years) and limited

to a project footprint. Therefore, the first objective of this thesis was to evaluate if community-based monitoring (CBM) can collect long-term regional biophysical data for CEA in addition to what is already known about CBM's potential to facilitate meaningful community engagement in environmental decision-making. I completed a pan-Canadian analysis of CBM projects to confirm the capability of CBMs to contribute long-term regional biophysical data to CEA. I also offer recommendations for designing CBM projects that aim to inform CEA. This study was completed in collaboration with Environment and Climate Change Canada, and represented a dual interest in improving methods within CEAs to support science-based environmental decision-making and in supporting CBM projects for greater community engagement in environmental decision-making.

Chapter 3: This chapter addresses the need for access to reusable environmental monitoring data to inform more robust CEAs. Open freshwater data will support CEAs for freshwater resource protection and restoration by maximizing the available long-term regional data. Open data will also allow community groups to share their community-based monitoring data—enhancing the impact of these data and, thus, the longevity of their projects. In addition, open data will give communities access to other data that they can include in assessments to inform their local decision-making. Therefore, the second objective of this thesis was to explore how freshwater data can be managed and shared in a way that they can be reused to support CEAs. I interviewed technology sector experts to explore options for the freshwater science sector that will accelerate open data initiatives to make freshwater data publicly accessible and reusable while filling critical data gaps. This study was completed in collaboration with the Canada Water Agency, which was interested in the insights gained from the technology sector to support the development of its National Freshwater Data Strategy.

Chapter 4: This chapter addressed how long-term regional data can be analyzed to generate an estimate of baseline conditions that can be used as a benchmark for identifying impacted sites. In particular, this chapter describes a method developed for estimating baseline conditions for surface water quality, which is one of the most common environmental components assessed in CEA but still lacks a standard approach. Therefore, the third objective of this thesis was to develop a statistical tool to analyze long-term regional water quality data to differentiate impacted and unimpacted sites in either project-level or watershed assessments. The natural range of variation (NRV) is an estimate of baseline conditions using statistical methods that define concentration ranges that signify unimpacted conditions and identify outliers (i.e., impacted samples). NRV methods have commonly been used for

soil and sediment studies. As a research outcome, I built a statistical package—accompanied by a lay-language guidance manual—that I designed for practitioners and the public. This study was completed in collaboration with the Government of the Northwest Territories Cumulative Impact Monitoring Program. Practitioners at the Cumulative Impacts Monitoring Program were interested in developing a reproducible and defensible method in NRV estimation that would strengthen the ability of researchers and decision-makers to make informed inferences and develop evidence-based policies regarding the influence of anthropogenic effects on surface water quality in the Northwest Territories.

Chapter 5: This chapter addressed how the restoration of water bodies impacted by cumulative effects of multiple stressors could be improved with the same knowledge that is foundational for effective CEAs. Essentially, baseline water quality data can be used to identify sites impacted by cumulative effects and that same baseline data can then be used to support decision-making associated with the restoration of that impacted site. The baseline data should be used by project managers in collaboration with rights holders, stakeholders, and disciplinary experts who share their environmental and socio-economic knowledge in the design of restoration projects that support community objectives for the watershed and maximize the positive outcomes of the project. Therefore, the final objective of this thesis was to demonstrate how the foundational elements of a CEA can help restoration projects achieve more sustainable outcomes. I summarise recommendations from the CEA and Impact assessment literature for foundational elements of effective CEA for freshwater ecosystems (regional scale, long-term monitoring, community engagement, transdisciplinary collaboration, a strategic approach, and sustainability-based decision-making) and show how these elements are also emerging as recommendations in the freshwater restoration literature. I used Frame Lake in Yellowknife, Northwest Territories, as a case study to illustrate how the proposed CEA approach to restoration could achieve more sustainable outcomes than a conventional habitat offsetting project.

The final chapter of the thesis (Chapter 6) integrates observations from the chapters, provides insights into how cumulative effects assessments can be improved, and makes recommendations for future studies.

Chapter 2

Pan-Canadian Review of Community-Based Monitoring Projects and Their Capacity to Enhance Environmental Monitoring Programs for Cumulative Effects Assessments

Reprinted from Kidd, J., Brammer, J., Courtenay, S., Swanson, H., & Avery-Gomm, S. (2024). Pan-Canadian review of community-based monitoring projects and their capacity to enhance environmental monitoring programs for cumulative effects assessments. *FACETS*, 9, 1-19.
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2.1 Abstract

While community-based monitoring (CBM) can support meaningful participation of the public in environmental decision-making, it remains unclear if and how CBM can support western science approaches to biophysical studies within cumulative effects assessment (CEA). We scored 40 Canadian CBM projects on their ability to enhance CEA's western science approaches to environmental monitoring. We used multivariate analyses to determine if the highest-scoring projects shared characteristics that could inform the design of CBMs to support CEA. Cluster analysis and non-metric multi-dimensional scaling ordination revealed that highest-scoring projects were distinct from lower scoring projects, and the Similarity Percentages Routine identified characteristics that differentiated these projects. The highest-scoring projects involved non-profit organizations as bridging organizations that coordinated community participation and received funding and in-kind support from provincial/territorial government agencies. Participants in these projects collected measurements and samples using standardized protocols described in training manuals. Their data were publicly accessible in georeferenced databases and were used for baseline studies and resource management. There are existing CBM projects in Canada that thus appear well positioned to enhance western science approaches to CEA. Further study is required to identify how CBM projects can be designed to braid Indigenous and western science approaches to mutually enhance CEA methods.

2.2 Introduction

Cumulative environmental effects are “environmental changes caused by multiple interactions among human activities and natural processes that accumulate across space and time” (Canadian Council of Ministers of the Environment, 2014). The importance of assessing cumulative environmental effects is increasingly recognized in Canadian environmental assessment processes (Cronmiller & Noble, 2018; Impact Assessment Act Canada, 2019; Sinclair et al., 2017). Cumulative effect assessments (CEAs) consider cumulative effects from multiple stressors over temporal and spatial scales and retrospective and predictive perspectives (Dubé, 2003; Dubé et al., 2006). CEAs' dual purposes are to generate knowledge of ecosystem conditions and inform sustainable environmental decision-making (Chilima et al., 2013; Duinker & Greig, 2006; Jones, 2016). Scholars have frequently described Canadian Impact Assessment (IA)—the largest driver of CEA in Canada—as ineffective in supporting sustainable development due to insufficient legislative framework, insufficient baseline

data, and insufficient meaningful participation of Indigenous people (Dubé et al., 2006; Dubé et al., 2013; Duinker & Greig, 2006; Gibson et al., 2020; Jones, 2016; Noble, 2008).

From a western science perspective, a key criticism of Canadian IA and CEA methods is the insufficient characterization of baseline conditions. Environmental baseline studies are foundational for IAs and CEAs that require an understanding of current environmental conditions. Unfortunately, environmental baseline studies tend to be short-term and take project-level rather than regional approaches (Arnold et al., 2019; Dubé et al., 2013; Johnson et al., 2011). The typical 1- or 2-year baseline datasets focused on project footprints are inadequate in their characterization of natural variability, and thus predicting the cumulative effects of past, current, and proposed projects is compromised (Arnold et al., 2019; Dubé et al., 2013; McKay & Johnson, 2017a). It is well established that longer term and regional-scale baseline data are needed to accurately represent the natural variability and reference conditions of many environmental indicators (Arnold et al., 2019; Cronmiller & Noble, 2018; Dubé et al., 2013; Foley et al., 2017). Yet, project proponents typically fulfill only the most basic requirements for project approval; long-term and regional data collection requires leadership and coordination beyond the scope of many individual projects (Arnold et al., 2019; Duinker & Greig, 2006; Foley et al., 2017; Noble, 2021; Seitz et al., 2011; Sheelanere et al., 2013).

Community-based monitoring (CBM) could help generate the baseline data needed to enhance western science methods within CEA and facilitate meaningful participation of communities in environmental decision-making (Arsenault et al., 2019; Gérin-Lajoie et al., 2018; Lawe et al., 2005; McKay & Johnson, 2017a; Wilson et al., 2018). CBM can expand the temporal and spatial scopes of environmental baseline data collection, making monitoring programs more regionally relevant and able to detect change through time (Hunsberger et al., 2005; Lawe et al., 2005; McKay & Johnson, 2017a). A review of 388 global CBM projects found CBM projects typically run seven years longer than scientific monitoring projects (Theobald et al., 2015). The long-term datasets collected by CBM projects can therefore better detect unanticipated impacts (Gérin-Lajoie et al., 2018; McKay & Johnson, 2017a). CBM's potential contribution to CEA has been considered for individual projects (e.g., Lawe et al., 2005), but not broadly across Canada.

In Canada, CEAs need to consider “scientific information, Indigenous knowledge, and community knowledge” as described in the *Impact Assessment Act* (s6(1j) Impact Assessment Act of

Canada, 2019). CBM projects may be able to draw from all of these knowledge sources, but CBM describes a broad diversity of projects with a wide range of objectives and structures (Kanu et al., 2016; Theobald et al., 2015). Some CBM projects are designed and executed by researchers from outside local communities with objectives that are irrelevant to the community (Danielsen et al., 2008; Kipp et al., 2019), while others are initiated and conducted solely by local communities for their purposes (Danielsen et al., 2008). Meaningful participation in monitoring requires that local communities co-design the CBM project, lead its data collection, and have internal uses for the data (Mahoney et al., 2009; Reed et al., 2020; Wilson et al., 2018). These projects are more likely to empower community members, contribute to decision-making, and be more sustainable over time as they garner greater interest and participation from community members (Kouril et al., 2016; McKay & Johnson. 2017a; Parlee et al., 2017). Here, we focus on CBM projects in which the data are primarily collected by community members who may have received training or guidance from professional researchers, and the data are used by either the local community and researchers or just the local community.

We aimed to understand if CBM has the potential to enhance the biophysical baseline studies that inform CEA by elevating the participation of local communities and by collecting datasets that meet western science standards. Our focus on western science methods in CBM is not intended to diminish the critical importance of Indigenous science and knowledge; instead, it reflects our positionality as non-Indigenous scientists. While we believe CBM projects can contribute to “scientific information, Indigenous knowledge, and community knowledge”, we focus here on the potential western science contributions of CBM to the biophysical components of CEA, as this is our area of expertise and experience. As such, we made no attempts to evaluate the ability of projects to include Indigenous knowledge, and Indigenous knowledge was not an attribute in our scoring rubric. We also did not attempt to extrapolate whether Indigenous knowledge was included in a project and only recorded Indigenous knowledge as a project characteristic when it was explicitly stated in the project documentation.

Our objectives were to evaluate the ability of CBM projects in Canada to collect biophysical data that could support western science approaches to CEA and what (if any) characteristics these projects shared. We developed a rubric to score the ability of CBM projects to contribute data to biophysical baseline studies for CEAs and determined whether the highest-scoring projects had common characteristics. Identifying shared characteristics could support the intentional design of

future CBM projects that intend to contribute western scientific data to CEAs while also empowering communities to lead local decision-making processes.

2.3 Materials and Methods

We conducted the data collection for this study from February to June 2020.

2.3.1 Community-Based Monitoring (CBM) Project Inventory

We generated a master list of CBM projects that monitor environmental variables typically included in environmental assessments (i.e., valued ecosystem components; Appendix A; Table A.1). We included projects from previous inventories (e.g., Kipp et al., 2019; Nadeau & Picard, 2019; Parlee et al., 2017; Raygorodetsky & Chetkiewicz, 2017; Sullivan & Beveridge, 2005). We used a standardized email (Appendix A, Document A.1) to ask colleagues who work in the field of CBM for assistance in identifying additional CBM projects. We also searched for CBM projects in the grey literature (e.g., Atlas of Community-Based Monitoring, 2020; Canadian Cryospheric Information Network, 2017; Canadian Polar Commission, 2014; DataStream, 2020; Indigenous Guardians Pilot Program, 2020; Northern Contaminants Program, 2020) and the peer-reviewed literature through Web of Science and Google Scholar. The search terms used were “community-based monitoring” + “environment” + “Canada;” “cumulative effects” + “community-based monitoring”; “participatory monitoring” + “environment” + “Canada”; and “cumulative effects” + “participatory monitoring”. Through these searches, we generated a master list of 317 CBM projects (Figure 2.1; Appendix A, External Resource A.1).

We screened our master list of CBM projects to identify those that met the following criteria: (1) collected data to detect environmental change (i.e., monitored environmental indicators, such as water quality, wildlife abundance, air quality, etc.); (2) sufficient project information was readily available online to allow further assessment (e.g., description of data collection techniques, monitoring location, and project participants); and (3) available information suggested community members collected data independent of researchers. We based this screening on online, project-specific information obtained through Google searches. A review of CBM projects by Kipp et al. (2019) found that many projects are described as community-based, but the extent of community member involvement varied and was often limited. We narrowed our focus to projects that enabled community members to collect monitoring data without the direct supervision of researchers or

professional scientists. For this study, we defined CBM projects as projects in which the data are primarily collected by community members who may have received training or guidance from professional researchers, and the data are used by either the local community and researchers or just the local community. We created this definition by merging three categories (3, 4, and 5) of CBM projects defined by Danielsen et al. (2008). For this study, community members encompass local community members who may or may not be paid to collect data or are members of the general public who volunteer their time. Sixty-two CBM projects in the project inventory met our study criteria (Figure 2.1; Appendix A, External Resource A.2).

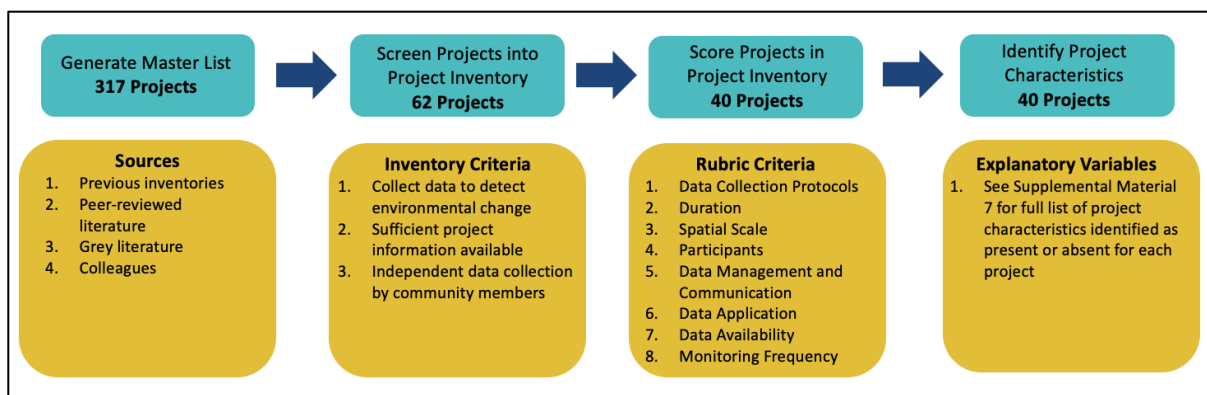


Figure 2.1. Flow chart of the methods used to a) generate a master list, b) apply screening criteria to develop a project inventory of CBM projects, c) develop a rubric to score the ability of CBM projects to collect environmental baseline data that could support western science approaches to regional CEAs and use it on a subset of projects from the project inventory, and d) identify the explanatory project characteristics that are associated with higher-scoring CBM projects.

2.3.2 Project Scoring

We developed a scoring rubric to evaluate the ability of CBM projects to collect environmental baseline data that could support western science approaches to regional CEAs. We identified eight project attributes that align with design considerations of environmental baseline studies and which address the need for regional CEAs (Table 2.1 and Figure 2.1; Appendix A, Document A.2). These eight project attributes were selected and defined based on recommendations for improving CEA baseline studies from the literature and our collective experience in conducting environmental monitoring programs, including CBM projects. As such, these project attributes reflect our experiences with western science methodologies and do not represent an exhaustive list of potentially useful project attributes. We welcome others to modify the scoring rubric, which we have made available in Table 2.1 and describe in detail in Appendix A, Document A.2, based on their knowledge and experiences.

Our selected project attributes included the rigour of data collection protocols, the project duration, the project spatial scale, the number of project participants, how well data were managed, sampling frequency, data application, and data availability. We gave each attribute a score between 1 and 5 (i.e., ordinal scale), with 5 indicating that the project had an exceptional ability to contribute environmental baseline data to regional CEAs. Scores were relative, and thus, “lower” scores did not necessarily indicate that a project could not contribute valuable data to baseline studies for regional CEA; instead, these “lower” scores indicate that other projects either offered or demonstrated evidence of greater capacity or complexity for that particular attribute. For example, monitoring an area of 50, 000 km² would yield valuable data for a regional baseline study, whereas monitoring an area of 500, 000 km² could yield valuable data for several regional studies and allow for comparisons among regions of varying levels and types of human activities that could offer greater insights into cumulative effects. While CBM projects that monitor larger areas do not necessarily collect more robust data, the capacity to monitor larger areas suggests the ability to overcome the greater logistical complexities of monitoring larger areas, which would be very valuable to learn from when considering the design of future CBMs for CEA.

We defined the score categories according to numerical ranges identified during the initial project search or possible options based on project descriptions. We then assigned the cumulative attribute score for each project to one of four score categories based on quartiles: Quartile 1 (project score $\leq$ 25th percentile), Quartile 2 (project score $\leq$ 50th percentile and $>$ 25th percentile), Quartile 3 (project score $\leq$ 75th percentile and $>$ 50th percentile), or Quartile 4 (project score $>$ 75th percentile). Projects with higher scores (e.g., Quartile 4 $>$ 3 $>$ 2 $>$ 1) can be interpreted as having a relatively greater ability to contribute environmental baseline data to regional CEAs, based on the information we were able to gather. Below is our rationale for selected project attributes presented in Table 2.1, where the scores are defined.

Table 2.1. Project attributes and scoring rubric.

Project Attribute	Score Descriptions
Data Collection Protocols	1 = No explicit data collection protocol reported or referenced. No indication a protocol exists for community members. 2 = An indication a protocol exists, but no other details. An indication of protocols includes mention of monitor training but lacks a description of the training. 3 = A protocol clearly exists, and some description of what it entails is provided. This includes statements that monitors are trained to use standardized protocols, including monitoring forms, but the protocol itself is not mentioned or described. Or there is evidence the protocol has not been consistently used throughout the project. 4 = It is clear that project participants follow a set protocol that is described to repeatedly collect data, but the protocol itself is not available. 5 = Project participants follow a set protocol to repeatedly collect data, and the protocol itself is easily accessible. This includes reference to standardized protocols and the source or citation for that protocol.
Project Duration	1 = 1–5 years 2 = 6–10 years 3 = 11–15 years 4 = 16–20 years 5 = >20 years
Spatial Scale	1 = <500 km² 2 = <5,000 km² 3 = <50,000 km² 4 = <500,000 km² 5 = >500,000 km²
Project Participants	1 = 1 community/organization OR <10 volunteers 2 = 2–4 communities/organizations 3 = 5–7 communities/organizations OR <100 volunteers 4 = 8–10 communities/organizations 5 = >10 communities/organizations OR >100 volunteers
Data Management & Communication ¹	1 = No explicit indication that data are managed and stored using any particular technique. An indication that data are stored, but no other details. 3 = Where and how data are managed is clear, but it is not clear whether data can or have ever been analyzed. Data may be available through a database but no indication of data analysis and results being communicated through reports or outreach materials. This includes when results are communicated in peer-reviewed publications (i.e., results withheld for publications or thesis). 5 = It is clear that data are analyzed, and results have been communicated in reports or outreach material to the community.
Monitoring Frequency	1 = Opportunistic (i.e. inconsistent sampling periods) 2 = Annual (i.e. 1x per year) 3 = Biannual (i.e. ≥2x per year) 4 = Seasonal (i.e. ≥4x per year) 5 = Monthly (i.e. ≥12x per year)

Table 2.1. (concluded).

Project Attribute	Score Descriptions
Data Application	1 = No mention of objective for data, or acknowledgement that decision-makers do not consider the data. 2 = The stated objective is to monitor change, but no mention of the decisions that will be informed by this monitoring data (e.g., caribou populations are monitored to document if populations are declining overtime). This ranking defines those projects that state the purpose of their data, but does not define who is supposed to use the data to make decisions (e.g., We collected water samples to identify phosphorous hotspots. No information is provided as to who will use this information, or how identifying phosphorous hotspots will inform decisions). 3 = The objective for the data is to inform decision-makers, but no details are provided as to how decision-makers will use the data (e.g., caribou populations are monitored to inform the resource management board). This ranking defines projects that state the proposed objective for the data and who the data is meant to be used by, but doesn't provide a clear indication of how that data can be used to inform decisions (just because they send their data to an industrial proponent, doesn't mean they consider it). 4 = Details for how decision makers can use the data and what decisions will be informed by the data are provided (e.g., caribou populations are monitored to inform resource management board's decision for the number of caribou tags to release each year). This ranking defines projects that clearly describe the objective for the data and how that objective will be fulfilled. So, who the data is used to make decisions, and what decisions do they use the data for? 5 = Evidence is provided that decision-makers consider the data and have used it to inform decisions (e.g., In 2015, the resource management board reduced the number of caribou tags after reviewing the project data that revealed a sustained downward trend in caribou abundances), or evidence is provided that the data has been incorporated into a decision-making process/framework (e.g., land use and management plans).
Data Availability	1 = No mention of data being available for use by anyone. Also includes projects where the data do not appear to be directly available to the community. 2 = Data are available to the community only. 3 = Data are available to the community and project partners, or when data are only made available through scientific publications. 4 = Data are available to the public, but only by request, or there is no evidence of the project data being readily available online. Or, the data are publicly available, but available data are not up to date (i.e. publicly available data is older than 2018). 5 = 2018 and older data are readily available to the public.

¹ The score categories were confined to three scores, as we found only three explicit variations in data management.

2.3.3 Data Collection Protocols

This criterion scored the projects based on whether standardized data collection protocols (i.e., a consistent approach to data collection) were consistently used and reported. Data collection methods should follow standardized protocols to collect defensible data that can inform western science approaches to environmental monitoring and decision-making (Conrad & Daoust, 2008; Herman-Mercer et al., 2018; Hunsberger et al., 2005; Kouril et al., 2016; McKay & Johnson, 2017a).

Standardized monitoring methods are essential for CEA to know which datasets can be compared

across space and time for regional assessments (Miller et al., 2022). Successful project-level and regional CEA integration requires standardized long-term monitoring methods (Arnold et al., 2019; Dubé et al., 2006; Foley et al., 2017). McKay and Johnson (2017a) found that government and industry representatives believed the effectiveness of CBM projects depended on “rigorous, robust, and defensible methods”. Furthermore, standardized monitoring approaches facilitate earlier detection of environmental effects and can improve adaptive management (Roach & Walker, 2017).

2.3.4 Project Duration

This criterion defines the number of years the project has been collecting monitoring data. Cumulative effects monitoring, assessment, and management are long-term processes (Environment and Climate Change Canada [ECCC], 2016; Hegmann et al., 1999). Long-term monitoring data are needed to inform robust baseline studies that better define natural variability, identify deviations from that variability, and produce more accurate impact prediction models (Duinker & Greig, 2006; Dubé et al., 2013; ECCC, 2016; Roach & Walker, 2017). Long-term monitoring before and after developments also helps identify when and where mitigative measures are needed and supports adaptive management (Dubé et al., 2013; Duinker & Greig, 2006; ECCC, 2016; Roach & Walker, 2017). The duration of a CBM project is also an indicator of its success in holding the interest of participants and funding agencies.

The total number of years did not include the time during which the project was designed or any years when the project was on hold (i.e., we only included years when data were collected in the total duration calculation). We did not include 2020 in the duration calculation for ongoing projects, as the sampling period for all projects would not have occurred by the time we completed our study. The duration of projects in the inventory ranged from 1 to 29 years, with a median of 8 years. We used data from an initial project inventory to generate a typical range of project duration. We divided this range into four equal-sized categories, with an additional category representing exceptionally long projects.

2.3.5 Spatial Scale

This criterion scored the project based on the project’s reported study area size. Scholars widely agree that effective CEA requires a regional approach (Arnold et al., 2019; Chilima et al., 2013; Dubé et al., 2006; Dubé et al., 2013; Duinker & Greig, 2006; Foley et al., 2017; Gibson et al., 2020; Johnson et

al., 2011; Jones, 2016; Noble, 2008). Thus, it is important to identify projects monitoring at large enough spatial scales to contribute to regional CEA. CBM projects that monitor larger spatial scales also demonstrate greater logistical complexity in coordinating monitoring efforts across a larger area.

For projects that monitored harvesting data and did not define a study area size, we estimated a 100 km radius (i.e., 31,416 km²) for each community that participated. The size of study areas monitored by the projects in the inventory ranged from 5 to 1,100,000 km², with a median of 3,939 km².

2.3.6 Project Participants

Cumulative effects monitoring, assessment, and management require coordination of activities among multiple participants (ECCC, 2016). CBM projects demonstrating coordination success, particularly the capacity to coordinate numerous communities, are valuable models. This criterion scored the projects based on the number of communities or non-profit groups that routinely participated in the project and was meant to help understand the scope of the logistics and coordination required to operate the project. This criterion was also meant to reflect how many communities/groups can be expected to be involved in one project. We scored some projects based on their number of volunteers because the number of communities or non-profit groups was not provided.

The number of communities or non-profit organizations participating in projects in the inventory ranged from 1 to 35, with a median of 2. We used data from an initial project inventory to generate a typical range of community participants. We used this range to define three equal-sized categories above 1, with an additional category representing abnormally large participant numbers.

2.3.7 Data Management and Communication

This criterion scored the projects based on data management and protocols that clearly articulated data handling and management procedures for analysis and regularly communicated results. Data management is critical to effective cumulative effects monitoring (ECCC, 2016). Data management systems can improve the integrity of monitoring projects and facilitate effective communication of data to partners, rights holders, stakeholders, and the public. Data management systems and communication are also essential when data from cumulative effects monitoring are used to develop management actions or responses (ECCC, 2016; Kipp et al., 2019; McKay & Johnson, 2017a). The

score categories were confined to three scores, as we found only three explicit variations in data management.

2.3.8 Monitoring Frequency

This score was based on the frequency of data collection for the indicators routinely monitored by the project. If project-specific frequencies varied among indicators or variables, we used the most frequent sampling for the scoring. We used this scoring criterion to understand if data collection protocols included consistent data collection and if the data could capture temporal variability. In addition, this criterion helped identify projects that required greater involvement and commitment by project coordinators and participants throughout the year (i.e., does the project only operate during one month of the year, or does sampling occur throughout the year?).

Some monitoring parameters only need to be sampled annually; however, monthly monitoring is recommended for other variables to understand seasonal variability clearly. As such, programs demonstrating the capacity to collect monitoring data throughout the year are particularly valuable and applicable to CEA. One of the purported benefits of CBM is more robust datasets that include data collected throughout the year (Gérin-Lajoie et al., 2018). Regardless of timing, samples should be repeatedly collected during specific times of the year to allow robust trend analysis (Carlsson et al., 2015).

2.3.9 Data Application

The purpose of this criterion was to rank the projects based on whether the data were used to inform decisions. Cumulative effects data are meant to be used in environmental policy, management, and decision-making (ECCC, 2016). The hope for CBM is that decision-makers will respect and use the data to inform decisions (McKay & Johnson, 2017a; Theobald et al., 2015). Some view CBM as an avenue for communicating with communities, while others see it as a data source to inform decisions (Kanu et al., 2016; McKay & Johnson, 2017a). Hence, it is important to identify whether the data were actually used to inform decisions. For example, the Indigenous Observation Network's data directly informed the Yukon River Watershed Plan (Living Lakes Canada, 2020), so it received a data application score of 5.

2.3.10 Data Availability

This scoring criterion was meant to define the availability of data in a form that can be analyzed and interpreted by those not directly associated with the project (e.g., project databases or technical reports that present data tables). Effective regional CEA requires project-level and regional monitoring data to be available to government agencies, project proponents, rights holders, and stakeholders across the region (Ball et al., 2013; Dubé et al., 2013; Foley et al., 2017; Johnson et al., 2011; Miller et al., 2022; Sheelanere et al., 2013). ECCC (2016) describes the importance of publicly sharing cumulative effects data for management actions and decision-making. Effective data communication is especially critical when data are meant to be used to develop management actions or responses (ECCC, 2016; Kipp et al., 2019; Moyer et al., 2008).

2.3.11 Project Characterization

To explore whether high-scoring projects shared distinct characteristics, we identified an *a priori* suite of project characteristics (i.e., explanatory variables) that we hypothesized would influence project scores (Table 2.2). We selected project characteristics based on key variables identified in the literature and our own experiences (Appendix A, Document A.3). We treated characteristics as binary explanatory variables depending on whether the characteristic was present or absent, as explicitly reported in the publicly available project information.

We scored and characterized 40 randomly selected projects from the 62 projects in the CBM Project Inventory (Figure 2.2). The majority (58%) of the 62 projects monitored study areas in northern Canada (Nunavut [NU], Yukon Territory [YT], Northwest Territories [NT], Nunavik, and Nunatsiavut; Figure 2). To achieve a reasonable representation of projects across Canada, we randomly sampled up to six projects from each province, territory, or northern region (i.e., Nunavik and Nunatsiavut). This criterion ensured we would select at least ten projects from the southern Canadian jurisdictions (British Columbia [BC], Alberta [AB], Saskatchewan [SK], Manitoba [MN], Ontario [ON], Quebec [QC; outside Nunavik], New Brunswick [NB], Nova Scotia [NS], Prince Edward Island [PE], and Newfoundland and Labrador [NL; outside Nunatsiavut]).

We only used publicly available information to score and characterize each project. If the available project information did not report sufficient detail to assign a score for any criterion, we classified the project as having insufficient information, and another project was randomly selected from the inventory. Seven of the projects we randomly selected from the inventory we found had

insufficient project information. We included scoring rationales as comments in the spreadsheet that we cross-referenced with the rubric description before analysis (Appendix A, External Resource A.3).

Table 2.2. List of project characteristics assessed for the 40 evaluated projects.

Category	Sub-categories
Land Claim Structure	Unceded; Modern Land Claim; Pre-1975 Title Treaty; Peace and Friendship Treaty
Data Collection Methods	Interview; Observations; Measurements; Sample Collection
Paid Monitors	Yes/No
Indigenous Knowledge	Yes/No
Routine Training Frequency	Yes/No
Trainer	Federal Government; Provincial/Territorial Government; Indigenous/Regional/Municipal Government; Co-Management/Local Resource Management; Community Members; Academic; Consultant; Non-profit; Project Alumni
Training Techniques	Training Manual; Training Video; Remote Presentation; Online Course; Field Training; Land Camps; Classroom
Intergenerational Engagement	Elder Engagement; Youth Engagement
Data Objective	Baseline; Cumulative Environmental Effects; Industrial Compliance; Environmental Conservation; Treaty/Harvesting Rights; Research; Resource Management; Human Health and Safety
Data Communication	Online Database; Online Georeferenced Database; Conferences; Peer-reviewed Publications; Routine Reports; Non-routine Reports; Community Outreach Materials
Data Collection Technology	App/Software; Data Recording Device
Data Management Technology	Project-specific Database; Third-party Database
Funding Sources	National (non-Canadian) Government; Federal Government; Provincial/Territorial Government; Indigenous/Regional/Municipal Government; Crown Corporation Co-management/Local Resource Management; Community; Industry; Academic; Non-profit
Project Partners	See Funding Sources
Bridging Organization	Yes/No
Community Involvement	Project Design; Data Management; Data Analysis & Interpretation; Data Reporting

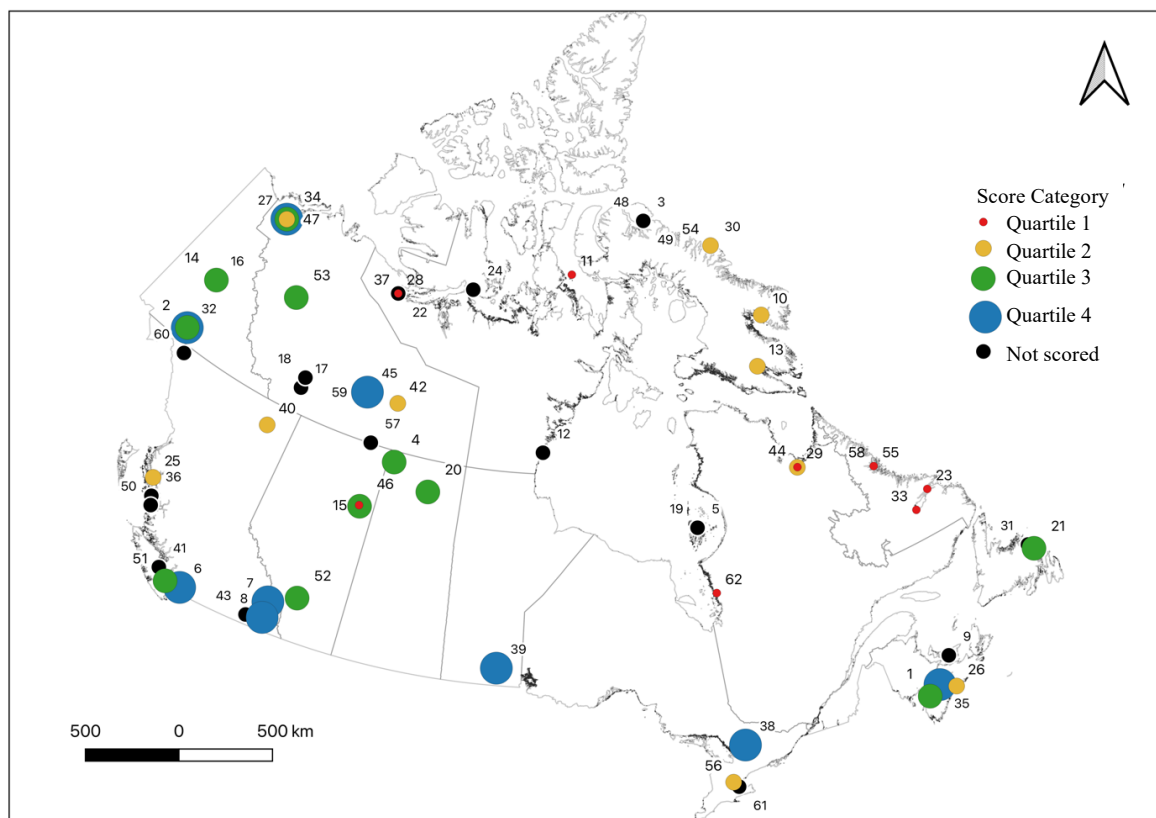


Figure 2.2. Map of the 62 community-based monitoring (CBM) projects included in the project inventory, coordinate reference system (CRS) EPSG:3347 – NAD83/Statistics Canada Lambert, with data from Statistics Canada (2016). The project ID numbers are displayed for each project and correspond to Table 2.6. Where assessed, the size and colour of the circle corresponds to the project’s score. See methods for score category definitions.

2.3.12 Cross-Validation

We undertook two rounds of cross-validation to ensure that our rubric scoring was reproducible (Appendix A, Document A.4). The reproducibility of our rubric was critical to ensuring reviewer bias did not influence project scoring and that scoring methods were transparent enough to allow others to iterate on them in the future. We encourage others to adapt and refine our rubric and improve its accuracy with new information.

Three authors individually evaluated 10 projects using the same project information and following the instructions in the rubric (data dictionary; Appendix A, External Resource A.3). We held discussions to identify the cause of all disagreements in project scores and updated the rubric to reduce inconsistency. We then completed a second cross-validation using the updated rubric. We calculated interrater agreement (i.e., Krippendorff’s alpha coefficient [α]) for each project attribute

and characteristic following the methods described in Roche et al. (2015). Cicchetti (1994) suggests that α values <0.4 indicate poor agreement. We carefully evaluated the potential causes of the low interrater agreement for any attribute or characteristic with a score <0.4 . We agreed to data dictionary changes, often combinations of categories, that would further improve the interrater agreement score. All remaining project attributes and characteristics had an interrater agreement of ≥ 0.4 , which we interpreted as an indication that our rubric was sufficiently reproducible to move forward.

2.3.13 Data Analysis

We used unconstrained ordination to evaluate if projects within the same score category were grouped based on a common set of project characteristics. We generated a Bray-Curtis similarity matrix (composed of similarities calculated between each pair of projects) as the basis for the multivariate analyses. We performed a hierarchical agglomerative cluster analysis using a group average linkage to determine if the score categories were separated into the same clusters based on common project characteristics. We assigned the score category (e.g., Quartile 1, Quartile 2) as a label in the cluster analysis to visualize if groupings were associated with the a priori categories. We used a similarity profile (SIMPROF) test to identify which groups produced by the cluster analysis were meaningful (Clarke et al., 2014). We set the significance of the SIMPROF test at 5% and permutations at 9999.

We used non-metric multi-dimensional scaling (nMDS) ordination to portray the differences between score categories to evaluate if score categories contained unique suites of project characteristics. We displayed the ten project characteristics that had the most significant influence on dissimilarity calculations between score categories on a vector plot adjacent to the nMDS ordination. We used the similarity percentages routine (SIMPER) to assess which project characteristics influenced dissimilarities between score categories and similarities within score categories. We used PRIMER version 7 software to complete all analyses.

2.4 Results and Discussion

The cumulative effects of climate change and human development continue to exacerbate environmental degradation and threaten environmental sustainability. Canada needs to improve CEA methodology to secure ecosystem sustainability for future generations (Ball et al., 2013; Cronmiller & Noble, 2018; Seitz et al., 2011; Sheelanere et al., 2013). CEAs should consider scientific information,

Indigenous knowledge, and community knowledge. While it is likely that CBM could contribute to all these components of CEAs, here we explored the degree to which current CBM projects appear prepared to contribute to the western science component of CEA biophysical baseline studies. Our objectives were to evaluate the ability of CBM projects in Canada to collect environmental data that could support western science approaches to CEA and what (if any) characteristics high-scoring CBM projects shared to inform the design of future CBM projects (Gérin-Lajoie et al., 2018; Hunsberger et al., 2005; Lawe et al., 2005; McKay & Johnson, 2017a). We found that higher scoring projects shared common characteristics (Table 2.3) that we propose should be considered when designing future CBM projects with the objective of supporting CEA.

Table 2.3. SIMPER results for similarities between Quartile 4 projects. See methods for score category definitions.

Project Characteristic	Average Abundance	Contribution to Similarity (%)	Cumulative Contribution (%)
Non-profit Partner	0.89	8.74	8.74
Data Objective – Resource Management	0.89	8.48	17.22
Provincial/Territorial Funding	0.78	6.51	23.73
Bridging Organization	0.78	6.43	30.16
Measurements for Data Collection	0.78	6.41	36.57
Training Manual	0.78	6.20	42.77
Provincial/Territorial Partner	0.78	6.20	48.97
Geo-referenced Database	0.67	4.61	53.58
Data Objective - Baseline	0.67	4.45	58.03
Sample Collection	0.67	4.36	62.39
Routine Reports	0.56	3.23	65.62
Pre-1975 Title Treaty Land Claim	0.56	3.18	68.79
Project-specific Database	0.56	3.13	71.92

Note: See methods for score category definitions.

Our evaluation of current CBM projects is novel in that we employ qualitative, semiquantitative, and quantitative components and decisions. We hope this approach catalyzes more efficient design and deployment of future CBM projects. Previous work that reviewed and assessed CBM project information used surveys, interviews, and content analyses to collect project information and presented tables and case studies to summarize key project attributes (e.g., Conrad & Daoust, 2008; Danielsen et al., 2005; Gofman, 2010; Johnson et al., 2016; Kipp et al., 2019; Kouril et al., 2016; McKay & Johnson, 2017b; Parlee et al., 2017; Raygorodetsky & Chetkiewicz, 2017). These previous approaches identified common characteristics among CBM projects and discovered from practitioners which attributes contribute to project success and sustainability. While our goal was

similar to these previous studies, we assessed if higher-scoring projects shared common characteristics using multivariate statistical analyses applied to a scoring rubric. We took this approach because (i) developers of policies and practices often prefer quantitative evidence in the design of western science (including CBM) projects and (ii) it facilitates future iterations, comparisons across iterations, and improvements on our methods. In the future, the collation of CBM project information could be expanded by requesting further information from CBM project managers, further cross-validation and modification of scoring criteria and project characteristics, and adding additional CBM projects to these lists. The project scoring spreadsheet and the data dictionary used to inform this analysis are available in Appendix A, External Resource A.3. Thus, the evaluations made here are presented in a transparent format and can be reassessed, adapted, and corrected at any time. In addition, others looking to achieve a different objective (e.g., answer a different question) can use our project list as a snapshot of CBM projects in Canada and develop new approaches for project evaluations.

Our analysis had an unavoidable circularity (i.e., we used the same information to score the projects and identify the presence of explanatory variables). We scored projects based on publicly available documentation. We then used this same documentation to determine whether there were any shared characteristics among score categories. We separated project characteristics from project scoring as much as possible in our rubric. Nonetheless, it is important to highlight that our analysis identifies suites of commonly shared CBM project characteristics rather than directional relationships between characteristics and scores. It may be useful to identify common associations, for example, the use of a bridging organization and the conduct of CBM with a larger number of communities and participants, but understanding the causality of these associations would require further research. The scope of this analysis (i.e., 317 potential projects screened; 40 projects scored and evaluated in detail) necessitated a focus on generally available documentation and associations between practices and characteristics. This focus may have disproportionately affected our understanding of small-scale, locally focused projects, especially those that focused on Indigenous knowledge.

The cluster analysis separated CBM projects into three significant groups according to the SIMPROF test (Figure 2.3). The first significant branching of the dendrogram separated one cluster containing seven (78%) Quartile 4 projects. The other cluster contained all 10 Quartile 1 projects and seven (70%) Quartile 2 projects. The Quartile 3 projects were almost equally divided into the two branches of the dendrogram (five vs. six). A further significant division in one branch grouped six

(60%) Quartile 1 projects with six (60%) Quartile 2 projects, three (27%) Quartile 3 projects, and two (22%) Quartile 4 projects. The final cluster appeared to be an intermediate or alternative grouping that contained four (40%) Quartile 1, one (10%) Quartile 2, and two (18%) Quartile 3 projects. These dendrogram branches suggested project characteristics differed between the Quartile 4 and Quartile 1 score categories, while the Quartile 2 and Quartile 3 projects were less distinct.

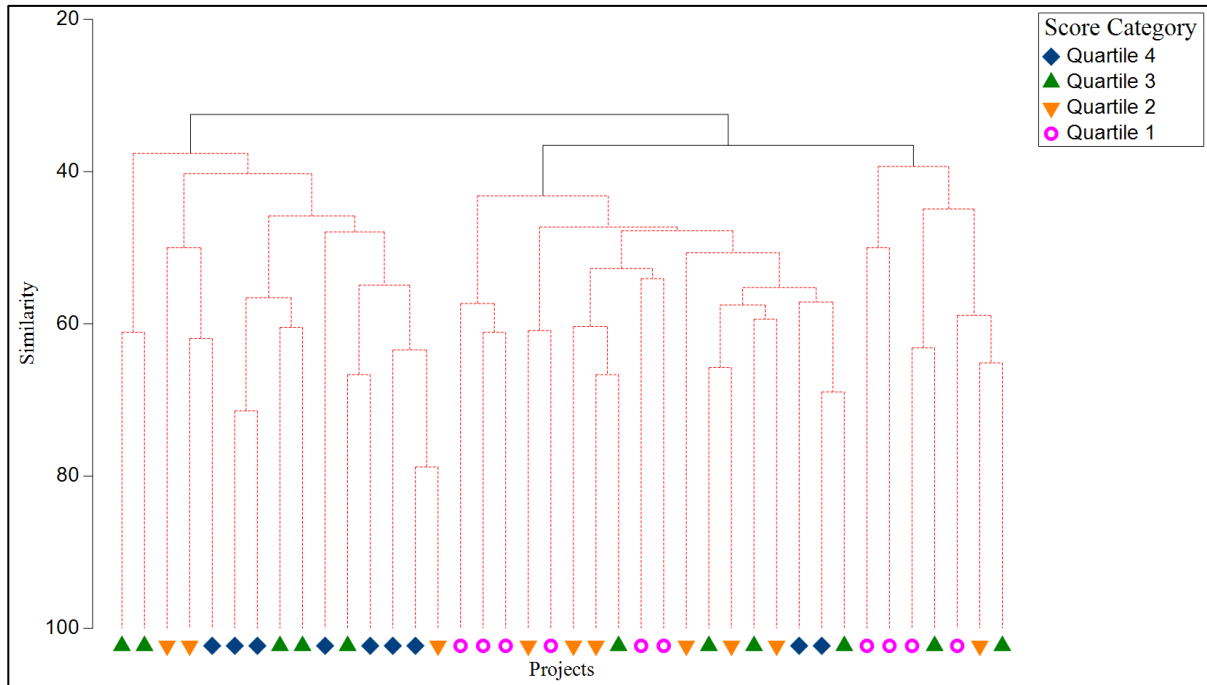


Figure 2.3. Dendrogram for hierarchical clustering of the 40 scored community-based monitoring (CBM) projects, using group-average linking of Bray-Curtis similarities calculated on project characteristics (presence/absence). See methods for score category definitions.

The nMDS ordination plot presented the Quartile 4 projects as clustered on the left side of the plot, whereas the Quartile 1 projects clustered on the right side (Figure 2.4). A secondary pattern further distinguished several Quartile 1 projects in the plot's lower right quadrant. The ordination's high stress (i.e., > 0.2) indicated that the points were close to being arbitrarily placed in two-dimensional space. However, the cluster analysis supported the general conclusion that the three groups were distinct (Clarke et al., 2014). We examined the three-dimensional plot (stress 0.17) to ensure that the Quartile 4 and Quartile 1 projects were generally clustered separately. After conducting the nMDS, we restricted further investigation to the Quartile 1 and Quartile 4 projects, as

there appeared to be no discernible difference in characteristics between the Quartile 2 and Quartile 3 projects.

Several identified shared characteristics could help support the intentional design of future CBM projects. Results of the SIMPER analysis are in Tables 2.3–2.5, and Figures 2.4 and 2.5. The vector plot adjacent to the nMDS displayed the 10 most influential project characteristics identified by the SIMPER analysis (Figure 2.4). We found that CBM projects in Quartile 4 (highest scoring projects) shared key characteristics that were uncommon in the Quartile 1 projects (Figure 2.4 and 2.5, and Table 2.4). Quartile 4 project participants followed standardized data collection protocols described in training manuals to collect measurements and samples in the field. Communities and project partners used project data to create baseline datasets and inform resource management decisions. These projects typically received funding and in-kind support from provincial/territorial government agencies. Raw data were publicly available through georeferenced databases that were often created and managed by a third party. These projects were typically administered by, or partnered with, non-profit organizations that typically acted as the bridging organization to coordinate community member involvement in the project

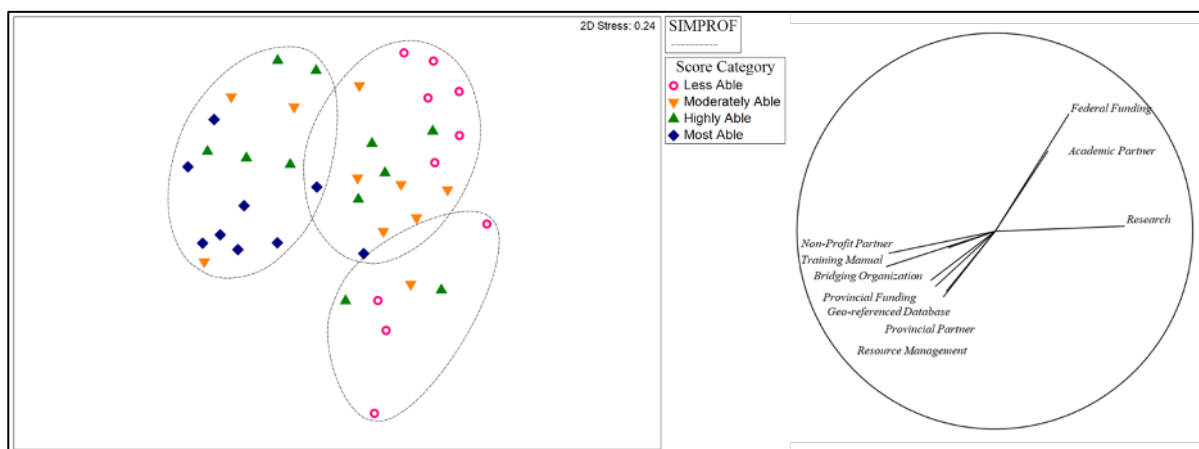


Figure 2.4. Non-metric Multi-dimensional Scaling ordination of the 40 scored community-based monitoring (CBM) projects based on the project characteristics (presence/absence) and Bray-Curtis similarities. The dashed circles indicate the project groupings identified as significant by the SIMPROF test. Vector plot displays the ten most influential variables in the differences between the Quartile 1 and Quartile 4 projects. See methods for score category definitions.

Table 2.4. SIMPER results for similarities between Quartile 1 projects. See methods for score category definitions.

Project Characteristic	Average Abundance	Contribution to Similarity (%)	Cumulative Contribution (%)
Data Objective - Research	0.90	12.81	12.81
Regional Partner	0.80	9.56	22.36
Modern Land Claim	0.80	9.34	31.71
Federal Funding	0.70	6.66	38.37
Academic Partner	0.70	6.66	45.03
Federal Partner	0.60	4.83	49.86
Indigenous Knowledge	0.60	4.80	54.65
Observations for Data Collection	0.50	3.73	58.39
Co-Management Partner	0.50	3.32	61.70
Data Objective – Human Health and Safety	0.50	3.27	64.98
Sample Collection	0.50	3.23	68.21
Paid Monitors	0.50	3.18	71.39

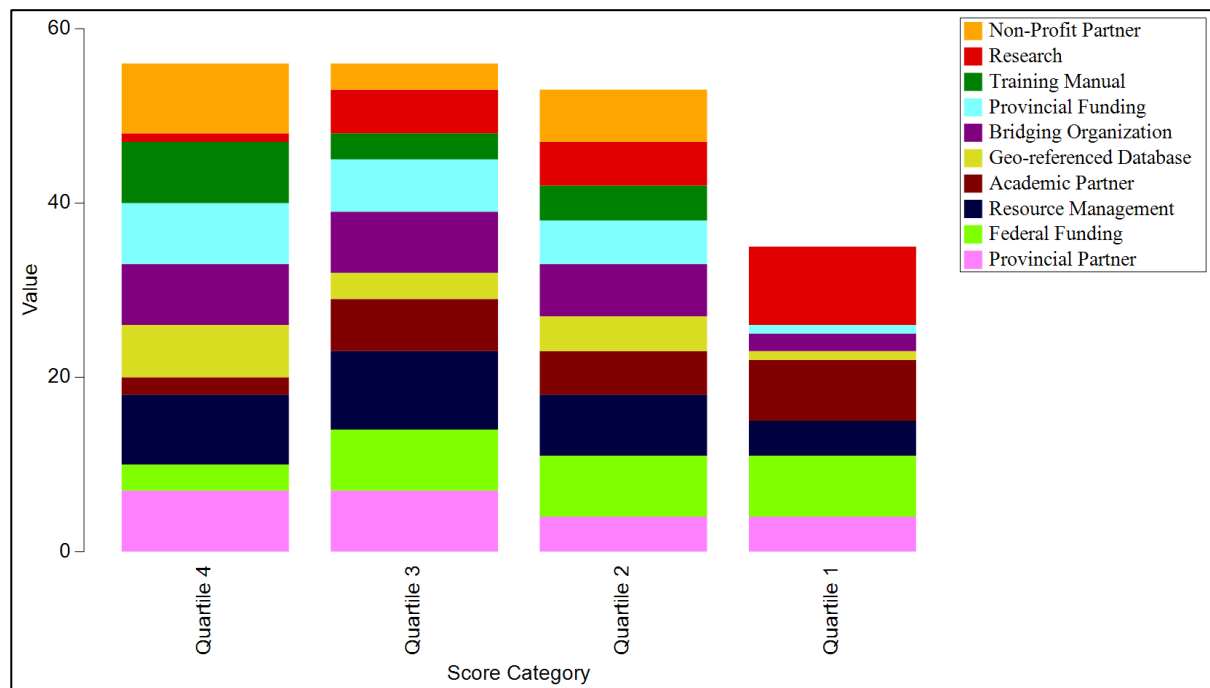


Figure 2.5. Bar plots of score category counts of 10 influential characteristics, as defined by the SIMPER analysis. The height of the bars indicates the occurrences of the explanatory variables in each score category. See methods for score category definitions.

2.4.1 Training materials

The support framework provided by training materials was positively associated with the Quartile 4 projects. All Quartile 4 projects described training community members to collect quantitative data through sample collection and field measurements, with 89% documenting their standardized monitoring protocols in training materials (e.g., manuals, videos, and online courses).

None of the Quartile 1 projects reported using training materials. Standardized data collection methods can help CBM projects inform environmental decision-making (Conrad & Daoust, 2008; Kouril et al., 2016; Herman-Mercer et al., 2018; Hunsberger et al., 2005; McKay & Johnson, 2017a). Training has been identified as a critical component of CBM projects that aim to collect data comparable to that collected by professional scientists (Fore et al., 2001; Sharpe & Conrad, 2006). The use of training materials may enable participants to collect data over long time periods without the high costs associated with routine in-person training sessions. Training materials may also facilitate training for the larger number of project participants that typified the Quartile 4 projects. Finally, these training materials provided concrete evidence of the standardized protocols used in quantitative data collection, which may have encouraged more decision-makers to use the data (Kouril et al., 2016; McKay & Johnson, 2017a), thereby increasing a project's data application score.

2.4.2 Project Objectives

The Quartile 4 projects had objectives linked to resource management decision-making, whereas the Quartile 1 projects more often had objectives related to research (Figure 2.4 and Table 2.5). Resource management project objectives were also associated with higher Data Application scores, as all Quartile 4 projects collected data to inform resource management decisions or environmental assessment, and many (67%) specifically aimed to generate baseline datasets. Projects with a resource management objective had a median data application score of 5. Conversely, Quartile 1 projects were typically research-focused and may not have sought to link results to decision-making directly. Note that this is not a weakness of Quartile 1 projects, just a difference in objectives. Projects with research-oriented objectives and no clear resource management objective had a median data application score of 3. Linking data to decision-making has been previously identified as a major contributor to CBM project sustainability (Kouril et al., 2016; McKay & Johnson, 2017b; Parlee et al., 2017). CBM projects designed to inform resource management decisions could be more attractive to project participants and funding agencies, leading to longer project durations and higher project participation rates (Carlsson et al., 2015; Danielsen et al., 2005; Kouril et al., 2016; McKay & Johnson, 2017b). Projects that scored ≥ 4 for project duration had a median data application score of 5, and projects that scored ≥ 4 for project participants had a median data application score of 4. Thus, high project duration and project participant scores were associated with projects with a high data application score

Table 2.5. SIMPER results for dissimilarities between Quartile 4 and Quartile 1 projects. See methods for score category definitions.

Project Characteristic	Average Abundance		Contribution to Dissimilarity (%)	Cumulative Contribution to Dissimilarity (%)
	Quartile 4	Quartile 1		
Non-Profit Partner	0.89	0.00	3.39	3.39
Data Objective - Research	0.11	0.90	3.08	6.47
Training Manual	0.78	0.00	2.88	9.34
Provincial Funding	0.78	0.10	2.72	12.07
Bridging Organization	0.78	0.20	2.54	14.60
Geo-referenced Database	0.67	0.10	2.39	16.99
Academic Partner	0.22	0.70	2.22	19.21
Data Objective - Resource Management	0.89	0.40	2.22	21.43
Federal Funding	0.33	0.70	2.13	23.57
Provincial Partner	0.78	0.40	2.13	25.69
Data Objective - Baseline	0.67	0.30	2.13	27.82
Indigenous Knowledge	0.11	0.60	2.12	29.94
Regional Partner	0.44	0.80	2.10	32.04
Pre-1975 Title Treaty Land Claim	0.56	0.10	2.07	34.10
Modern Land Claim	0.44	0.80	2.06	36.16
Third-Party Database	0.56	0.00	2.05	38.21
Federal Partner	0.22	0.60	2.05	40.26
Routine Reports	0.56	0.20	2.03	42.29
Infrequent Reports	0.56	0.10	1.97	44.25
Data Collection - Observations	0.00	0.50	1.95	46.20
Data Collection - Measurements	0.78	0.50	1.93	48.14
Field Training	0.56	0.40	1.93	50.07
Community Outreach Materials	0.56	0.10	1.92	51.99
Project-Specific Database	0.56	0.40	1.91	53.90
Data Collection - Sample Collection	0.67	0.50	1.90	55.80
Co-Management Partner	0.33	0.50	1.86	57.66
Data Objective – Human Health & Safety	0.11	0.50	1.84	59.50
Paid Monitors	0.22	0.50	1.83	61.33
Community Involvement - Project Design	0.44	0.40	1.79	63.12
Unceded Land Claim	0.44	0.20	1.76	64.88
Non-profit Trainer	0.44	0.00	1.71	66.59
Non-Profit Funding	0.33	0.20	1.59	68.17
Community Involvement - Data Analysis	0.33	0.30	1.57	69.75
Routine Training	0.33	0.30	1.57	71.32

Note: See methods for score category definitions.

2.4.3 Funding

We also observed an association between project objectives and project funding and partnerships. The Quartile 4 projects' objectives of collecting resource management and baseline data were often associated with funding and partnerships with provincial/territorial governments. In contrast, the Quartile 1 projects' objective of research was often associated with federal funding. Federal research funding may less frequently target large-scale and long-term projects, reducing project duration and project participant scores. Projects that received federal funding—and no

provincial/territorial funding—had median project duration and project participant scores of 2. Federal funding sources may also target projects with objectives not typically associated with CEA (e.g., research, community capacity building, fostering community connections to the land, food security, etc.). In contrast, provincial and territorial sources of project funds are often targeted at resource management objectives since these are frequently matters of provincial/territorial jurisdiction.

2.4.4 Data Availability, Accessibility, and Management

Provincial/territorial government funding was frequently associated with publicly available data, resulting in projects with high data availability scores. We found that the majority (63%) of the projects we scored with provincial/territorial funding also allowed public data access. Since 2011, Canadian provincial/territorial governments have increasingly recognized the importance of open data (e.g., Government of British Columbia, 2022; Government of Northwest Territories, 2022; Government of Ontario, 2021). Thus, provincial/territorial funding could have placed stricter requirements on project data availability. It is also possible that provincial/territorial agencies can provide more support to CBM organizations in meeting their data accessibility requirements than federal funding agencies, and provide data-sharing platforms that are highly accessible. In addition, provincial/territorial governments often employ technical personnel in regional offices with considerable experience working with community-based groups. Note that public data access is not always desirable for CBM projects (e.g., projects that involve protected or sensitive information, such as highly valued sites and Indigenous knowledge, or seek to advance entirely local monitoring objectives). The Quartile 4 projects generally provided public data access through georeferenced databases (i.e., sampling locations displayed on online maps). Georeferenced databases provide interactive maps that make quantitative and qualitative data accessible to non-technical users (Gérin-Lajoie et al., 2018). These databases may be built-for-purpose or third-party databases. Our findings are consistent with recommendations made in the literature regarding the use of digital databases (Hunsberger et al., 2005), as the long-term sustainability of CBM projects depends on data being managed to facilitate analysis and communication of results (Eamer, 2011) and provide data access to project partners and decision-makers (McKay & Johnson, 2017b). The Quartile 4 projects offered excellent examples of the rich data that can be easily accessible to support CEA and other applications, such as research and resource management—potentially increasing their data application score.

2.4.5 Bridging Organizations

The participation of bridging organizations was also common in the Quartile 4 projects (78%). In this context, a bridging organization is a non-profit organization, private consultant, or co-management organization tasked with coordinating community member involvement in the project. Bridging organizations act as the liaison between external researchers and community participants to ensure ongoing community engagement, expand opportunities for knowledge exchange, and build trust among project partners (Carlsson et al., 2015; Kouril et al., 2016; Wilson et al., 2018). The bridging organizations for our Quartile 4 projects were primarily non-profit organizations, with one case of a local co-management agency. Non-profit organizations may have been instrumental in sustaining relationships with and coordinating the larger number of project participants in the Quartile 4 projects. The median project participant score for projects without bridging organizations was 2. The Gwich'in Harvest Study was the only project in the Quartile 4 score category to report a co-management agency as the bridging organization (Raygorodetsky & Chetkiewicz, 2017). It involved the smallest number of project participants (four communities with multiple participants per community) among the Quartile 4 projects. While coordinating a CBM project across four communities would already be logistically challenging, the other Quartile 4 projects engaged with even more communities (21–31) or a considerable number of volunteers (14–600) or non-profit groups (6–10). All these projects involved non-profit bridging organizations, suggesting that these kinds of organizational structures could benefit current and future CBM projects that aim to involve more communities and participants not tied to a single local government.

2.5 Other Project Attributes and Considerations

We found the majority (67%) of Quartile 4 projects were situated in southern and western Canada, while the majority (80%) of Quartile 1 projects were in northeastern Canada (Nunavut, Nunavik, and Nunatsiavut; Figure 2.2 and Table 2.6). This geographic pattern may reflect a non-uniform distribution of CBM project objectives throughout the country. For example, CBM projects in southern and western Canada frequently reported resource management as a project objective (74%), and they often shared data publicly (79%). Conversely, CBM projects in northeastern Canada frequently reported research (100%) or health and safety (50%) as project objectives. These projects emphasized local communication efforts more; public data access was only reported by 8%. It is important to note that we scored the data availability of projects that published project information in

scientific journals as 3/5 since the raw data were not publicly available and the release of the project findings depended on publication timelines. CBM projects in northeastern Canada may less frequently publish detailed project information due to project collaborations, the presence of sensitive data, or foundational data objectives that do not extend to general public use.

This geographic pattern reflects a fundamental limitation of our study: our analysis depended on project data that were available online. Our master list is not an exhaustive list of all CBM projects within Canada, although we strived to create a comprehensive list. Our compilation of CBM projects was biased toward projects known by our respective networks, projects discussed in the peer-reviewed literature, projects with online documentation, and projects included in previous CBM project reviews. In addition, we only used project information readily available online to evaluate the projects. This approach under-represents CBM projects that do not target reporting to a public audience (e.g., those focused on reporting in small communities or regarding sensitive information) and thus have a small online footprint. Verifying details from project managers or participants through interviews should more accurately reflect the structures and procedures of CBM projects that do not target a public audience.

CBM projects with restricted public data access would have scored low for data availability. Some projects—particularly those that involve Indigenous knowledge—were less likely to report public data access, for very good reasons related to ownership, control, access, and possession (OCAP; First Nations Information Governance Centre, 2023) and Indigenous data sovereignty. We identified Indigenous knowledge as a project characteristic only for projects that explicitly described the use of Indigenous knowledge for a particular project stage (e.g., design, data collection). It is important to note that not all Indigenous-led projects explicitly describe the incorporation of Indigenous knowledge into their projects. As such, the Indigenous knowledge use project characteristics do not identify all Indigenous-led projects in our inventory. The average data availability score for the projects that explicitly reported Indigenous knowledge was 3/5, suggesting data sharing in these projects was less frequently directed towards a public audience. Restricted data sharing and access was likely due to sensitivities surrounding sharing Indigenous knowledge publicly and ownership of Indigenous knowledge by the community (Gérin- Lajoie et al., 2018; Thompson et al., 2020). It is important to note that these are not project weaknesses; they are often features of design. Since our study depended solely on online project documentation, projects with data sharing protocols that aimed to protect Indigenous sovereignty (including data sovereignty) would likely

score lower for project attributes such as data collection protocols and data management, which only reflects the fact that this study was aimed at CBM efforts that were directed toward western science, where open data are now often a requirement.

Projects oriented towards a local audience that are collecting and protecting sensitive data may be able to contribute to CEA in many ways (e.g., describing baseline biophysical or socioeconomic conditions and providing different forms of knowledge), but this is not captured by our rubric based solely on publicly available documentation and scoring that is focused on western scientific methods. This is an important gap to recognize with our rubric because Indigenous knowledge is widely acknowledged as essential for environmental monitoring and effective CEA by contributing a holistic understanding of the socio-ecological systems, past, present, and future (ECCC, 2016; Gofman, 2010; Johnson et al., 2016; Kouril et al., 2016; McKay & Johnson, 2017b). While Indigenous Knowledge is critical to effective CEA, individual project managers must address the project-specific sensitivities surrounding sharing Indigenous knowledge publicly and ownership of Indigenous Knowledge by its community; each community and the individuals who choose to share their Indigenous Knowledge will need to play an equitable role in CEA (Gérin-Lajoie et al., 2018; Thompson et al., 2020). Among many other reconciliatory actions that include respect for Indigenous sovereignty, impact assessment and CEA processes must evolve to facilitate meaningful participation of Indigenous peoples in both the western science and Indigenous science aspects of assessments (Arsenault et al., 2019; Eckert et al., 2020). Thus, it is imperative that improvements to western science approaches to CEA include avenues for meaningful participation by Indigenous peoples and opportunities to be informed by Indigenous knowledge. Future work could build on our study by focusing on the CBM project characteristics that are important for Indigenous-led CBM. A study of Indigenous-led CBM in Canada could use our project list as a starting point and focus on the projects we identified as having explicitly included Indigenous knowledge (see Appendix A, External Resource A.3).

Table 2.6. Final cumulative scores (score) and score categories for the 40 evaluated projects. See methods for score category definitions.

Project Name	Project ¹ Number	Locality	Score	Score Category
Lake Partnership Program	38	ON	39	Quartile 4
Indigenous Observations Network	32	YT	37	Quartile 4
BC Lake Stewardship and Monitoring Program	6	BC	37	Quartile 4
NWT-wide Community Based Water Quality Monitoring Program	45	NT	36	Quartile 4
Lake Winnipeg Community-Based Monitoring Program	39	MN	35	Quartile 4
Columbia Basin Water Quality Project	8	BC	34	Quartile 4
Gwich'in Harvest Study	27	NT	32	Quartile 4
Columbia Basin Groundwater Monitoring Program	8	BC	32	Quartile 4
Kings County Lake Monitoring Program	35	NS	32	Quartile 4
Arctic Borderlands Ecological Knowledge Co-op	2	NT, YT	31	Quartile 3
Regional District of Nanaimo Community Watershed Monitoring Network	51	BC	31	Quartile 3
Rocky View County Community Based Groundwater Monitoring Project	52	AB	31	Quartile 3
Annapolis River Guardians	1	NS	30	Quartile 3
Eastport Lobster Monitoring Program	21	NL	29	Quartile 3
Peace-Athabasca Delta Ecological Monitoring Program	46	AB	29	Quartile 3
Sahtu Wildlife Health Monitoring Program	53	NT	29	Quartile 3
Community Moose Monitoring Project	14	YT	29	Quartile 3
Eastern Athabasca Regional Monitoring Program	20	SK	29	Quartile 3
Athabasca Working Group Environmental Monitoring Program	4	SK	28	Quartile 3
Inuvialuit Settlement Region Community-Based Monitoring Program	34	NT, YT	28	Quartile 3
Gitga'at Guardian Watchmen	25	BC	27	Quartile 2
Sea Ice Monitoring Network	54	NU	27	Quartile 2
Nunavik Integrated Community-Based Monitoring Program	44	QC*	27	Quartile 2
Peel River Fish Study	47	NT	27	Quartile 2
Groundswell Community Based Groundwater Monitoring	26	NS	27	Quartile 2
Sequencing the Rivers for Environmental Assessment and Monitoring	56	National	25	Quartile 2
Community-based fishery monitoring for Arctic Char in Baffin Region	13	NU	23	Quartile 2
Ni Hat'Ni Dene Program	42	NT	23	Quartile 2
Community-based Wildlife Monitoring Network	13	NU	23	Quartile 2
Liard Basin Monitoring Initiative	40	BC	23	Quartile 2
Kugluktuk Berry Monitoring Project	37	NU	22	Quartile 1
Community Odour Monitoring Program	15	AB	22	Quartile 1
Wemindji Community Fisheries Program	62	QC	21	Quartile 1
Sources of Methylmercury, Perfluoroalkyl Substances, and Polychlorinated Biphenyls to Ringed Seal Food Webs of Lake Melville, Northern Labrador	58	NL*	21	Quartile 1
Ice Monitoring in Deception Bay/Hudson Strait	29	QC*	20	Quartile 1
Innu Nation Environmental Guardians	33	NL*	19	Quartile 1
eNuk Environment and Health Monitoring Program	23	NL*	17	Quartile 1
Community-Based Monitoring of Ice-Breeding Seals and Polar Bear Feeding in the Gulf of Boothia	11	NU	17	Quartile 1
Harvest and Environmental Records Operational System	28	NU	17	Quartile 1
Sea-Run Char Monitoring Program	55	NL*	16	Quartile 1

QC*: Nunavik, NL*: Nunatsiavut

¹Project numbers align with numbers in Figure 2.

It is important to note that the CBM projects included in our study had various objectives independent of contributing to CEA. Our assessment of the ability of each project to contribute environmental monitoring data to baseline studies for CEAs was not an evaluation of project quality or efficacy in fulfilling their stated and original objectives. Furthermore, we base project scoring entirely on available documentation. Newly available documentation could describe project practices in greater detail, which could result in score changes. We generated our project scores using an ordinal scale rubric, resulting in relative project rankings. Thus, projects that did not receive the highest scores (Quartile 1–3 projects) may be able to contribute valuable baseline data to CEAs but were simply ranked lower than other projects that demonstrated exceptional ability (Quartile 4 projects) as per our score criteria. Despite these limitations, we think that quantitative identification of characteristics shared by high-scoring projects can advance the design of future effective CBM projects.

2.6 Conclusions

Overall, this snapshot of CBM in Canada confirms there are projects that are already collecting data that could inform western science approaches to biophysical baseline studies for CEA. These findings demonstrate CBM's capacity to address criticisms of CEA's western science methodology, particularly a shortage of adequate baseline data. With this knowledge, we can recommend CEA practitioners and natural resource managers use CBM to enhance their cumulative effects monitoring and assessment practices. Our scoring rubric and subsequent analysis revealed the organizational and methodological practices most associated with projects that appear well-prepared to support CEA baseline studies. Characteristics that CBM projects looking to contribute to CEAs should consider in their design include the use and publication of training manuals for data collection and management, the formation of partnerships with provincial/territorial levels of government, the use of a georeferenced database for data sharing, and the presence of a non-governmental bridging organization to facilitate community engagement. Well-designed CBM holds the potential to augment the science in CEA; CBM's potential and its design considerations to enhance the role of Indigenous knowledge in CEA are exciting fields for future study.

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Chapter 3

A Fresh Perspective on Freshwater Data Management and Sharing: Exploring Insights from the Technology Sector

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3.1 Abstract

The efficacy of measures adopted to manage and restore freshwater ecosystems in Canada is often limited by the availability of data. Although numerous public, private, and nonprofit organisations collect data from freshwater ecosystems across Canada, much of the data collected remains inaccessible or unusable to rights holders, end users, and practitioners. The Canada Water Agency (CWA) is drafting a National Freshwater Data Strategy that aims to improve practices around data management and sharing. The CWA is seeking feedback and guidance from stakeholders within the freshwater science sector. Our study aimed to support these efforts by gaining insights from the technology sector, where data management and sharing practices are more mature. We interviewed 12 experts from the technology sector who offered insights and advice. Using a Reflexive Thematic Analysis of interviewees' responses to semi-structured interview questions, we identified 10 recommendations for the freshwater science sector with respect to data management and sharing. Recommendations centred on motivations for data-sharing, data licensing, and development of requisite skills and tools. Interviewees stated that as a national agency, the CWA is well-positioned to implement some of these recommendations, including incentives that support a culture of open data, building a centralised data solution, and developing a freshwater data standard.

3.2 Introduction

Freshwater resource protection and restoration requires sufficient data to understand current conditions and cumulative effects, and predict effects of current and future cumulative stressors (Arnold et al., 2019; Blakely & Russell, 2022; Environment and Climate Change Canada [ECCC], 2021; Miller et al., 2022; Smits et al., 2025). Freshwater data are “*paramount to supporting evidence-based decision-making*” in freshwater resource management (ECCC, 2021, p. 25). The ability to discover and access freshwater data is critical as the global community recognizes the rapid loss of freshwater biodiversity (ECCC, 2021, Schmidt-Kloiber et al., 2019), and the importance of freshwater ecosystem services to human health and community well-being (Lynch et al., 2022; Ncube et al., 2021; Valenca Pinto et al., 2023). Most Canadian watersheds are considered to be data-deficient for baseline studies, ecosystem health assessments, and design of water resource development projects (Arnold et al., 2019; Carver et al., 2020; Goucher et al., 2021; Ho et al., 2021; Miller et al., 2022; Mishra & Coulibaly, 2010; Water Rangers, 2025) and decision-makers urgently need more timely

access to comprehensive freshwater data (Hartwig et al., 2024; Miller et al., 2022; Stanley & Gunn, 2018).

Global efforts to collect freshwater data have intensified in response to the degraded state of freshwater ecosystems and decline in freshwater biodiversity, resulting in fresh waters being among the most intensively monitored ecosystems worldwide (Schmidt-Kloiber et al., 2019). Data from freshwater ecosystems across Canada, including surface water chemistry, water flows, fish tissue chemistry, and fish habitat are collected by a diversity of government agencies, non-profit organizations, academics, community members, and private companies, but are mostly inaccessible (Chilima et al., 2013; DataStream, 2024; Ho et al., 2021; Jacob et al., 2018; Stanley & Gunn, 2018). These data often remain in filing cabinets and field books, floppy disks, bookshelves, and on personal hard drives (Chilima et al., 2013; Gunn & Stanley, 2018; Ho et al., 2021; Smits et al., 2025; Stall et al., 2019). Freshwater scientists can be reluctant to share their data due to concerns about competition from other researchers, the time required to manage data for sharing, lack of recognition for data sharing, and fears of others misinterpreting data or exposing errors (Goucher et al., 2021; Gunn & Stanley, 2018; Hahnel et al., 2023; Roche et al., 2015; Smits et al., 2025). Datasets are also sometimes withheld because of perceived liability concerns and data readiness (Goucher et al., 2021). Those who are willing to share their data may be unable to do so for a variety of reasons, including a lack of data literacy, lack of detailed guidance on data sharing, confusion over who owns the data, inadequate digital infrastructure, staff turnover, lack of time and/or support, and/or weak data management policies and procedures (Hahnel et al., 2023; Ho et al., 2021; Kroetsch, 2021; Roche et al., 2020; Smits et al., 2025).

Even when datasets are available, they can be difficult to find (ECCC, 2021; Gunn & Stanley, 2018; Wrona & Munkittrick, 2024). In Canada, the various organizations that collect and manage freshwater data store them on multiple platforms, resulting in a large, disparate, and fragmented network of data (Canadian Water Quality Association [CWQA], n.d.; DataStream, 2024; Miller et al., 2022; Wrona & Munkittrick, 2024). This issue extends to the global community, where online freshwater databases are created in isolation; this results in data remaining scattered and a consequent lack of synthetic analyses across multiple jurisdictions or across long temporal timescales (Schmidt-Kloiber et al., 2019). When synthetic or collative exercises are undertaken, considerable time and effort are required to discover and organise data which creates inefficiencies that reduce the time available for data analysis and interpretation (Goucher et al., 2021; Johnson et al., 2011; Miller et al.,

2022; Stanley & Gunn, 2018; Wilkinson et al., 2016). Further, limited budgets and resources allocated for freshwater studies do not allow for extensive data searches and collation efforts. Overall, inefficient, non-standardised data management and sharing practices in freshwater science reduce the quality of the studies and limit the applicability of data collected for decision-makers (Stanley & Gunn, 2018; Smits et al., 2025).

The use of open and discoverable data is inhibited when data are poorly or inconsistently managed (Gunn & Stanley, 2018; Miller et al., 2022; Smits et al., 2025). Natural scientists struggle to know how to share their data effectively because they typically receive minimal formal data management training (Roche et al., 2015; Roche et al., 2020). Many natural scientists are self-taught and develop personal protocols for data preparation (i.e., data wrangling; the process of data cleaning, transformation, and structuring), managing, and sharing (Lowndes et al., 2017). Consequently, data are often manually prepared (without coding) in Microsoft Excel with data processing decisions documented in Excel, Word, or emails, if documented at all (Lowndes et al., 2017). A 2015 survey of datasets from natural science research studies published in open-access journals found that 56% of the datasets were incomplete (e.g., missing data or insufficient descriptors about how the data were collected – i.e., metadata) and 64% were only partially available—e.g., processed rather than raw data, non-machine-readable file formats (Roche et al., 2015). Journals and data repositories can lack the incentives and/or funding and resources required for data quality control that ensures data are reusable (Roche et al., 2015). Researchers also tend to lack the funding and support needed to make their data open (Goucher et al., 2021; Hahnel et al., 2023). Data must be analysis-ready to inform freshwater resource management decision-making (Great Lakes Observing System [GLOS], 2021).

The newly formed Canada Water Agency (CWA) is creating a National Freshwater Data Strategy to ensure resource management decisions are informed by robust datasets (ECCC, 2021). To date, many of the recommendations for the strategy have come from stakeholders within the freshwater science sector who have environmental science education and experience (ECCC, 2021; Goucher et al., 2021). While this expertise is essential, the CWA may be missing insights from sectors with more mature data management and sharing practices. Learning from different sectors will help the agency accelerate progress, avoid duplication of effort, and facilitate creation of a strategy that will effectively and efficiently achieve its goals.

We gathered insights from the technology (tech) sector to explore how the freshwater science sector can improve its data management and sharing practices to achieve data that are discoverable, accessible, interoperable, and reusable. There is no standard definition for the “tech sector”, but the term is commonly used to generally refer to companies that build or use advanced technology as part of their business model (Hooton, 2018). For this study, we narrowed our focus to tech companies that have incentive structures associated with effective data management and sharing. We spoke with technology experts (software engineers, software developers, and data scientists) working in the tech sector to discover if there are pragmatic and effective solutions that the freshwater science sector has not yet considered or currently struggles to implement. We believed that technology experts who have worked in the tech sector would have in-depth knowledge of methods and tools not yet considered broadly by freshwater science experts. We present our findings as recommendations for improving freshwater data management and sharing that can be undertaken by individuals and organisations, including the federal Canada Water Agency.

3.3 Methods

3.3.1 Study Design

We used Reflexive Thematic Analysis (RTA) to gather recommendations for improving data management and sharing practices from the tech sector (Braun & Clarke, 2021; Braun & Clarke, 2023; Byrne, 2022). RTA was particularly appropriate for our cross-sector approach. As freshwater scientists, we did not have a preconceived idea of the recommendations that the technology experts would offer, and we needed an inductive and iterative approach that would allow us to use our sectoral knowledge to interpret responses from technology experts and formulate applicable recommendations through development and refinement of codes as the interviews progressed. Figure 3.1 illustrates the approach we undertook, and how it aligns with the core steps of Virginia Braun and Victoria Clarke’s approach to RTA (Braun & Clarke, 2006; Byrne, 2022). Unlike codebook reliability approaches, the reflexive approach allowed us to learn from participant responses and organically revise codes to identify themes as we learned more with each successive interview (Braun & Clark, 2021; Byrne, 2022). Further, RTA does not require coding all data—like Grounded Theory methods—but instead allows flexibility in the coding coarseness to focus on addressing key research objectives (Braun & Clarke, 2021). Our approach was pragmatic, as we coded only opinions and insights that supported recommendations for freshwater data management and sharing. Themes

identified through interview results were reframed as recommendations once coding all of the interview transcripts was complete.

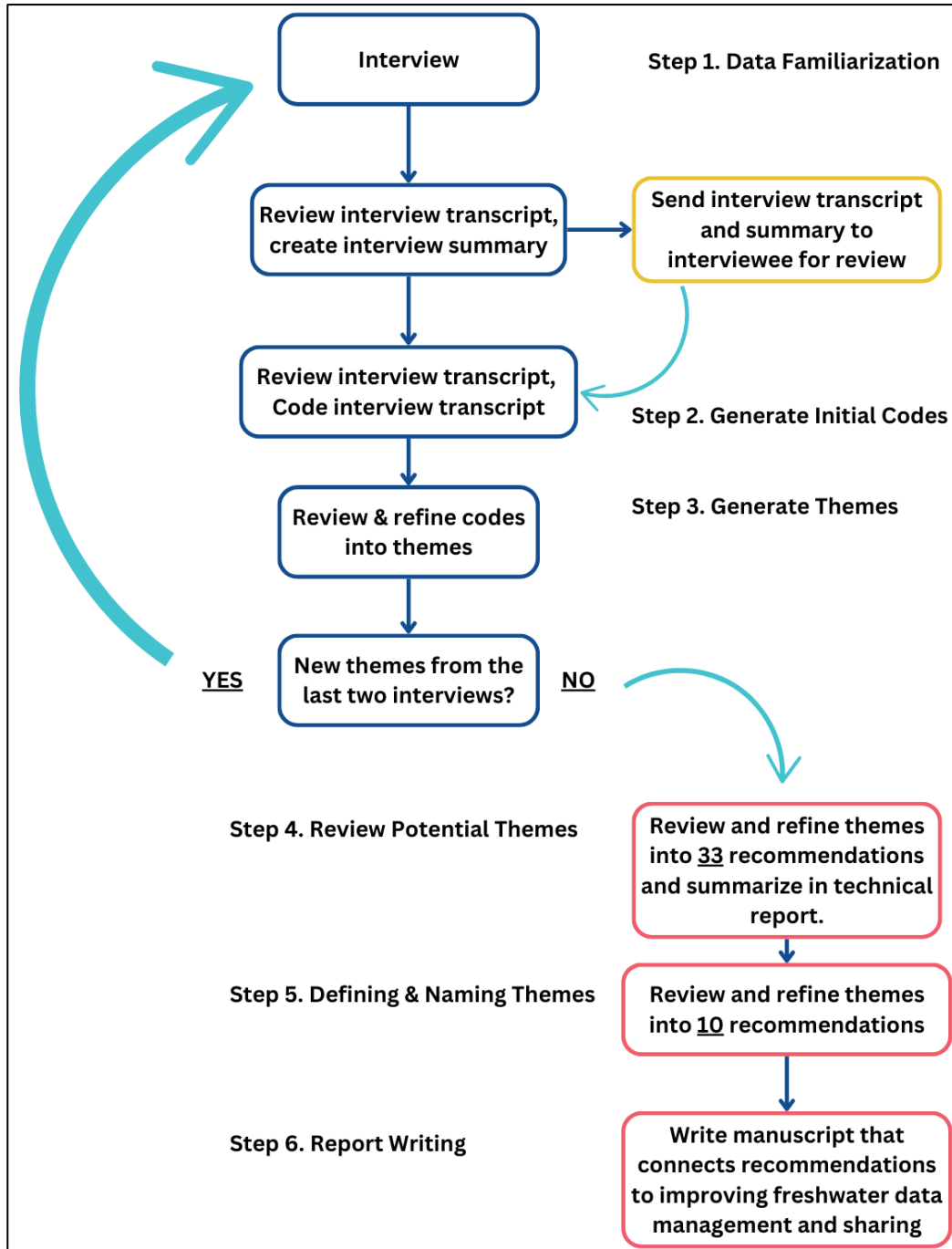


Figure 3.1. Illustration of study methods and how methods align with the core steps of Reflexive Thematic Analysis (Braun & Clarke, 2006; Byrne, 2022).

3.3.2 Interviews

Between August and October 2025, we conducted one-on-one semi-structured interviews with 12 key informant technology experts (Table 3.1). The duration of each interview was approximately 60 minutes. First, we targeted people we knew to be technology experts and knowledgeable about data management and sharing best practices (Young et al., 2018). We then used snow-ball sampling by subsequently contacting additional potential participants who were recommended by initial participants (Young et al., 2018). However, only two participants were gained from the snow-ball sampling.

Using the methods described by Guest et al. (2020), we assessed our data saturation rate every two interviews following the first four interviews. No new themes emerged in the two interviews following our first ten interviews. We thus inferred that we had reached data saturation—no new information gained—with our first ten interviews (Appendix B, Table B.1) and did not seek new participants after completing 12 interviews.

Before reaching out to potential study participants, ethical approval was obtained from the University of Waterloo Research Ethics Board (REB #46395). Informed consent was secured from all participants, who were assured of their right to withdraw from the study at any point ahead of publication without consequence.

We used strict recruitment criteria. Our inclusion criteria for study participants were: minimum five years experience as a software developer, software engineer, or data scientist AND currently works for a company where revenue is directly linked to effective data management OR is not currently working, but held a senior role in a company/organisation where revenue was directly linked to effective data management for a minimum of 10 years. Currently working individuals included those who work independently as contractors. Key informants were sourced from the lead author's personal network. Participants were recruited using a standard recruitment email (Appendix B, Document B.1).

At least one week prior to scheduled interviews, each participant was sent a study background document that summarised the current state of data management and sharing in the freshwater science sector (Appendix B, Document B.2). This allowed all participants to have the same base understanding of issues to be discussed during the interview. Each participant was also sent the

interview guide so that they could come to the interview with prepared responses (Appendix B, Document B.3).

Interviews were semi-structured, with prepared and emergent questions that allowed the interviewer to lead each interview based on participant responses. When participants described experiences or offered insights and opinions, the interviewer reframed the response as a recommendation for the freshwater science sector and asked for feedback. The participant would then agree or disagree with the interviewer's interpretation and could add further clarification. Interviews were conducted online and audio was recorded using Microsoft Teams. The audio files were uploaded to Otter.ai for transcription (Otter.ai Inc., 2024). Transcripts were edited in Otter.ai and, when necessary, recordings were used to confirm accuracy of the transcripts. The transcripts were reviewed to identify where participants offered insights and opinions that could be framed as recommendations for the freshwater science sector.

For each interview, recommendations, along with quotes from the transcript that supported them, were documented in an interview summary document. The summary document and the full interview transcript were sent to the participant for their review prior to analysis. While participant validation is not necessary in RTA, it is commonly used in thematic analysis to avoid misinterpretations (Braun & Clarke, 2023). We asked participants to review specific recommendations captured from their interviews, not the final recommendations we developed from interpreting the collection of recommendations from all of the interviews. Thus, our final recommendations were a product of our interpretive work, which is an appropriate outcome from RTA (Braun & Clarke, 2023).

3.3.3 Analysis

We completed a thematic analysis of the participants' recommendations discussed during interviews. "[Thematic analysis] can be likened to a distillation process by which the researcher identifies or comes face to face with the explicit and implicit meanings they have discerned in the data, and then synthesises these findings" (Finlay, 2021, p. 104). Recommendations included statements and discussion points around what the participants thought the freshwater science sector should do and/or should not do to improve data management and sharing practices. We uploaded transcripts to NVivo software (version 14.24.0; QSR International Pty Ltd., 2023), which was used to code participant responses. We coded all recommendations, opinions, and insights that were directly relevant to how

the freshwater science sector can improve data management and sharing. As described by Finlay (2021), thematic analysis involves creating initial codes, searching for themes in the initial codes, and then collapsing or splitting initial themes such that they can be woven together into a narrative that answers the research question (Finlay, 2021). Initial codes reflected specific recommendations offered by each participant. As the interviews progressed and themes emerged, specific recommendations were re-coded under more general recommendations to capture overarching themes. The top-level themes were: open data culture, building centralised data solutions, standard development, data licences, skills and training, and roles for the Canada Water Agency. Each of these high-level themes contained at least one subtheme that was framed as a specific recommendation for the freshwater science sector. JK reviewed the complete list of specific recommendations with co-author NB who collaborated on developing the final list of high-level broad recommendations. The themes and corresponding recommendations are described in our codebook (Appendix B, External Resource B.1). We excluded recommendations that did not receive support from at least three participants.

Table 3.1. Profile of study participants, including their participant number identifiers (No.), current job title (title), years of professional experience (years), skills and expertise, and formal education from a post-secondary academic institution.

No.	Title	Years	Skills & Expertise	Formal Education
1	Independent Open-Source Developer	20+	Build open-source software, some of which is used by millions of people.	Bachelor of Computer Science, specialisation in software engineering
2	Director of Engineering	12	Web application development at scale	Bachelor of Science in Physics
3	Software Developer	15	Product development and web front end technology	Bachelor of Fine Arts
4	Software Developer & Entrepreneur	20	Specialising in knowledge translation in the technology sector	Bachelor of Computer Science
5	Data Scientist in E-Commerce	7	Big data analysis, machine learning, a/b testing, SQL, Python	Bachelor of Mathematics, minor in Computer Science
6	Chief Software Architect for a Market Research Company	25	Large data processing and distributed systems, designed some of the largest performing order processing systems in the world.	None
7	Software developer, Chief Technology Officer, and entrepreneur.	8	Location data and mapping.	Bachelor of Computer Science
8	Software Developer for mobile apps.	16	Building and using relational databases	Masters Degree in Software Engineering
9	Technical leader	30	Data architecture and data science	None
10	Chief Technology Officer in technology startups	20+	Data engineering and data platforms	Bachelor of Computer Engineering
11	Software Engineer	15	Data streaming systems	PhD in Programming Languages and Stream Fusion
12	Data Scientist in Energy and Tech	7	Generalist	PhD in Math

3.3.4 Study Limitations

Our key informants were not randomly selected. It is possible that interviewing a different group of people would have yielded different recommendations. The lead author's social network was selected because it contained many highly experienced technology experts with a broad array of educational backgrounds and work experiences that span a range of companies in the tech sector. Participants included entrepreneurs that run one-person companies and employees of some of the largest

technology firms in the world. Academic backgrounds ranged from no formal computer science training to a PhD in computer science (Table 3.1). Thus, while our participants were not randomly sampled, we believe the interviewees reflected a diverse range of experiences, and that the captured common themes would have emerged from other groups.

The interviews were largely guided by the study background document. We strived to make this document a comprehensive snapshot of the current state of data management and sharing struggles within the freshwater science sector. However, it is possible that a different research team would have created a different summary that could have directed the interviews in different directions.

Developing codes as interviews progressed could have caused codes from earlier interviews to bias coding of later interviews. We did address this concern with interview summaries that we used to gain participant verification for the initial recommendations we distilled from the interviews. However, not all participants reviewed their interview summary. We could have improved the rigour of this study with triangulation of researcher interpretations by having other co-authors independently review and code interview transcripts. Instead, JK independently coded the interview transcripts to create the initial list of 33 recommendations that closely reflected the recommendations made by the study participants. After reviewing these 33 recommendations, JK brainstormed with co-author NB to define the final list of the high-level broad recommendations. It is possible that different reviewers would have developed different broader recommendations. We welcome others to review our original list of 33 specific recommendations in Appendix B, Table B.2 to see if they have different interpretations of our results. De-identified quotes that support each of the 33 specific recommendations are also available upon request.

All authors of this study are natural and/or social scientists that research freshwater topics. It is possible that including a co-author who was a technology expert would have led to different interpretations of participants' responses. However, a technology expert may have imparted their own bias based on their experiences and preferences. Instead, we had a senior software developer (with over 20 years of experience) who we did not interview and was available to clarify topics or terms without influencing coding or theme development.

3.4 Results & Discussion

Below we use several data science terms when describing recommendations for improving freshwater data management and sharing. These terms also appear in several quotes from our participants. These terms are used interchangeably by some and can be defined differently based on the context (e.g., statistical analysis vs. database design). We describe these terms here to clarify for our readers what they mean in the context of our study (Table 3.2). While these terms refer to independent processes, they are sometimes used as umbrella terms that include multiple processes. For example, while data cleaning and data transformation are different steps in the data preparation process, some people consider data transformation as a step in data cleaning, and data cleaning as a step in data transformation (Enterprise Big Data Framework, 2023). All of these terms refer to important steps in the data preparation process that ensures data can be joined with other data sets and/or analyzed. We use the term data preparation to generally refer to the process that encompasses all of the terms described in Table 3.2.

We organized interviewees responses into 10 broad recommendations for the freshwater science sector to improve data management and sharing practices (Table 3.3). These broad recommendations encompass the initial specific 33 recommendations, except for those that were supported by less than three interviewees' responses. The original list of 33 specific recommendations is available in Appendix B, Table B.2. The 10 broad recommendations are described in detail below and each recommendation is **bolded**.

Table 3.2. Definitions of data science terms used in describing recommendations.

Term	Definition
Data cleaning	Data cleaning is the process of removing data that should not be in your dataset (Salesforce, 2025). This process includes removing duplicate data; identifying and correcting errors, inconsistencies, and missing values; and removing problematic outliers (Salesforce, 2025). Data cleaning is a typical step in Quality Assurance and Quality Control (QA/QC) processes. Some view data cleaning as also ensuring the data is in a consistent format that conforms to a data standard, and transforming the data into a format that is useful for analysis (Enterprise Big Data Framework, 2023).
Data transformation	Data transformation involves converting data from one format or structure into another (i.e., data wrangling, data munging) to prepare it for storage and analysis (Salesforce, 2025). Transformations include converting data from wide to long or long to wide dimensions.
Data standardisation	<i>“Data standardization is the process of converting data from various sources into a common, uniform format”</i> (Teradata, 2025). The process of data standardisation involves data transformation (Teradata, 2025). This process involves standardising data formats, naming conventions, and values (Teradata, 2025). For example, dates may appear in two different formats, such as "DD-MM-YYYY" and "MM-DD-YYYY". Data standardisation transforms all dates into a selected uniform date format (e.g., "YYYY-MM-DD").
Data normalisation	Data normalisation is a term typically used to refer to database design (Ibitola, 2023). Data normalisation is used to “clean up” unstructured or semi-structured data that are difficult to analyze (Snowflake, 2025). Data normalisation is a process that applies a set of rules to standardise and organize data, and removes data anomalies and redundancies so that data can then be easily grouped, understood, and interpreted (Snowflake, 2025). Data normalisation is important to be able to combine datasets from multiple sources (Snowflake, 2025). There are different rules associated with data normalisation. For example, the first rule is meant to make the data easier to search by ensuring all attributes have a unique name, each entry is unique, and each cell has only a single value (Snowflake, 2025). Although they are distinct, data normalisation is sometimes used interchangeably with data standardisation and data cleaning, partly because one of the goals of normalisation is standardisation (Ibitola, 2023; Snowflake, 2025; Teradata, 2025). Data normalisation aims to achieve clean, structured, and standardised data (Ibitola, 2023).

Table 3.3. Summary of recommendations from technology experts for the freshwater science sector.

Theme/Recommendation
Open Data Culture
1. The freshwater science sector should create a culture of open data with incentive structures that reward data sharing and leaders who demonstrate and promote effective open data practices.
Data Licences
2. Freshwater scientists should use data licences to support data reusability.
Skills Development
3. Data literacy in the freshwater science sector should be strengthened by integrating data skills into academic curricula and fostering workplace mentorship and peer-to-peer learning.
Freshwater Data Standard Development
4. A freshwater data standard is needed to guide data collection and management so that data are reusable and comparable across datasets.
5. A freshwater data standard should be created through a collaborative process, and offer examples and support to ensure it is widely adopted and achieves standardisation.
Building Centralised Data Solutions
6. A centralised data solution should be designed based on available resources, with the simplest focused on data discoverability to the most advanced and resource-intensive focused on data reusability.
7. The manager of a centralised data solution needs to plan for its long-term maintenance.
8. A centralised data solution should be designed with user-friendly features, protections for sensitive and private data, and a community forum that attracts users so that it actually becomes the centralised solution.
9. The freshwater science sector should not seek out Blockchain technology.
Roles for the Canada Water Agency
10. The Canada Watershed Agency can use its position as a national agency to help develop and support the centralised data solution, a national data standard, and incentives for data sharing.

3.4.1 Open Data Culture

The freshwater science sector should create a culture of open data with incentive structures that reward data sharing and leaders who demonstrate and promote effective open data practices (Participants 1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12). *“That’s my big-picture take away from all this stuff. If you can’t solve the social problems, the technology won’t really help”* (Participant 4). Participants generally focused on the need to prioritise cultural and social motivations that encourage people to

want to share their data, over the technical solutions and skills people need to know *how* to share their data.

The freshwater science sector can learn from the tech sector's open-source culture to foster an environment that motivates open data sharing (Participants 1, 2, 3, 4). *"Even if you're working for a large corporation, you're still using open-source software where people have contributed for free to the shared project. It's kind of crazy that it works. Everybody's using this software that nobody paid for. But the reason it works is because the social dynamics have been figured out"* (Participant 4). Over the past 20 years, open-source culture has permeated the tech sector, spurring rapid innovation by allowing everyone to build on each other's work—for free (Participants 1, 4, 10). *"...open-source is one of the key reasons that software has developed as quickly as it has and the space has moved as quickly as it has..."* (Participant 10). Similarly, open data culture could accelerate the freshwater science sector's progress toward the goals of freshwater resource protection and restoration.

To achieve such a culture shift in the freshwater science sector, there needs to be incentives beyond *"a vague sense that you should do it out of obligation"* to encourage open data sharing (Participants 4). The open-source culture works in the tech sector because there is a lot of prestige, recognition, and social credit granted to individuals who contribute to open-source (Participant 4). *"At tech conferences, all the headline speakers are open-source contributors. The stars of the field are open-source contributors"* (Participant 4). Employers also generally show a preference toward hiring open-source contributors and will review open-source contributions to evaluate an applicant's competencies (Participant 4). *"So, it's a really easy way to gauge whether someone is full of shit or knows what they're doing"* (Participant 4). These social incentives motivate people to work on open-source projects during their evenings and weekends and seek employment with companies that contribute to open-source projects (Participant 4).

Incentives that make open data sharing prestigious and professionally valuable can motivate scientists of all career stages to upgrade their data skills, including recognizing data as formal publications, rewards for reproducible datasets, and open data mandates for funding and publications (Participants 1, 4, 5, 9, 12). *"I think incentive alignment is going to be probably the most important factor"* (Participant 3). Scientists have also acknowledged the need for incentives that reward open data sharing to promote a culture change (Gunn & Stanley, 2018; Hahnel et al., 2023; Roche et al., 2015; Smits et al., 2025; Stall et al., 2019; Zipper et al., 2019). However, to be effective, participants

stressed these incentives must be paired with processes that verify data against a standard; otherwise, data sharing remains merely a checkbox that fails to encourage people to spend the time and effort required to manage and share reusable data (Participant 1, 4, 5, 12).

While incentives are developed at the institution level, individual freshwater scientists can promote the open data cultural transition by acting as thought leaders who widely communicate the *how* and *why* of open data sharing through blog posts, conference talks, social media posts, journal articles, and guest lectures (Participants 1, 3, 5). In addition to success stories and examples of useful tools and methods, thought leaders can motivate data sharing by communicating how open data can maximise the positive impacts of one's work (Participant 1, 2, 3). According to Participant 1, open-source became popular, in part, because people realised that was how they could “*make impactful improvements on our world*” (Participant 1). Freshwater researchers are beginning to take on these leadership roles by publishing papers (e.g., Miller et al., 2022; Schmidt-Kloiber et al., 2019; Smits et al., 2025) and attending workshops (e.g., Goucher et al., 2021; CWA, 2025) that discuss the need for open data to conserve freshwater ecosystems. When freshwater researchers see clear benefits to data sharing, mastering the technical skills to do so becomes a goal to achieve rather than a burden to avoid.

3.4.2 Data Licences

Freshwater scientists should use data licences to support data reusability (Participants 1, 2, 3, 8). “*I feel like licensing is going to inevitably be a big part of this... part of the reason open-source software grew as much as it did and had as much success as it has had, I think that's because people had the right licences early on and tended towards very open licences...*” (Participant 3). Data licences are documents that describe how data can be used (Participant 1, 2, 3). “*When data is released, by default the author holds the full copyright to it. That means other people don't have rights to use it.*” (Participant 1). Thus, freshwater scientists who want to maximise the impact of their data, need to share it under a licence that allows others to reuse it (Participant 1, 2, 3). An awareness of data licences may also encourage scientists to share their data, since licences also ensure the contributor receives the right attribution and protection from liability associated with the reuse of their data (Participant 1, 3). Rather than create new licences, the freshwater science sector should use Creative Commons Licences, which are already appropriate for data sharing and allow a range of data reuse restrictions (Participants 1, 2, 3, 8). Using non-standard data licences can make accessing data

time consuming for those who have to interpret them (Schmidt-Kloiber et al., 2019) Through widespread use of Creative Commons Licences, freshwater scientists will maintain control over how their data are used and credited while freshwater science is advanced through data reuse.

3.4.3 Data Skills Development

Data literacy in the freshwater science sector should be strengthened by integrating data skills into academic curricula and fostering workplace mentorship and peer-to-peer learning

(Participants 2, 3, 4, 6, 7, 10, 12). *“In science, I see a lot of really not normalised data, like data that can't really be brought together into a centralised database, because it's just a bit of a mess...”*

(Participant 3). Some participants agreed with scientists who have previously recommended formal education-based strategies to address the lack of data management training in the natural sciences (Goucher et al., 2021; Lowndes et al., 2017; Powers & Hampton, 2019; Roche et al., 2015). In particular, data management and sharing practices should be embedded in all academic courses that deal with data (Participants 3, 10, 12). Participants also stressed the importance of skills building outside of academia. The tech sector particularly values mentorship and peer-to-peer learning since academia does not provide up-to-date knowledge and skills development for technology that is constantly changing (Participant 2, 3, 4, 6). *“I'm a huge advocate for mentorship...because, a lot of times that works out better than any kind of formal training”* (Participant 6). Accordingly, the tech sector frequently hires people without academic degrees in computer science, including 42% of our participants (Table 3.1). Employers in the freshwater science sector should also offer employees mentorship and peer-to-peer learning opportunities to continuously develop their data skills (Participants 2, 3, 10, 12). Continuous training keeps everyone updated on changing technology and increases exposure to data literacy, making it *“less scary and less intimidating”* (Participants 10, 12). Academia can ensure scientists enter the workforce with a strong data literacy foundation while employers support the current cohort of scientists and keep the sector up-to-date on best practices and current technology.

3.4.4 Freshwater Data Standard Development

A freshwater data standard is needed to guide data collection and management so that data are reusable and comparable across datasets (Participants 4, 6, 7, 8, 9, 10, 12). Participant 4 described the development of a freshwater data standard as *“a huge win, because even if you don't have complicated IT solutions, or a centralised database, you are getting data that can be compared*

against other researchers without doing too much work.” The freshwater science sector has acknowledged the need for a freshwater data standard, although one has not yet been developed (ECCC, 2021; Miller et al., 2022; Sheelanere et al., 2013). The standard should include data collection and entry methods so that data are in a reusable format from the start, simplifying data management and sharing (Participant 10). *“...let's make the experience at data collection and entry way better, so that it's already in the format that we want to be able to then reuse”* (Participant 10). A standard ontology (i.e., definition of standard terms and their relationships) and clear metadata standards (i.e., information describing how, when, where, and why the data were collected) are also needed to ensure data are reusable and comparable across datasets (Participants 4, 6, 8, 9, 12). While developing a complete ontology may be difficult and unnecessary, there needs to be at least standard definitions and formats for the minimum data required for reuse, such as units of measurement, dates, and location data (Participant 8, 9, 12). The minimum data requirements should be guided by the current and future questions freshwater data users will likely want to answer (Participants 7, 12). Essentially, a freshwater data standard must guide data collectors to enter their data in a way that others can understand and reuse.

A freshwater data standard should be created through a collaborative process, and offer examples and support to ensure it is widely adopted and achieves standardisation (Participants 1, 2, 4, 5, 6, 7, 8, 12). *“For anything that's about standardisation, you need buy-in from the people who are going to have to be using it”* (Participant 12). Various freshwater stakeholders should be involved to create a data standard that makes sense for everyone (Participant 1, 4, 12). A draft standard, along with example datasets, should be publicly released for stakeholders to test the standard with real-world data and offer feedback (Participants 1, 4, 6, 8). This feedback process avoids a completely new standard having to be created in a few years (Participants 1, 8). *“It's totally okay to have a version two of the [standard]...But ideally, version two is an evolution, not a revolution”* (Participant 8). The standard needs to provide specific guidance along with clear examples that help people know exactly how to use it; otherwise, people will interpret it in various ways and it will fail to achieve standardisation (Participants 1, 2, 5, 8). *“I think giving people examples is always the best way to get them to understand the standard”* (Participant 5). Managers of the standard can support users with checklists of required components, personnel that offer guidance, scripts that demonstrate how data should be aggregated and formatted, and tools that ingest data and return error messages with clear instructions on how to fix the data (Participants 1, 6, 8). Freshwater

science stakeholders need to work together to create a data standard that is easy to follow and widely adopted so that freshwater data becomes reusable.

3.4.5 Building a Centralised Data Solution

A centralised data solution should be designed based on a spectrum of complexity, with the simplest and most essential being one that facilitates data discoverability, then advances with accessibility functionality, and culminates with functionality that ensures data reusability (Participants 1, 2, 4, 5, 6, 7, 8, 9, 11, 12). A centralised data solution is a digital platform that can function as a data registry and/or repository to consolidate data discovery and access in a single place. The participants agreed with the freshwater science sector that a centralised freshwater data solution is needed to reduce the time and resources spent finding, accessing, and reusing data (CWQA, n.d.; Ducks Unlimited Canada, 2023; ECCC, 2021; Maasri et al., 2022; Miller et al., 2022; Sheelanere et al., 2013; Wrona & Munkittrick, 2024). However, the participants had a variety of opinions on what a centralised freshwater data solution should provide, presenting a spectrum of options that can be selected based on the resources available. These options range from the simplest that allows users to discover data from one location to the most resource intensive option that hosts analysis-ready data that conform to a single data standard on a single platform.

The “*minimum viable product*” for a central data solution would be a data registry—a website with links to freshwater data to support data discoverability (Participant 5). “...as long as there’s a solution that allows me to know where I can get this data first, whether or not it’s standardised, whether or not it’s easily downloadable, that’s a problem for another day, as long as I can find it, I think that’s the key” (Participant 5). Data discoverability is important to prioritise because it is unlikely that a single repository will ever contain all freshwater data (Participants 1, 2, 12), which has held true in the freshwater science sector where centralisation efforts remain fragmented with open data records stored in different data portals and repositories (Miller et al., 2022; Schmidt-Kloiber et al., 2019). Rather than create yet another repository, a tool should be built that helps users search and access data from pre-existing sources (Participants 1, 5, 9, 12). Once the discoverability problem is addressed, this solution can eventually evolve into a platform with more advanced functions that improves data accessibility by providing a centralised place where people can share their data (Participants 5, 12).

Data repositories that host and share data should focus on features that make data sharing easy (Participant 5). “...avoid having too many requirements and making it too much of a barrier to actually add the data...because then if people see that it's a lot of work, they might just give up and not add it.” (Participant 5). Data uploads should be simple without numerous steps or detailed forms, and the repository should be easy to find without having to click through several pages to access it (Participant 5). Data contributors should not have to adhere to a data standard, especially freshwater scientists who tend to lack the skills and time required for data preparation (Participants 5, 6, 7, 8, 12). “Data cleaning is a tough, tough thing...So, I worry that it's hard for the repository to push that back onto the researcher or the company who says, ‘Hey, I want to give you this data.’ And then you say, ‘Oh, well, can you spend 28 hours cleaning it?’ ” (Participant 8). Data contributors can still be encouraged to follow a data standard, especially for new datasets (Participants 4, 8, 11, 12). The repository can identify which datasets comply with the standard to help data users select datasets that are appropriate for them based on the time and skills they have for data preparation (Participants 2, 8, 9, 12). Thus, data contributors and users who cannot complete data preparation tasks are not blocked from using the repository (Participant 8).

To maximize data contributors and users, a centralised solution would make it easy to reuse data by ensuring all data meet the same standard and are prepared for reuse (Participant 6). “You're wanting to get it to the point where you have a data warehouse, where you have normalised the data in such a way that you can utilise it more effectively” (Participant 6). To achieve this, the repository needs personnel and tooling to prepare data that are received from contributors to ensure it meets a single standard and is reusable (Participants 6, 7). Volunteers, such as citizen scientists or students, can be recruited to help with data preparation tasks (Participant 11). For example, the Canadian Institute of Ecology and Evolution runs the Living Data Project that recruits students to help archive historical environmental science datasets (Canadian Institute of Ecology and Evolution, n.d.). While this is the most resource-intensive solution, it could be the most efficient because it relieves the need for all teams throughout the freshwater science sector to acquire data preparation skills—which is unrealistic.

The manager of a centralised data solution needs to plan for its long-term maintenance (Participants 1, 2, 5, 6, 7, 11). “...people not in software want to treat it like their civil engineering project where we built this bridge, now we can mostly leave it alone. The software tends to be a living thing that accrues rot much more quickly.” (Participant 6). Regardless of the type of data solution

selected, it needs to be maintained to stay up-to-date with the latest data (Participant 1, 2, 5). *“It’s like a garden, you have to keep grooming it and make it up to date”* (Participant 2). The long-term maintenance of existing online open freshwater databases has been complicated by a lack of project funding and commitment (Schmidt-Kloiber et al., 2019). This issue should be addressed and mitigated at the design stage. For example, four research institutes worked together to fund the Freshwater Information Platform, which was designed for long-term use and maintenance (Schmidt-Kloiber et al., 2019). The choice of data solution should be guided by the long-term funding that is available to maintain necessary full-time staff and technology (Participants 1, 2, 5, 6, 7, 11).

A data sharing platform should be designed with user-friendly features, data access controls, and community engagement functionality to naturally emerge as the centralised solution (Participants 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12). *“I think the fragmentation is a big problem here. That’s something I don’t really have a lot of good solutions for myself, other than a community organising around something that works well for them...”* (Participant 3). As online freshwater data platforms proliferate, scientists lament that data continue to be fragmented and difficult to find (Schmidt-Kloiber et al., 2019). True centralization occurs when data contributors and users unite behind a single platform that they recognize as superior to alternatives (Participant 10). Participants offered features and functionality that attract users to a data platform—so that it becomes *the* centralised solution.

Builders of a centralised data solution should first explore pre-existing tools to inform the design of new tools with features that work well (Participants 1, 3, 7, 10). *“...before whoever is the next organization to want to build one of these repositories, first look at a pre-existing tool like GitHub that is very popular in the tech space, and consider, can we just use that, and if not, what can we learn from it to then apply to our own model”* (Participant 10). GitHub became the preferred platform in the tech sector because it *“had the best tooling, the one that made discoverability the easiest, community contributions the easiest”* (Participant 10). Accordingly, GitHub was the tool participants most commonly recommended for the freshwater science sector to explore (Participants 1, 3, 4, 5, 7, 8, 10). *“I can’t think of a better example than GitHub”* (Participant 5). The natural science community is beginning to use GitHub, as described by Lowndes et al. (2017) who demonstrated how their lab used it to make their research more efficient and reproducible. Participants highlighted two GitHub features: data tags, which improve data discoverability with descriptive identifiers that allow users to find the data they need; and version control, which supports

data reusability and study reproducibility by allowing data users to know when/if datasets have changed (Participants 1, 2, 5, 7, 8, 9). Regardless of the feature, functionality must be user-friendly to attract users (Participants 5, 10).

Data contributors are more willing to share their data with repositories that offer options to control access to sensitive and private data (Participants 2, 8). “...*companies and people with a lot of useful, valuable data are never going to share their data with you unless you have some basic controls in place*” (Participant 2). Although making all data openly accessible is easiest, the freshwater science sector must consider and respect data sovereignty and privacy (Zipper et al., 2019). Indigenous data sovereignty stipulates that Indigenous governments and communities have jurisdiction over the collection and sharing of data collected by or about their peoples and land (Carroll et al., 2020; Zipper et al., 2019). As such, data sharing platforms need to support Indigenous Data Governance principles, including OCAP (ownership, control, access, and possession) and CARE (collective benefit, authority to control, responsibility, and ethics) (GLOS, 2021; Wilson et al., 2024). While participants did not have experience with data sovereignty, they offered techniques to protect private and sensitive data, including allowing data contributors to restrict data access to certain individuals and organizations, mask sensitive data within a dataset, control the level of data aggregation, or have the authority to approve/deny data access requests (Participants 5, 8, 12). The ability to restrict data access will be important to scientists with data containing sensitive information such location data for rare or endangered species (Powers & Hampton, 2019). Data platforms need functionality that enables data contributors to control access to their data to avoid missing out on valuable datasets.

Community support is one of the most important determinants of the popularity of a data platform. Community support can be gained by ensuring functionality that facilitates peer-to-peer learning and reciprocity amongst data contributors and users (Participant 7). “*All the contributors are part of a forum. If they have questions, if they have concerns, it's like a whole community where people help each other out.*” Online forums allow platform users to interact with questions, guidance, and analytical insights (Participant 7). The platform also needs mechanisms for data users to engage with data contributors about their data to support data reusability (Participants 2). Community members form a symbiotic relationship as contributors share their data with users, who return the favour by reporting data errors and sharing prepared and analysed datasets (Figure 3.2; Participants 3, 7, 8, 9, 10, 12). Data users become data contributors, which can be especially important when original

data contributors share their data but then become disengaged or unresponsive to questions about their data. The community benefits are amplified when the code used for data preparation and analysis are also shared, exposing errors, reducing duplicated efforts, and making research truly reproducible (Participants 5, 8, 12). Essentially, the community works together to improve and iterate on each other's work, accelerating collective progress (Participant 10). This community attracts and engages data contributors and users, and works to address data fragmentation because the sector unifies around one solution (Participant 3, 7, 8, 12).

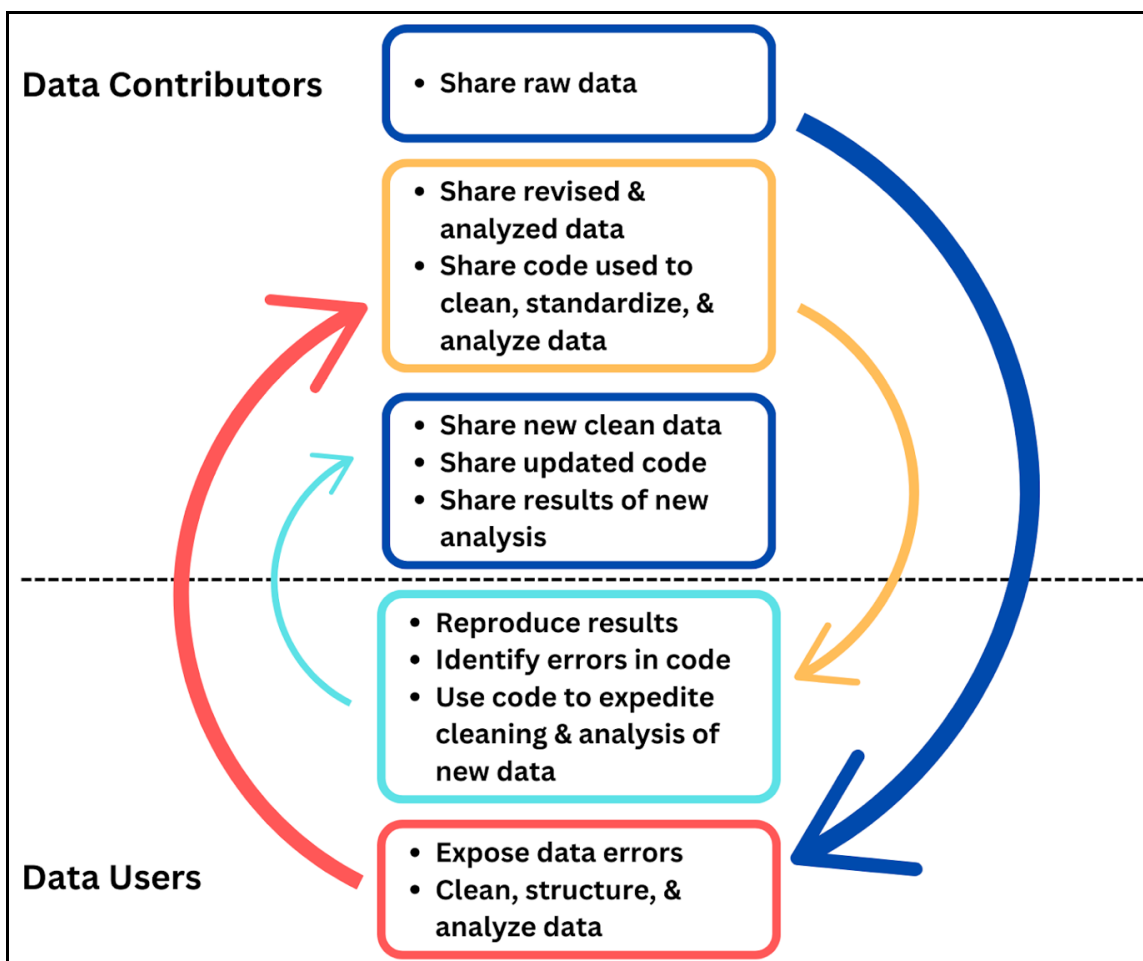


Figure 3.2. Symbiotic relationship between data contributors and users that can be facilitated with a data repository.

The freshwater science sector should not seek out Blockchain technology (1, 3, 4, 6, 7, 8, 9, 10, 11). *“The big problem you have to focus on solving is getting people to come together and share data. And the technology part should be as boring and as simple as possible. And blockchain*

technology is not boring and simple. It's abstract, complicated, and unapplied" (Participant 4). Blockchain technology is the only recommendation in the study background document (Appendix B, Document B.2) that respondents mentioned as something they would not recommend. Blockchain technology has previously been recommended for the freshwater science sector for data security and transparency, with the caveat that it may be cost-prohibitive (DataStream, 2018; Gunn & Stanley, 2018). However, none of the participants thought Blockchain would be useful for the freshwater science sector, and none mentioned costs as its limiting factor. *"I'm not a blockchain prioritizer in any way, shape or form. So, let's get that one off the table"* (Participant 9). The blockchain recommendation from Gunn and Stanley (2018) was based on recommendations for environmental data from the Fintech sector when blockchain was an emerging technology being widely considered for its potential applications. It is important to note that none of our participants identified themselves as working in Fintech, indicating perhaps a bias toward blockchain in the Fintech sector where the technology is useful. Our study participants cautioned Blockchain is relatively new, complicated technology with few proven real-world applications and may deter data contributions as attribution can never be altered or removed (Participants 1, 3, 4, 7, 8, 10). Rather than be a first mover with novel and complicated technology, the freshwater science sector needs solutions that are simple to adopt (Participant 1, 3, 4, 7, 8).

3.4.6 Roles for the Canada Water Agency

The Canada Water Agency can use its position as a national agency to help develop and support the centralised data solution, a national data standard, and incentives for data sharing (Participants 1, 3, 4, 5, 6, 7, 8, 9, 10, 12). The CWA could lead the development of a centralised data solution, which it could either own and manage or support by funding, selecting, and coordinating the organization that manages it (Participants 4, 5, 6, 7, 10, 9, 12). The federal government is already undertaking the first step by creating an inventory of the freshwater data it owns (Participant 9; Miller et al., 2022). After the inventory is complete, the CWA will have a holistic understanding of the various types of freshwater data, which will help in drafting the freshwater data standard (Participant 9). The CWA already plans to develop a data standard as part of the National Freshwater Data Strategy (ECCC, 2021; Miller et al., 2022), which will allow stakeholders throughout the freshwater science sector to have a single standard to point to rather than developing or finding their own (Participants 5, 6, 10). The CWA has the widespread reach and influence to take on the difficult task of getting people to use the standard (Participant 3, 4, 7). The

CWA's national influence is also needed to bring stakeholders together to identify and support incentives for individuals and private and public organisations to share their data (Participant 3, 4, 7). As a national agency with broad knowledge of, and influence in, the freshwater science sector, the Canada Water Agency (CWA) is well positioned to take a leading role in improving freshwater data management and sharing, especially where collaboration with stakeholders and widespread adoption is needed (Participants 1, 3, 4, 5, 6, 7, 9, 12).

3.5 Conclusion

From interviews with twelve experts from the tech sector, we developed ten recommendations to help the freshwater science sector improve its data management and sharing practices. Exploring how the recommendations made here could be aligned with Indigenous Data sovereignty principles was beyond the scope of this research study but could be explored in the future by Indigenous-led studies. Future work could also seek to validate our recommendations with a survey of a larger sample of experts from the technology and freshwater science sectors.

One of the biggest hurdles the freshwater science sector needs to overcome is the general reluctance of people to share their data. To address this issue, a culture change that embraces open data is needed, which can be achieved through incentives and leadership that encourage open data sharing. Once people are motivated to want to share their data, they need to become knowledgeable of data sharing practices that make data reusable. Data literacy foundations should be offered in academia and continuously developed in the workplace. A freshwater data standard can help make data reusable and comparable across datasets—if it contains clear guidance for data collection and entry that is developed in collaboration with freshwater stakeholders. Finally, the freshwater science sector needs simple digital tools that facilitate data discovery and access. The recommended options for a centralised data solution ranged from solutions focused on discovering data in its various original formats, to the most resource intensive option that focuses on data reusability by sharing data that are prepared internally. The best option should be selected based on the need for sophistication and available resources. Regardless of the option selected, the solution must have user-friendly features and functionality that attracts and retains data contributors and users so that it becomes the centralised data platform for freshwater scientists. As a national government agency, the Canada Water Agency can help with many of the recommendations, including building the centralised data solution, developing a national data standard, and supporting incentives that promote effective data

management and sharing. Ultimately, these recommendations can help guide many of the initiatives throughout the global freshwater science sector that are striving to improve open data practices. Freshwater data that are findable, accessible, interoperable, and reusable will help progress the collective goals of the freshwater science sector to advance the practices of freshwater ecosystem protection and restoration.

3.6 References

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Chapter 4

Calculating the Natural Range of Variation for Regional Baseline Surface Water Quality Studies

Kidd, J. A., Brekke, L., Courtenay, S. C., Swanson, H. Calculating the Natural Range of Variation for Regional Baseline Surface Water Quality Studies. Prepared to submit to Journal of Environmental Management.

4.1 Abstract

Insufficient baseline data is a common issue in surface water quality monitoring. Contemporary estimates of natural variation at watershed scales are needed to understand and investigate cumulative effects of climate change and human activities on surface water quality (e.g., contaminants, nutrients), but the several years of seasonal data required to characterize baseline conditions often do not exist. When these data do exist, it is often unclear to practitioners how to quantify baseline conditions. We investigated whether two quantification methods commonly used to estimate the Natural Range of Variation (NRV) in soils—Tukey Inner Fence (TIF) and median ± 2 median absolute deviation (M2MAD)—can be adapted to estimate baseline conditions in surface waters. We 1) tested the sensitivity of NRV methods to inclusion of varying proportions of data from sites known to be impacted by industrial activities, and 2) compared the effectiveness of the NRV method to other contemporary assessment approaches used to identify sites impacted by point-source pollution. We found that TIF was superior when datasets contained only data from unimpacted (i.e., reference) sites, whereas M2MAD was more suitable when datasets contained data from impacted sites. When applied to a regional dataset, the NRV estimations, in combination with temporal trend analysis and spatial assessment of regional concentrations, successfully differentiated unimpacted from impacted sites, regardless of historical impacts and/or temporal trends. The NRV method provided an objective, replicable, and insightful analysis of the data. Our findings indicate that estimating the NRV can help distinguish between regional climate change impacts and point-source impacts. We suggest that the approach could be useful in several regulatory and assessment settings, including cumulative effects assessments and formulation of remediation targets.

4.2 Introduction

The first step in many types of environmental assessments, including cumulative effects assessment (CEA) is to establish baseline (i.e., reference, background) conditions (Dubé, 2003). Baseline conditions for biophysical ecosystem components are typically described as quantitative estimates of select indicators. For example, baseline can be defined as ranges of elemental and molecular concentrations in media (e.g., soil, water, animal tissue) that have either: 1) not been influenced by any human activities; or, 2) more commonly, not been influenced by a particular industrial project or activity (Miller & Miller, 2007). Baselines serve as benchmarks in quantifying how environments have changed beyond natural variability, and are used to detect, quantify, and evaluate environmental

impacts of human activities (Dubé, 2003; Dung et al., 2013; Murawski et al., 2016; Worrall et al., 2019).

Effective CEA requires long-term regional monitoring data, which better define natural variability and provide a more accurate representation of baseline conditions than short-term monitoring of project footprints (Arnold et al., 2019; Chilima et al., 2013; Cronmiller & Noble, 2018; Dubé et al., 2013; Duinker & Greig, 2006; Foley et al., 2017; Heino et al., 2020; Johnson et al., 2011; Jones, 2016). Quantity and quality of baseline data are often lacking due to the high costs—in terms of both time and money—of obtaining them (Ball et al., 2013; Jones, 2016). Short-term cost savings in the production of baseline data often lead to long-term uncertainty regarding the true environmental impacts of a project. Insufficient baseline data continues to be one of the main criticisms of CEA, and there is still no consistent protocol for defining baseline (Arnold et al., 2019; Ball et al., 2013; Dubé, 2003; Dubé et al., 2013; Dung et al., 2013; Foley et al., 2017).

Defining baseline conditions of surface water quality parameters is complicated by widespread and ongoing anthropogenic influences on water chemistry (Miller & Miller, 2007; Sahoo et al., 2019). While it would obviously be ideal to characterize baseline conditions before any anthropogenic influences have occurred, there is growing acknowledgement that areas unimpacted by anthropogenic activities no longer exist (Jarva et al., 2010; Mali et al., 2015; Sahoo et al., 2019). As such, reference sites that are unimpacted by point-source pollution are used to monitor and understand ambient baseline conditions.

Water quality parameters are naturally dynamic and vary temporally, among seasons and years (Ball et al., 2013; Sahoo et al., 2019), and spatially, reflecting sometimes small-scale variation in landscape characteristics, such as soil and sediment geochemistry. Thus, natural background conditions in water quality are understood to be best represented by ranges rather than single values (Dung et al., 2013; Miller & Miller, 2007; Reimann et al., 2005; Reimann & de Caritat, 2017). Once established, natural ranges of variation can be used to identify samples that are impacted by human activities and which may require further investigation (Reimann & de Caritat, 2017; Sahoo et al., 2019).

The natural range of variation (NRV) is an estimate of baseline conditions, quantified using statistical methods, that defines ranges that are reflective of unimpacted environments. In this method, samples from impacted sites appear as outliers, or outside the natural range (Accornero et al., 2015;

Ander et al., 2013; Dung et al., 2013; Mali et al., 2015; Miller & Miller, 2007; Reimann et al., 2005; Sahoo et al., 2019). Exploratory geochemists first used the NRV concept over 50 years ago to locate areas of anomalous mineral concentrations that could be used to prioritize sites for exploration (Ander et al., 2013; Galuszka & Migaszewski, 2012; Reimann et al., 2005; Reimann et al., 2018). NRV estimates are now used in applications relating to environmental protection and restoration, including characterization of baseline conditions in environmental monitoring programs and risk assessments (Barrett et al., 2015; Kilgour et al., 1998; Mikkonen et al., 2017; Reimann et al., 2018; Sahoo et al., 2019), and in setting realistic remediation targets for contaminated sites (Rothwell & Cooke, 2015; Shackleford et al., 2021). The NRV method has most commonly been used to establish geochemical baselines for soil and sediment (e.g., Ander et al., 2013; Dung et al., 2013; Mali et al., 2015; Sahoo et al., 2019); however, further study is needed to assess the applicability of NRV methods for surface water quality data (Sahoo et al., 2019). Further, the NRV calculation methods have rarely been tested with real environmental data, and particularly with datasets that comprise high percentages of samples from impacted sites (Mikkonen et al., 2017). While NRV methods are meant to detect impacted data (i.e., outliers), their effectiveness with datasets containing impacted data is unknown.

Our objective was to assess and refine the NRV method for surface water quality data, with an overall goal of providing practitioners with an additional tool to support cumulative effects assessments of freshwater ecosystems. We investigated whether two quantification methods commonly used to estimate NRV in soils—the Tukey Inner Fence (TIF) and median ± 2 median absolute deviation (M2MAD)—can be adapted and used to estimate baseline conditions in surface waters. To support our investigation, we 1) tested the sensitivity of NRV methods to varying proportions of data from industrially impacted sites, and 2) assessed how results from an NRV method—integrating NRV thresholds, temporal trend analysis, and spatial assessment of regional concentrations—applied to a regional dataset with multiple reference sites and temporal trends, compared to results from a regulator-approved contemporary water quality assessment approach. For both study components, we used long-term, open datasets with project reports that identified sites as unimpacted (i.e., reference sites) or impacted (i.e., influenced by point-source pollution). While the reference sites were unimpacted by the point-source pollution being assessed, they could still be influenced by watershed-scale impacts, such as climate change. Both point-source and watershed-scale impacts can interact and accumulate across space and time causing cumulative effects in aquatic ecosystems. As such, impacted sites may be altered by the combined impacts of point-source and

watershed-scale influences. Demonstrating how practitioners can detect and distinguish point-source impacts from watershed-scale impacts can support the understanding of cumulative effects in freshwater ecosystems, which can inform sustainable watershed planning and realistic remediation targets.

4.3 Methods

4.3.1 Calculations for Natural Range of Variation

NRV thresholds were calculated for this study in RStudio version 2023.06.1+524 (RStudio Team, 2023) using the following equations:

- 1) The TIF method (Reimann et al., 2005)

Upper threshold = 75th percentile + (Interquartile Range [IQR] * 1.5)

Lower threshold = 25th percentile – (IQR * 1.5); and,

- 2) The M2MAD method (Reimann et al., 2005)

Upper threshold = Median + (2*Median Absolute Deviation [MAD])

Lower threshold = Median – (2*MAD)

The above TIF and M2MAD calculations are included in an R package we created for this study. The R package and an accompanying guidance manual (README file) that contains step-by-step instructions for how to access and use the package is available in Appendix C, External Resources C.1. For anyone who wants to reproduce this study or apply the NRV method for their own applications, specific data requirements and treatments we applied prior to the NRV calculations are outlined in Appendix C, Document C.1.

4.3.2 Testing the Sensitivity of Natural Range of Variation Calculations to Varying Proportions of Data from Impacted Sites

4.3.2.1 Study Approach

To assess and refine the NRV approach for surface water quality data, we tested the sensitivity of the TIF and M2MAD methods to inclusion of varying proportions of data from sites impacted by point-source pollution. To accomplish this, we sought a real-world water chemistry dataset that contained

long-term monitoring data for a site that is known to be impacted by point-source pollution and a second site that is clearly an appropriate reference site (i.e., unimpacted site). Our overall approach is illustrated in Figure 4.1 and detailed below.

We used these data to compare the performance of the TIF and M2MAD methods when calculating the NRV thresholds for: i) a dataset that contains only data from the unimpacted site; and, ii) datasets that contain known proportions of data from both unimpacted and impacted sites. We refer to thresholds calculated using only data from the unimpacted site as “*baseline NRV thresholds*”, whereas we refer to thresholds calculated for datasets that included both unimpacted and impacted data as “*impacted NRV thresholds*.”

We used the baseline NRV thresholds to understand if either the TIF or M2MAD method perform better in differentiating impacted from unimpacted samples when thresholds are calculated using only data from reference sites. After calculating both the TIF and M2MAD NRV thresholds, we inspected the unimpacted site data to determine how many samples exceeded each threshold. We then evaluated the relative risk of Type I errors for each NRV method by calculating how often unimpacted samples (true negatives) were correctly identified (versus incorrectly identified as impacted [false positives]).

We used the impacted NRV thresholds to compare performance of TIF and M2MAD methods in differentiating impacted from unimpacted samples when thresholds are calculated for datasets that include varying proportions of data from an impacted site. We calculated impacted NRV thresholds for eight “percent impacted data” categories (10, 20, 25, 30, 35, 40, 45, and 50 percent). We evaluated the relative risk of Type II errors for each NRV method by calculating how often impacted samples (true positives) were correctly identified (versus incorrectly identified as unimpacted [false negatives]). We used the results to compare performance of the TIF and M2MAD methods in differentiating impacted from unimpacted samples in datasets that include various proportions of impacted data.

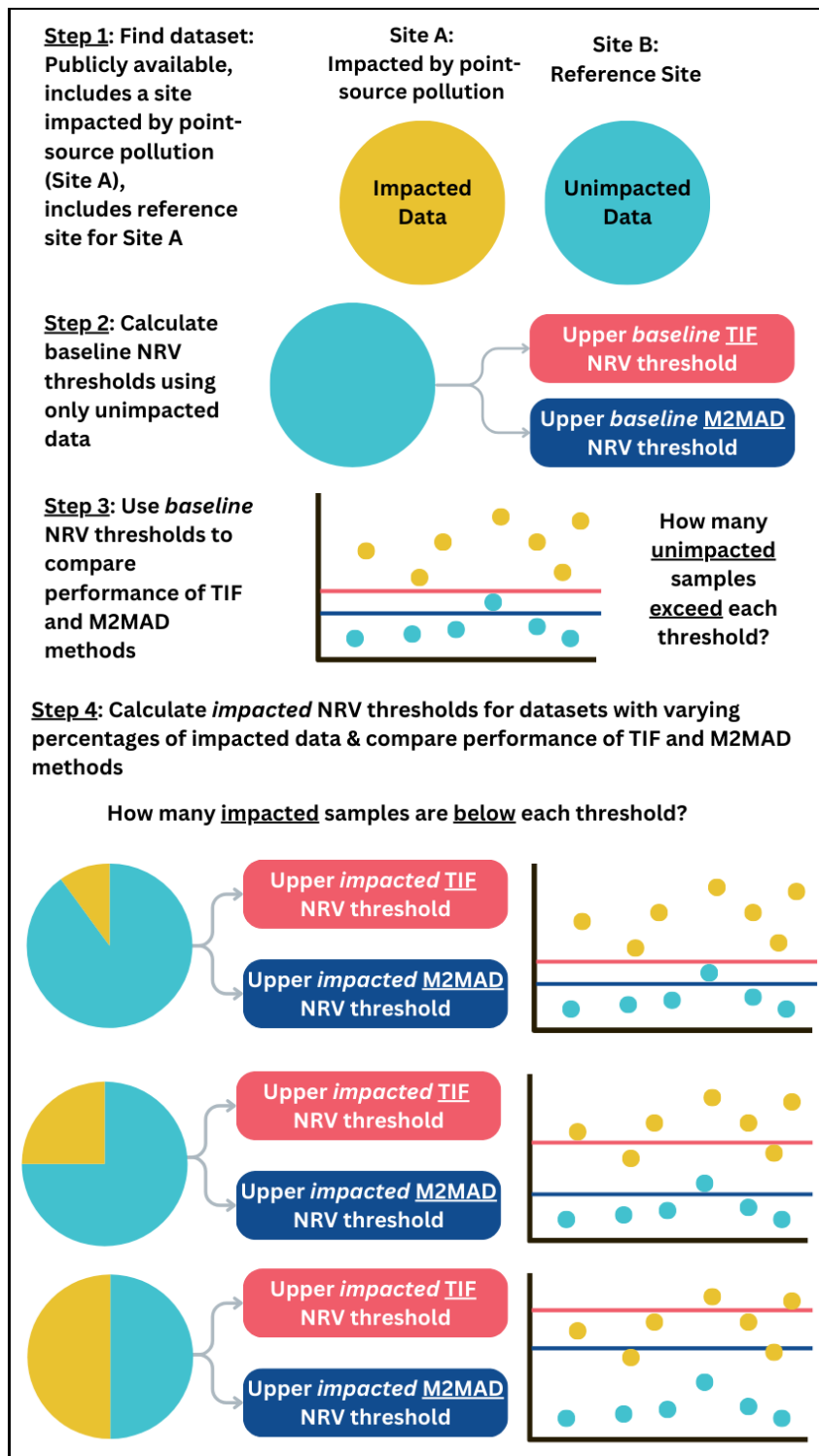


Figure 4.1. Approach to testing the impact of varying proportions of impacted data on the Tukey Inner Fence (TIF) and median ± 2 median absolute deviation (M2MAD) methods.

4.3.2.2 Study Area and Data Selection

We accessed an openly available surface water quality dataset for a gold mine from British Columbia's Environmental Monitoring System (EMS; British Columbia Environmental Monitoring System, 2023). The gold mine site is located 25 km north of Stewart, British Columbia, within the Nisga'a Nation Treaty Lands (Ascot Resources Ltd. [Ascot], 2024a, p. 1). The site has been periodically mined for gold since 1918, and the dataset contains surface water quality results of samples collected from 1994 to 2023 in support of monitoring the impacts of historical mine operations on surface water quality (Ascot, 2024a).

We selected data from two sites located on a creek (Cascade Creek) that runs through the gold mine site; one site is located upstream of the mine and represents surface water conditions that are unimpacted by mine activities, whereas the second site is located downstream of the mine operations and is a monitoring site that represents surface water conditions influenced by mine discharges (Boliden, 2016, p. 16). Detailed site maps are available in an annual water quality report, with the upstream and downstream sites labelled S-7 and S-27, respectively (Ascot, 2024b, Figure 1.1-1). Based on detailed previous reporting and the fact that the sites are located on the same watercourse, we were confident that the upstream reference site is an appropriate comparator for the monitoring site, and that these sites would be useful for assessing how each of the TIF and M2MAD NRV calculation methods perform with impacted and unimpacted surface water quality data. Further site and data selection details are available in Appendix C, Document C.1.

4.3.2.3 Natural Range of Variation Calculations With and Without Impacted Data

We first calculated *baseline NRV thresholds* for total metals parameters using each of the TIF and M2MAD methods with only the upstream site data (i.e., unimpacted data) for parameters with <50% censored values (i.e., values below the laboratory detection limit). We then calculated impacted NRV thresholds for total cadmium and zinc data, because they were known to be impacted by historical mine activities (Palmer, 2024, p. 27). We created datasets with varying proportions of impacted data by adding randomly selected downstream site samples (i.e., impacted samples) to the upstream dataset to achieve “percent impacted data” categories of 10, 20, 25, 30, 35, 40, 45, and 50 percent. Before creating these datasets, we removed any upstream samples that exceeded the *baseline upper NRV threshold* to avoid skewing results (one sample from each dataset was removed).

4.3.3 Natural Range of Variation Comparison to Contemporary Water Quality Assessment Methods

4.3.3.1 Study Approach

Our aim was to compare the sites identified as impacted by contemporary methods (i.e., methods currently being used) to sites identified as impacted by the NRV methods to demonstrate the real-world application and benefits of the NRV method. To accomplish this objective, we sought a real-world water chemistry dataset that contained long-term monitoring data for multiple reference (i.e., unimpacted) sites with statistically significant temporal trends for several parameters, as well as data from multiple sites exposed to point-source pollution from an industrial source. This dataset also had to be associated with an operational monitoring program with publicly available annual reports and impact assessment methods that were recently approved by a regulator; we thus avoided comparing our proposed NRV method to an approach already deemed out-dated. We use results to demonstrate how practitioners can use the proposed NRV method to detect and distinguish point-source impacts from cumulative effects in freshwater ecosystems. This methodological approach is illustrated in Figure 4.2.

4.3.3.2 Study Area and Data Selection

We combined datasets collected from two surface water quality monitoring programs in the Upper Coppermine Basin (UCB), Northwest Territories, Canada. The first dataset reflects sampling performed under the Aquatic Effects Monitoring Program (AEMP) for a diamond mine development. The second dataset reflects sampling conducted as part of the Government of Northwest Territories (GNWT) Water Management and Monitoring Division monitoring program (WMMD program). The UCB is one of the most important and least impacted watersheds in the Canadian Central Arctic, but is influenced by the cumulative effects of diamond mining and climate change (Stantec, 2015). We selected data from the UCB because statistically significant temporal trends in several water chemistry parameters from both impacted and unimpacted sites provided an opportunity for us to evaluate how NRV methods can be adapted to handle trends and assess cumulative effects from both point-source pollution and likely climate change. In addition, both unimpacted reference sites and sites impacted by mining activities are represented in publicly available datasets and are assessed annually in the publicly available diamond mine AEMP reports.

Data were collected as part of the AEMP and WMMD monitoring programs from 1998-2023 and 2000-2023, respectively. The publicly available AEMP dataset did not include historical baseline data collected from 1993 to 1997 (i.e., data collected prior to mine operations). Any reference to historical baseline data in this study thus refers to time series graphs presented in the 2023 AEMP report (ERM Consultants Canada Ltd [ERM], 2024). The publicly available AEMP dataset was also missing some data within the operational time period between 1998 and 2023 for specific sites and parameters, which are presented in Table C1.1 in Appendix C, Document C.1.

The combined AEMP and WMMD dataset contained data from four reference sites and ten potentially impacted sites (Figure 4.3). Potentially impacted sites included Kodiak, Grizzly, Leslie, Moose, Nema, and Slipper lakes, which are located within the Koala Watershed. The Koala Watershed contains most of the diamond mine's infrastructure (ERM, 2024a, p. 2-1). Kodiak and Grizzly lakes do not receive direct mining discharges, but are located close to mine infrastructure and may be impacted by roads and by an airstrip, emissions, and spills (Arctic Canadian Diamond Company [ACDC], 2023, p. 2-6 to 2-7). Kodiak Lake is also potentially influenced by weathering of a diversion channel and runoff from an ammonium nitrate building (ACDC, 2023, p. 2-7). Leslie Lake receives discharge from the Long Lake Containment Facility (LLCF), which contains processed kimberlite and other mine waste (ACDC, 2023). Nema Lake is influenced by seepage from the Fox Pit and Waste Rock Storage Area (ACDC, 2023, p. 2-7). Water flows sequentially through Leslie, Moose, Nema, and Slipper lakes. The Koala Watershed drains downstream of Slipper Lake into Lac de Gras, which directly receives mine discharge from a second diamond mine (Stantec, 2015). The potentially impacted sites S2 and S3 are located in Lac de Gras near the Koala Watershed inflow, and the LDG site is located at the Lac de Gras outlet. The potentially impacted site Destaffany Lake is located 58 km downstream of Lac de Gras (Deck, 2020; Figure 4.3).

Monitoring activities conducted as part of the AEMP result in publicly available annual reports that assess impacts of the mine on the aquatic environment. These reports include information on which monitoring sites are impacted by mine-related activities, and in what ways (ERM, 2024a, p. 1-1). While the AEMP has been monitoring the impacts of the diamond mine for over 20 years, its methods are re-evaluated and revised every three years (ERM, 2023, Table 1.1-1), with the most recent plan approved by the Wek'èezhii Land and Water Board (WLWB) in 2023 (WLWB, 2023). We used the most recent AEMP report that employed revised methodological approaches—the 2023

Annual Aquatic Effects Monitoring Program (ERM, 2024a), in our comparison of AEMP and NRV methods.

4.3.3.3 Comparing Natural Range of Variation and Aquatic Effects Monitoring Program Methods for a Mine Site

We used the AEMP (2023) and NRV methods to identify sites that were impacted by mine-related activities, and then we compared results between the two methods. Specifically, we compared conclusions regarding which sites were impacted by mine-related activities during the sampling year of 2023. Mine-related impacts were assessed separately for each parameter (e.g., arsenic concentrations could be identified as impacted by mine-related activities, whereas barium concentrations could be identified as unimpacted). We selected total arsenic, barium, nickel, and strontium as priority parameters to apply the NRV method to. For the NRV method, data were treated following the same methods described in the 2023 AEMP, including separating data into open-water and under-ice seasonal datasets. Detailed data preparation and treatment steps are described in Appendix C, Document C.1. It is important to note that the openly available dataset did not contain the complete AEMP data. Generally, the AEMP collected baseline data from 1993–1997; these data were unavailable in the open dataset. The AEMP did not include the baseline data in their regression analysis but did include them in the time series plots they visually assessed. Table C1.C in Appendix C, Document C.1 lists the sample years and seasons available for each site and parameter for this study and the AEMP.

4.3.3.3.1 Natural Range of Variation Methods

With the NRV method, we identified impacted sites as those with 2023 samples that exceeded the calculated upper NRV thresholds. We calculated seasonal (open-water and under-ice) NRV thresholds for each parameter using data from the four reference sites. We combined the data from the four reference sites into a single “pooled dataset” and calculated NRV thresholds for each of the pooled and individual reference site datasets; we selected the highest NRV threshold to perform the most conservative assessment of which sites were impacted to avoid unnecessary differences between the NRV and AEMP results. The TIF method was selected for each parameter based on a decision matrix that we established using results of the tests described in 4.3.2; the decision matrix is presented in Appendix C, Document C.1, Figure C1.1. If concentrations from 2023 data exceeded either the under-ice or open-water NRV thresholds, sites were then identified as “impacted.”

Inferences regarding whether or not sites were impacted by mine-related activities were supported by temporal trend analysis and spatial assessment of regional parameter concentrations. We first performed a non-parametric monotonic temporal trend analysis on each parameter of interest. Mann-Kendall tests were used, and considered statistically significant when $p < 0.05$. The Mann-Kendall test was performed in RStudio version 2023.06.1+524 (RStudio Team, 2023) using the `mk.test` function within the “Kendall” package version 2.2.1 (McLeod, 2022). Mann-Kendall tests were performed on annual median values for each parameter separately for each sampling season (i.e., open-water vs under-ice). The data were collected during the open-water and under-ice seasons from 1998–2023 and 2003–2023, respectively. The magnitude of each significant trend was determined with the Sen’s slope calculated in RStudio using the `sens.slope` function within the “trend” package version 1.1.6 (Pohlert, 2023). The magnitudes of temporal trends were compared across impacted and reference sites to determine if trends were likely mine-related or caused by ambient conditions.

A spatial assessment of regional parameter concentrations was also used to support inferences related to effects of mining activities. We compared parameter concentrations across sites to determine if there were concentration gradients downstream from mine activities that would indicate a mine-related impact. Since the NRV dataset contained monitoring site data from both the diamond mine’s AEMP and the GNWT’s WMMD program, the spatial assessment covered a broader regional spatial scale than the AEMP alone.

4.3.3.3.2 Aquatic Effects Monitoring Program Methods

The AEMP used regression models to identify sites that may be impacted by mine-related activities (ERM, 2024a, p. 2-8). Regression analysis is one of the most commonly used statistical tools for water quality assessments (Schreiber et al., 2022), including Environmental Effects Monitoring (EEM) programs that assess impacts of metal mines on aquatic environments (Environment Canada, 2012). In EEM, regression analysis is used to detect differences in fish size and gonad weight at reference versus exposed sites (Environment Canada, 2012). Multi-level regression models, such as Linear Mixed Effects models, are increasingly used to address known deficiencies in simple linear regression techniques when applied to environmental data (Schreiber et al., 2022). The AEMP used one of these more contemporary multi-level regression models—Linear Mixed Effects—to detect differences in water quality parameter concentrations over time at each of the potentially impacted

sites compared to the reference sites (ERM, 2024b, p. 1-1). Essentially, this method simultaneously models multiple sites and formally tests for differences in patterns between those sites. Baseline data collected prior to mine construction and operations were excluded from the regression models (ERM, 2024b, p. 1-2). Statistically significant differences in changes over time in the potentially impacted sites relative to the reference sites indicated a possible change related to mine activities (ERM, 2024b, p. 1-6).

AEMP practitioners supported their conclusions of whether or not sites were impacted by mine-related activities with visual graphical analysis of time-series plots of parameter concentrations at the potentially impacted and reference sites (ERM, 2024b, p. 1-1). Professional judgement of the practitioners hired by the industrial proponent continues to be a common method used to inform impact predictions and conclusions in environmental assessments (Hodgson et al., 2019; Mehdic et al., 2020; Zang et al., 2018).

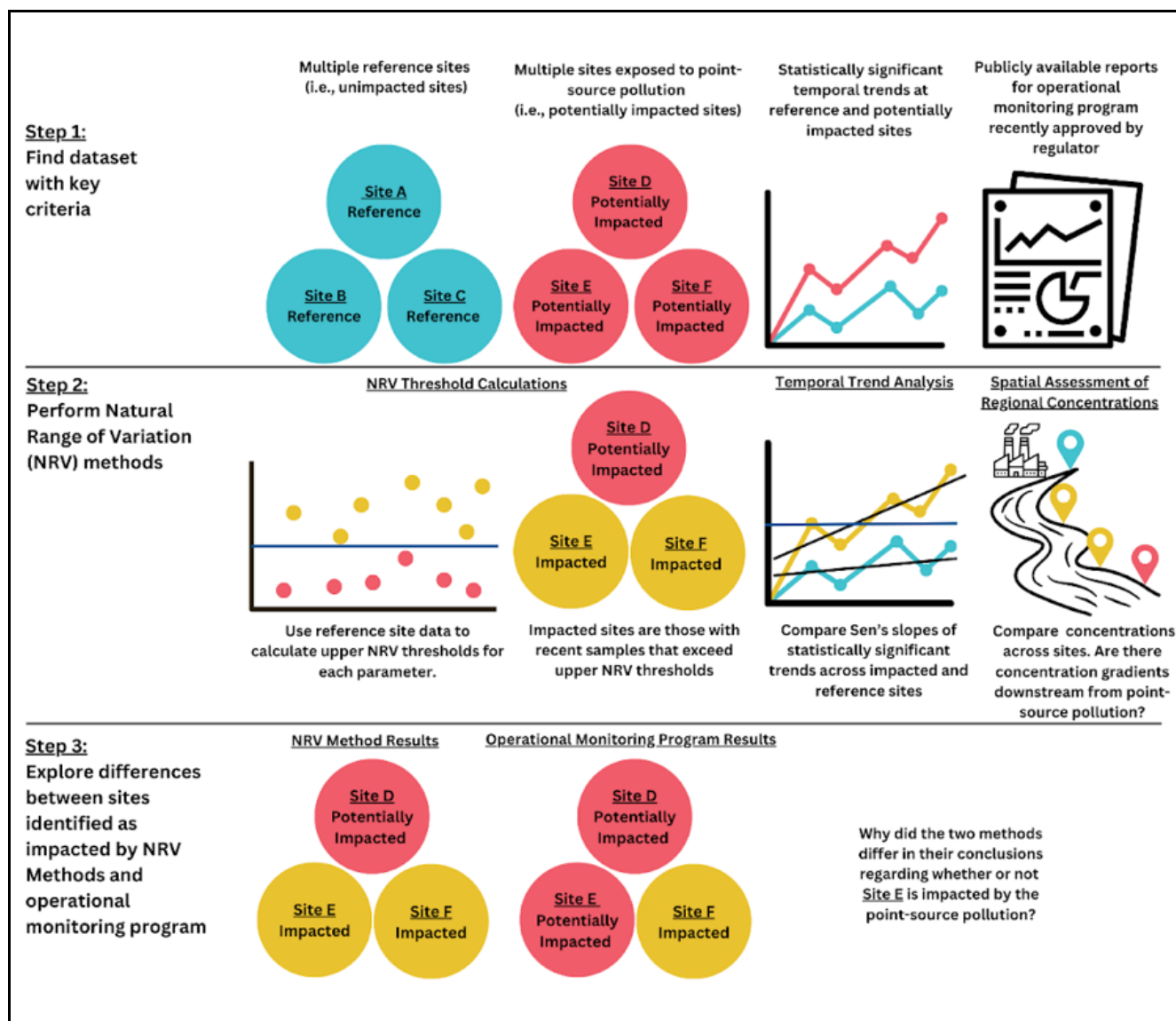


Figure 4.2. Approach to comparing the Natural Range of Variation (NRV) and a mine's Aquatic Effects Monitoring Program (AEMP) methods.

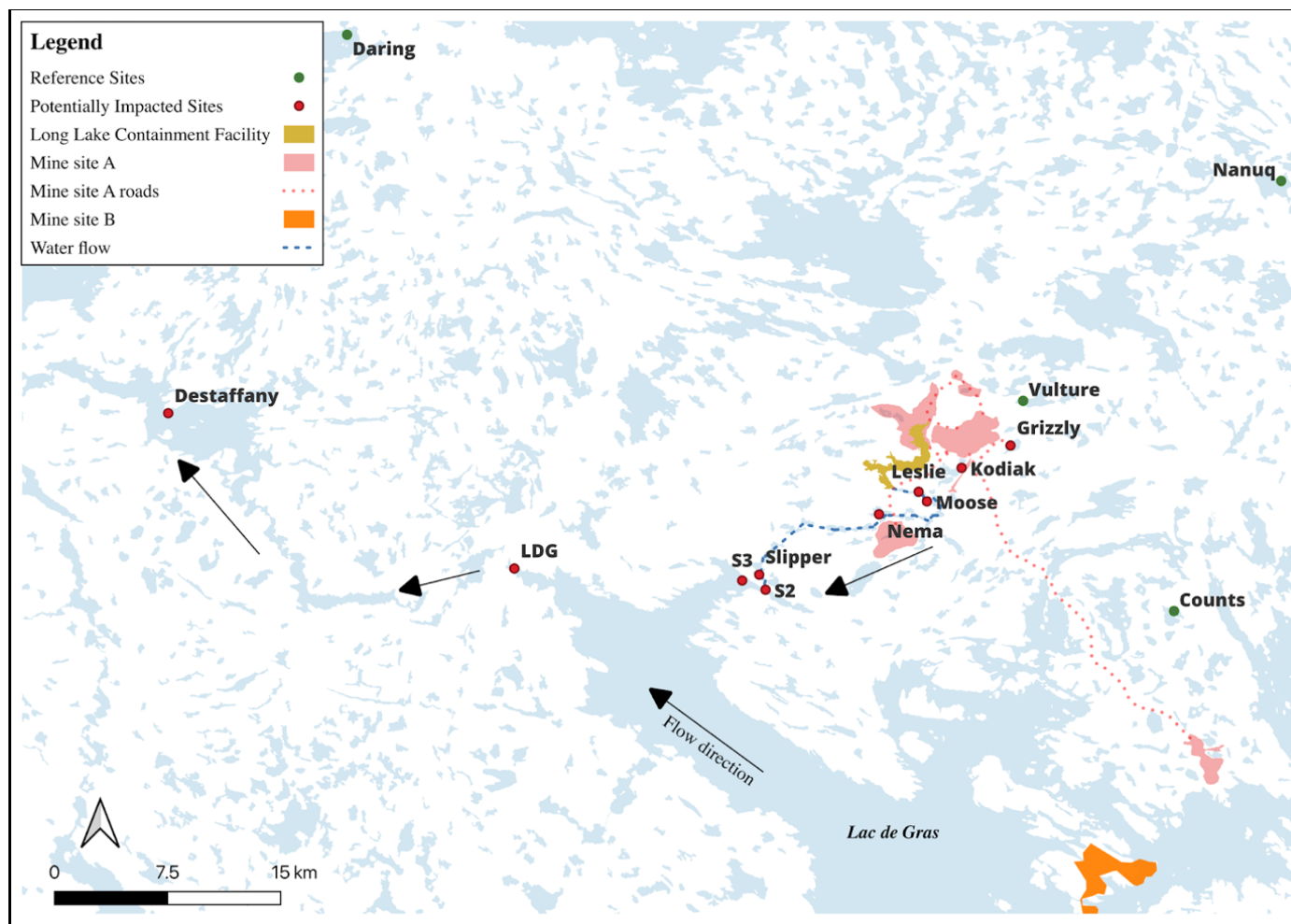


Figure 4.3. Mine sites A and B (site A is the mine site with the Aquatic Effects Monitoring Program used in this study) and the Upper Coppermine Basin surface water quality sampling sites. Mine sites are approximations only. Map created using QGIS version 3.32 (QGIS Development Team, 2025), lake boundaries are from HydroSHEDS (2016).

4.4 Results and Discussion

4.4.1 Testing the Sensitivity of Natural Range of Variation Methods to Varying Proportions of Impacted Data

4.4.1.1 Calculating Natural Range of Variation Without Impacted Data

The calculated upper *baseline NRV thresholds* for each parameter are listed in Table 4.1. Similar to previous studies that compared NRV calculation methods (e.g., Gao et al., 2022; Mikkonen et al., 2017; Reimann & de Caritat, 2017; Rothwell & Cooke, 2015), we found that the M2MAD method was more conservative than the TIF method. As a result, the TIF thresholds resulted in fewer upstream (i.e., reference) samples being misidentified as coming from impacted sites compared to the M2MAD thresholds. This was true for all parameters except zinc. That is, with the exception of zinc, thresholds calculated using the TIF method had a lower Type I error rate than thresholds calculated using the M2MAD method. The difference between zinc and the other parameters was that there was a high percentage of censored data (45%) for zinc. We thus infer that the TIF method is the more appropriate method when censored data comprise less than 25% of the dataset, because the TIF calculation is not influenced by data below the 25th percentile—if censored data with detection limits that exceed measured values are removed. However, even with the higher percentage of censored values, the TIF method misidentified the same number of upstream samples as impacted as the M2MAD method. Therefore, to minimize Type I errors, we recommend the TIF method when calculating the NRV using only reference site data. The NRV thresholds should not be calculated at all when 50% or more of the dataset consists of censored data.

Table 4.1. Comparison of the *baseline upper NRV thresholds* calculated using Tukey Inner Fence (TIF) and median ± 2 median absolute deviation (M2MAD) methods. Data represent sites located upstream (unimpacted) of a mine site on Cascade Creek, BC. Percentages of upstream samples misidentified as impacted are shown, as well as sample size, percentage of censored data, and percentage of outliers for each total metals parameter (P).

P	Sample Size	Censored (%)	Outliers (%)	TIF		M2MAD	
				Upper Threshold ($\mu\text{g/L}$)	%Upstream Impacted	Upper Threshold ($\mu\text{g/L}$)	%Upstream Impacted
Al	34	0	3	127.2	0%	55.5	3%
As	34	0	0	0.24	0%	0.21	6%
Ba	34	0	9	62.9	3%	56.9	9%
Cd	53	0	2	0.0412	2%	0.0329	11%
Pb	53	23	7	0.229	4%	0.155	15%
Mn	34	0	6	9.56	3%	4.01	8%
Mo	34	0	0	0.412	0%	0.326	3%
Se	23	4	9	0.112	4%	0.098	4%
Si	34	0	3	1264	0%	1134	6%
Sr	34	0	9	204	3%	186	21%
U	34	0	0	0.077	0%	0.057	6%
Zn	53	45	2	6.3	2%	6.3	2%

4.4.1.2 Calculating Natural Range of Variation with Varying Proportions of Impacted Data

The calculated *impacted NRV thresholds* for each category of “percent impacted sites” for cadmium and zinc data are listed in Table 4.2. The TIF thresholds resulted in downstream samples being misidentified as unimpacted when the datasets contained at least 25% impacted samples (Table 4.2). The M2MAD thresholds resulted in all downstream samples being successfully identified as impacted until the datasets contained 50% impacted data. Similarly, Mikkonen et al. (2017) found that the TIF method was adequate when datasets contained less than 25% impacted data. To minimize Type II errors, we recommend the M2MAD method when datasets may contain data from impacted sites or when practitioners have insufficient information to identify reference sites. Mikkonen et al. (2017) also concluded that when a dataset contains an unknown percentage of impacted data, the conservative M2MAD method is more appropriate.

Our recommendation for when to use the TIF or M2MAD methods diverges from Reimann et al. (2005), who suggested selecting either the TIF or M2MAD method based on the percentage of outliers. Reimann et al. (2005) recommended the TIF method when outliers comprised up to 15% of

the dataset and the M2MAD method for datasets that contained greater than 15% outliers. We found that the percentage of outliers decreased as we added more impacted data (Table 4.2), and thus, the percentage of outliers is not a good indicator of the percentage of impacted data in the dataset.

Table 4.2. Comparison of *impacted upper NRV thresholds* calculated using Tukey Inner Fence (TIF) and median ± 2 median absolute deviation (M2MAD) methods. Data represent sites located downstream (impacted) of a mine site on Cascade Creek, BC. NRV thresholds were calculated using upstream Cascade Creek data (unimpacted data) with varying percentages of downstream Cascade Creek data. Percentages of downstream samples misidentified as unimpacted are shown, as well as sample size, percentage of censored data, and percentage of outliers for total cadmium and zinc. The number in brackets of sample size is the number of samples from the impacted dataset.

% Impacted Dataset	Sample Size	Censored (%)	Outliers (%)	TIF		M2MAD	
				Upper Threshold (µg/L)	%Downstream Unimpacted	Upper Threshold (µg/L)	%Downstream Unimpacted
Cadmium, total							
10%	58 (6)	0	0	0.0456	0%	0.0351	0%
20%	65 (13)	0	20	0.0545	0%	0.0377	0%
25%	70 (18)	0	16	0.3487	39%	0.0417	0%
30%	75 (23)	0	8	0.5212	74%	0.0440	0%
35%	80 (28)	0	4	0.6753	89%	0.0475	0%
40%	87 (35)	0	2	0.8322	94%	0.0550	0%
45%	95 (43)	0	0	0.9653	100%	0.0650	0%
50%	104 (52)	0	0	0.9418	100%	0.1673	6%
Zinc, total							
10%	58 (6)	41	10	7.4	0%	6.6	0%
20%	65 (13)	37	20	9.3	0%	6.9	0%
25%	70 (18)	34	17	35.8	28%	7.2	0%
30%	75 (23)	32	3	72.8	91%	7.2	0%
35%	80 (28)	30	0	84.7	100%	7.2	0%
40%	87 (35)	28	0	97.4	100%	8.7	0%
45%	95 (43)	25	0	93.8	100%	10.8	0%
50%	104 (52)	23	0	100.5	100%	30.9	25%

4.4.2 Natural Range of Variation Comparison to Contemporary Water Quality Assessment Methods

While results from both the NRV and AEMP methods generally supported similar inferences regarding which sites were impacted by mine-related activities, for each parameter there were discrepancies in site assessments based on data from at least one season (i.e., ice-covered vs open-water; Table 4.3). The evidence used to support all of the conclusions of the NRV method, including seasonal 2023 sample concentrations, upper NRV thresholds, and Sen's slopes for each parameter with a statistically significant temporal trend are summarised in Table 4.4, and the detailed results are available in Appendix C, Tables C.1 to C.4). The evidence and inferences used to support each impact conclusion that differed between the two methods are summarized in Table 4.5. The implications of these differences between the two methods and how they may influence different management actions and decision-making are discussed below.

Table 4.3. Comparison of impact conclusions between Natural Range of Variation (NRV) and Aquatic Effects Monitoring Program (AEMP, ERM, 2024a) methods for mine-related impacts. Impact assessments were based on 2023 concentrations of total arsenic, barium, nickel, and strontium during under-ice and open-water seasons. Discrepancies between methods are highlighted in bold and red text. While both methods generally reached consistent conclusions (unimpacted [U] or impacted [I]), discrepancies occurred for at least one season for all parameters examined.

Site	Season	Parameter/Method							
		Arsenic		Barium		Nickel		Strontium	
		NRV	AEMP	NRV	AEMP	NRV	AEMP	NRV	AEMP
Kodiak	Ice	U	U	I	U	I	I	I	I
	Open	U	U	I	U	I	U	I	I
Grizzly	Ice	U	U	I	U	U	U	U	U
	Open	U	U	I	U	I	U	I	U
Leslie	Ice	I	I	I	I	I	I	I	I
	Open	I	I	I	I	I	I	I	I
Moose	Ice	U	I	I	I	I	I	I	I
	Open	I	I	I	I	I	I	I	I
Nema	Ice	U	I	I	I	I	I	I	I
	Open	I	I	I	I	I	I	I	I
Slipper	Ice	U	I	I	I	I	I	I	I
	Open	I	I	I	I	I	U	I	I
S2	Ice	U	U	U	U	U	U	I	I
	Open	U	U	U	U	U	U	I	I
S3	Ice	U	U	U	U	U	U	I	I
	Open	U	U	U	U	U	U	I	I

Table 4.4. Seasonal 2023 sample results (µg/L) and Sen's slope of statistically significant (P<0.05) temporal trends of total arsenic, barium, nickel, and strontium from the Upper Coppermine Basin sites during mine operations (1998–2023). These results were used as evidence to determine impact conclusions in the Natural Range of Variation (NRV) method for identifying mine-related impacts. Bolded values are concentrations that exceed the calculated upper NRV threshold. For the Sen's Slope, positive values are increasing trends and negative values are decreasing trends, and no value indicates no statistically significant trend.

Parameter	Under-ice / Open-water Season							
	Arsenic		Barium		Nickel		Strontium	
	Result	Sen's Slope	Result	Sen's Slope	Result	Sen's Slope	Result	Sen's Slope
<i>Reference Sites</i>								
Daring	0.30 / 0.10	- / -	3.00 / 1.10	- / -	0.4000 / 0.2000	- / -	12.3 / 6.0*	- / +0.071
Counts	0.20 / 0.31	+0.003 / +0.002	2.51 / 1.02	- / -	0.4415 / 0.2823	- / +0.006	6.9 / 5.4	+0.066 / +0.052
Nanuq	0.21 / 0.11	- / -	2.43 / 1.42	+0.028 / -	0.3503 / 0.1928	+0.009 / -	5.9 / 5.7	+0.085 / +0.059
Vulture	0.12 / 0.15	- / -	2.43 / 2.24	- / -	0.3650 / 0.3783	+0.004 / +0.005	5.6 / 5.4	- / +0.034
<i>Potentially Impacted Sites</i>								
Grizzly	0.10 / 0.12	- / -	3.94 / 3.85	-0.097 / -0.036	0.8018 / 0.8595	-0.015 / -	7.9 / 7.4	- / +0.018
Kodiak	0.23 / 0.31	- / +0.003	23.45 / 10.06	+0.275 / -	4.2350 / 2.3450	- / +0.031	56.5 / 28.8	+1.058 / +0.452
Leslie	0.49 / 0.41	- / -	107.00 / 55.63	- / -	5.8200 / 2.9750	- / +0.142	1405.0 / 713.8	+58.650 / +33.172
Moose	0.29 / 0.40	-0.011 / -	37.53 / 23.32	- / -	3.1750 / 2.0067	- / +0.130	289.5 / 212.5	- / +22.083
Nema	0.32 / 0.35	- / +0.004	63.70 / 18.55	- / -	2.8750 / 1.2050	- / +0.044	545.5 / 209.3	+29.750 / +12.568
Slipper	0.37 / 0.52	+0.006 / +0.010	23.30 / 13.15	+1.020 / +0.534	1.2700 / 0.8100	+0.036 / +0.020	214.5 / 120.5	+14.206 / +6.410
S2	0.27 / 0.22	- / -	2.70 / 2.48	- / -	1.4050 / 0.8950	- / -	21.4 / 23.3	+0.918 / +1.619
S3	0.25 / 0.22	- / +0.002	2.88 / 2.12	+0.039 / -	1.2300 / 1.0400	- / -	27.0 / 19.5	+1.025 / +0.821
LDG	0.20 / 0.15 ^a	- / -	2.90 / 2.05 ^a	+0.075 / +0.038	1.2000 / 1.0000	- / -	19.6 / 17.0*	+0.784 / +0.588
Destaffany	0.20 / 0.25 ^a	- / +0.005	2.40 / 1.75 ^a	+0.042 / -	1.0000 / 0.7000*	- / -	17.1 / 13.2*	+0.625 / +0.367

^a Value is the average of two samples.

Table 4.5. Findings for sites at which Natural Range of Variation (NRV) and Aquatic Effects Monitoring Program (AEMP; ERM, 2024a) methods reached different conclusions about mine-related impacts in 2023. The table presents the evidence that led to divergent conclusions of impacted (I) versus unimpacted (U) sites, including: NRV threshold exceedances (TE [Yes: 2023 concentrations exceeded upper NRV threshold, No: 2023 concentration below upper NRV threshold]), trend analysis results, spatial assessment findings, regression analysis (R [Yes: statistically significant result, No: result not statistically significant]), and graphical analysis interpretations. Data are organized by site, seasons (S[Ice: under-ice, Open: open-water]), and parameter (P). Abbreviations: ref site = reference site, impact site = potentially impacted site, US = upstream, DS = downstream.

Site	S	P	NRV Method				AEMP Method		
			C	TE ^b	Trend Analysis	Spatial Assessment	C	R ^c	Graphical Analysis
Kodiak	Ice	Ba	I	Yes	Increasing, steeper than ref sites	No spatial findings	U	No	Variable, no consistent trend
	Open	Ba	I	Yes	None detected	No spatial findings	U	Yes	Variable, no consistent trend; 2023 sample 23% higher than historical baseline, but similar past increases returned to historical values
	Open	Ni	I	Yes	Increasing, steeper than ref sites	No spatial findings	U	No	Stable and similar to historical values
Grizzly	Ice	Ba	I	Yes	Decreasing, recovering from historical impact	No spatial findings	U	No	Low and stable
	Open	Ba	I	Yes	Decreasing, recovering from historical impact	No spatial findings	U	No	Low and stable
	Open	Ni	I	Yes	None detected	No spatial findings	U	No	No spatial analysis
	Open	Sr	I	Yes	Increasing, similar to ref sites	No spatial findings	U	No	No spatial analysis
Moose	Ice	As	U	No	Decreasing, recovery from historical impact	No DS gradient from Leslie to Slipper	I	Yes	Recent stabilization/decrease, but above historical values; DS gradient from Leslie to Slipper
Nema	Ice	As	U	No	None detected	No DS gradient from Leslie to Slipper	I	Yes	Recent stabilization/decrease, but above historical values; DS gradient from Leslie to Slipper
Slipper	Ice	As	U	No	Increasing, steeper than ref site	No DS gradient from Leslie to Slipper	I	Yes	Recent stabilization/decrease, but above historical values; DS gradient from Leslie to Slipper
	Open	Ni	I	Yes	Increasing, steeper than ref sites, similar to US impact sites	DS gradient from Leslie to Slipper	U	Yes	Elevated relative to historical baseline, but trend similar to ref sites

4.4.2.1 Assessing Current Impacts for Sites That Were Previously Impacted

The objective of the two methods is to identify sites that are currently impacted, which for our study was sites that were impacted during 2023. Compared to the regression analysis used for the AEMP, the NRV thresholds more effectively identified current impacts at sites that were previously impacted but have since returned to baseline conditions. The regression model compares changes in parameter concentrations over time at each potentially impacted site to changes at the reference sites (ERM, 2024b, p.1-6). While this type of analysis is useful for comparisons of conditions at potentially impacted and reference sites over an entire long-term monitoring period, it is not appropriate for assessments of current conditions. Sites that experience impacts during the monitoring period will have slopes that diverge from the reference sites and consequently, the regression analysis will yield a significant result even if recent samples have returned to baseline levels. In contrast, the NRV method compares current samples to thresholds that are calculated using only reference site data—so, the assessment of current impacts is not influenced by historical conditions at potentially impacted sites.

The difference in how these two methods handle historical impacts is demonstrated in the assessment of under-ice arsenic concentrations. The regression analysis detected significant changes in under-ice arsenic concentrations relative to reference sites at Leslie, Moose, and Nema lakes, indicating mine-related impacts (ERM, 2024a, p. 3-85). However, inferences based on results from the NRV threshold calculation indicate that only Leslie Lake was impacted; 2023 concentrations at Moose and Nema were within the NRV thresholds (Table 4.5). Inspection of the time series plot of under-ice arsenic concentrations (Figure 4.4) at Moose and Nema lakes revealed that concentrations were periodically elevated above the NRV between 2005–2021 and 2013–2015, respectively. These previous NRV threshold exceedances indicate a historical mine-related impact that was not sustained at either Moose or Nema but persists at Leslie. Thus, we infer that the NRV method may allow decision-makers to focus on currently impacted sites and to confirm when mitigative measures for previous impacts have been successful.

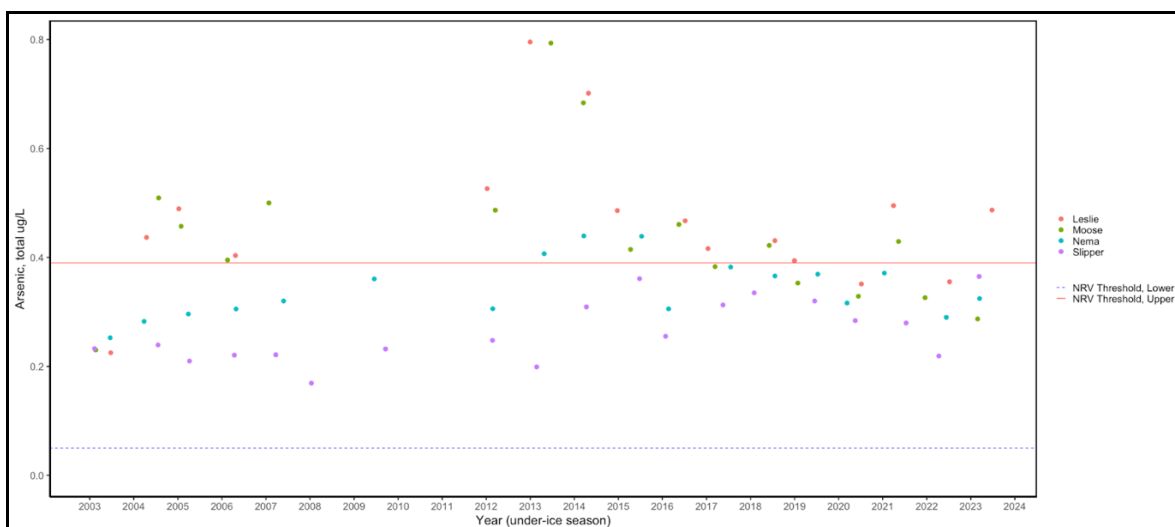


Figure 4.4. Time series plot of under-ice total arsenic concentrations at the potentially impacted sites Leslie, Moose, Nema, and Slipper lakes with the upper and lower NRV thresholds calculated using the TIF method on log-transformed data. Plot shows concentrations at Moose and Nema lakes were periodically elevated above the NRV, indicating historical mine-related impacts that were not sustained, and 2023 concentrations at Slipper Lake were higher than further upstream lakes Nema and Moose, indicating typical influence from Long Lake Containment Facility discharge into Leslie Lake is not impacting further downstream lakes. Plots created in R using ggplot2 package (Wickham, 2016).

4.4.2.2 Temporal Trend Detection

The monotonic Mann-Kendall trend analysis, which was used to support the NRV threshold calculations, detected more temporal trends in parameter concentrations compared to the regression models and visual graphical analysis of time series plots that supported the conclusion of the AEMP (Table 4.5). It is important to note that the dataset we had access to for the Mann-Kendall trend analysis was not the complete AEMP dataset and was missing data for certain years depending on the season and parameter (Table C1.1 in Appendix C.1, Document C.1). However, Mann-Kendall trend analysis performs well and can be used to detect trends when some data are missing (Kamal & Pachauri, 2018).

The ability to detect trends is critical for practitioners to know when sites are either returning to baseline concentrations (e.g., decreasing trend, indicating mitigative measures are working) or are continuing to diverge away from baseline concentrations and thus require mitigative measures to prevent concentrations reaching a threshold that could seriously damage the aquatic ecosystem. Parametric regression analysis is less appropriate than a non-parametric analysis, such as Mann-Kendall, for assessing changes in water quality parameters over time, because parametric regression is impaired by outliers and skewness that are common in water quality datasets (Helsel et al., 2020, p. 270). As a result, the regression slope is less likely to be significantly different, and thus less likely to

indicate a trend has occurred, even when the Mann-Kendall trend analysis produces a strong significant difference (Helsel et al., 2020, p. 275). Visual assessments of graphically presented time series data, such as those used in the AEMP, are subjective, and practitioners may miss subtle but informative trends. Therefore, the non-parametric Mann-Kendall trend analysis is superior to parametric methods and subjective visual analysis in detecting temporal trends that help practitioners identify sites that are either diverging from or returning to baseline conditions.

The Sen's slope calculated for temporal trends that were significant according to the Mann-Kendall results, provide a quantitative assessment of the magnitude of trends, which visual assessments can miss or struggle to accurately describe (Tables 4.4 and 4.5). As climate change intensifies, ambient conditions will increasingly change, making it important to not only be able to detect temporal trends but also compare their magnitudes between potentially impacted and reference sites. An example of this is described below.

An assessment of nickel concentrations during the open-water season illustrates how Mann-Kendall trend analysis combined with the Sen's slope calculation differ in detecting and evaluating temporal trends from the regression analysis supported by the visual graphical analysis. The results of the parametric regression analysis of time series data at Kodiak Lake relative to the reference sites were insignificant, indicating that conditions at Kodiak Lake were similar to all reference sites. Visual graphical analysis supported the conclusions of the regression analysis, and it was reported that concentrations of nickel during the open-water season at Kodiak Lake were stable. However, the Mann-Kendall trend analysis indicated a significant increasing trend at Kodiak Lake in nickel concentrations, which, according to the Sen's slope, was an order of magnitude steeper than the trends detected at the reference sites Counts Lake and Vulture Lake (Table 4.4); no trend was detected at the other reference sites. Also, although the parametric regression analysis did yield a significant result for open-water nickel concentrations at Slipper Lake, authors of the AEMP assessment concluded that there were no mine-related impacts because the visual graphical analysis indicated the increasing trend to be similar to trends observed at the reference sites. While the Mann-Kendall trend analysis also detected significant increasing trends at the reference sites, the Sen's slope of the trend at Slipper Lake was an order of magnitude higher than the trends at the two reference sites, indicating mine-related impacts were exerting additional influence on nickel concentrations at Slipper Lake (Table 4.4). As climate change progresses, trends at reference sites are expected to become more prevalent. Therefore, surface water quality assessment methods must be able to

differentiate between trends representing ambient conditions and those representing cumulative effects of climate change and point-source pollution.

4.4.2.3 Objective Versus Subjective Methods

The NRV methods—which included NRV threshold calculations, non-parametric trend analysis, and spatial assessment of regional concentrations—were generally more objective than the professional judgement used to visually assess time series plots and interpret results for the AEMP to conclude which sites were impacted by mine-related activities. Objective methods should lead to conclusions that are more reproducible and repeatable among practitioners. Although environmental assessments are meant to be objective, many researchers have identified how the subjectivity of professional judgement often shapes impact assessment conclusions and can lead to differences among practitioners (Mehdic et al., 2020). There is still a need for further research into the consequences of this subjectivity to support changes in environmental assessment (Mehdic et al., 2020; Zang et al., 2018).

The NRV threshold calculation is a quantitative estimate of the range of baseline values, which reduces the potential for different practitioners to reach varying conclusions about which sites are impacted based on parameter concentrations that exceed baseline values (i.e., thresholds provide a clear “yes” or “no” as to whether or not a value is within baseline values). In contrast, the AEMP used professional judgement to determine when concentrations were similar enough to baseline values. Several AEMP conclusions, including those for under-ice arsenic concentrations at Moose and Nema lakes, and open-water nickel concentrations at Slipper Lake, were based on the professional’s visual assessment of time series plots to assess whether concentrations were similar to historical baseline values (Table 4.5). The quantitative and objective NRV method should be more acceptable to stakeholders than subjective contemporary methods for setting surface water quality thresholds that are meant to indicate changes outside the natural range of variation, and signal that a significant effect has occurred (Dubé et al., 2006; Dubé et al., 2013; Foley et al., 2017).

The AEMP’s graphical analysis used to support the AEMP conclusions was based on a practitioner’s visual assessment of time-series plots of data, which can be prone to error. For example, the graphical analysis concluded that under-ice arsenic concentrations decreased with distance downstream from the Long Lake Containment Facility (LLCF), leading to the interpretation that the LLCF discharge impacted sites downstream from Leslie to Slipper lakes (ERM, 2024a, p. 3-85).

However, the 2023 sample data revealed a different pattern: the highest concentration occurred at Leslie (furthest upstream), followed by Slipper (furthest downstream), then Nema (second furthest downstream; Table 4.4). Our findings offer evidence of the risk of errors when using subjective methods in environmental assessment.

The use of the regression and graphical analysis findings to support impact assessment conclusions of the AEMP was also subjective. The graphical analysis was used inconsistently to either support or refute regression analysis results. While the graphical analysis always supported regression results if they were insignificant (i.e., no impact), it was occasionally used to refute significant results (i.e., mine-related impact). For example, the regression analysis result was significant for open-water barium concentrations at Kodiak Lake, but the AEMP concluded no mine-related impact based on the graphical analysis finding that previously elevated concentrations returned to historical baseline values (Table 4.5). Other practitioners may conclude periodic elevated concentrations are actually evidence of mine-related impacts for a site like Kodiak that does not receive point-source discharges, and thus impacts would be expected to be sporadic and periodic.

The tools used to support the NRV threshold calculations, including non-parametric trend analysis and regional concentration comparisons, illuminated possible causes of observed impacted conditions (e.g., point-source pollution or cumulative effects), and possible issues in monitoring program design. For example, nickel concentrations at S2 and S3 (sites within Lac de Gras) exceeded upper NRV thresholds throughout the monitoring period for both seasons with no temporal trends, suggesting either consistent mine impacts or that the choice of reference sites was inappropriate (Table 4.4). It is impossible to be confident in either conclusion without access to historical baseline values. However, data from LDG, which is a site further downstream at the outflow of Lac de Gras, yielded valuable insights. Although S2 and S3 exceeded the NRV thresholds during both seasons, they were greater than or similar to concentrations at Slipper Lake (which is further upstream, closer to mine activities) during both seasons. In addition, open-water concentrations at S3 were similar to LDG and elevated above S2. If elevated nickel concentrations were caused by mine-related activities, we would expect a downstream spatial gradient with concentrations decreasing from Slipper Lake downstream to S2, then S3, and lowest at LDG. Since this spatial gradient is lacking, elevated nickel concentrations at S2 and S3 indicate Lac de Gras nickel concentrations are either naturally higher than those in the Koala Watershed and are increasing due to watershed-scale influences rather than mine impacts. Therefore, it is likely that the reference sites do not represent unimpacted nickel

concentrations in Lac de Gras, and that the diamond mine's influence on nickel concentrations did not extend into Lac de Gras. This finding is important to alert managers that the monitoring program needs to be updated with appropriate reference sites for S2 and S3 in order to have the capacity to detect mine-related impacts at those sites. Thus, NRV threshold exceedances always provide valuable information for practitioners, and support tools are not used to ignore threshold exceedances.

4.4.2.4 Importance of a Regional Spatial Scope

A broader regional spatial scope, such as the one used to support the NRV method in comparing concentrations at sites monitored by the mine to additional sites sampled further downstream by the GNWT, can support project-level impact assessments. The above example (Section 4.4.2.3) of nickel concentrations at S2 and S3 likely representing ambient conditions despite exceeding the NRV thresholds, is an example of how a wider regional spatial scope can provide useful evidence for impact assessments, especially when baseline data are lacking. The site LDG, which is sampled by the GNWT and located at the outflow of Lac de Gras, is useful for determining if elevated concentrations observed at S2 and S3 reflect naturally higher concentrations in Lac de Gras compared to the Koala watershed. In addition, data from LDG could be used to detect impacts from the second diamond mine that is located within Lac de Gras (Figure 4.3). These findings indicate that a regional assessment can support project-level impact assessment conclusions that elevated concentrations are not related to project activities but rather are the result of ambient conditions or other point-source pollution. As such, these findings support long-standing calls from the CEA literature to integrate project-level and watershed-scale assessments to understand cumulative effects (Chilima et al., 2013; Dubé, 2003; Lerner, 2018; Sheelanere et al., 2013). Collecting data at regional scales helps identify watershed-wide influences, and data collected at finer scales (i.e., project-level data) are needed to differentiate watershed-scale versus local impacts (Ball et al., 2013).

4.4.2.5 Importance of Appropriate Reference Sites

Applying the NRV method to the UCB regional dataset demonstrated how crucial appropriate reference sites are when using NRV thresholds to successfully identify impacted sites. The reference sites must accurately represent the natural variability of the potentially impacted sites being assessed, otherwise there is a risk that unimpacted sites will be misidentified as impacted. For example, open-water strontium concentrations at Grizzly Lake (potentially impacted site) were elevated above the upper NRV threshold, suggesting that it was impacted (Table 4.4). However, the trend analysis

provided some evidence that these concentrations may be naturally elevated, as the increasing trend detected at Grizzly was similar to trends detected at the reference sites. The 2023 AEMP provided historical baseline strontium concentrations at Grizzly (5-10 µg/L), which were higher than reference sites (<5 µg/L; ERM, 2024a, Figure 3.2-21b), indicating the reference sites did not represent unimpacted conditions at Grizzly Lake. Consequently, strontium concentrations at Grizzly Lake are likely to exceed upper NRV thresholds calculated using the reference site data even if the lake remains unimpacted by mine-related activities. The NRV baseline estimations are only as good as the data that are used to calculate it—if reference sites do not truly represent the natural variability of the potentially impacted sites being assessed, Type I errors can occur.

4.4.2.6 Natural Range of Variation and Cumulative Effects Assessment

The integration of multiple approaches in the NRV method—NRV thresholds, temporal trend analysis, and spatial assessment of regional concentrations—may be used to effectively distinguish among mine-related impacts, broader watershed-scale changes, and cumulative effects of both. As a project-level assessment, the AEMP did not aim to identify cumulative effects. However, even project-level assessments can benefit from knowledge of cumulative effects. Results of our analyses indicated that concentrations of arsenic, barium, nickel, and strontium were impacted by both mine-related activities in the Koala Watershed and regional increases across the UCB. Climate change may be causing permafrost thawing that is increasing concentrations of metals in the UCB water bodies (Lim et al., 2020; Stimmler et al., 2023; Thompson et al., 2021). With this knowledge, practitioners may conclude that the mine is not solely responsible for changes from historical baseline values in water quality parameters, and thus that historical baseline values may not be appropriate remediation targets. Instead, the NRV should be recalculated annually to determine what concentrations should be expected without the influence of the mine and despite the influence of climate change. This finding demonstrates the utility of the NRV method for cumulative effects assessment; practitioners can distinguish between regional climate change impacts and point-source pollution—an approach even project-level assessments could benefit from.

4.5 Conclusion

We refined and applied an approach for using the Natural Range of Variation (NRV) method to estimate baseline water quality conditions in surface waters. The NRV thresholds should ideally be calculated using only reference site data (i.e., sites known to be unimpacted by the impact of interest).

To minimize the risk of Type I errors, the TIF method should be used when the NRV is calculated using only data from reference sites. If there is uncertainty about which sites are reference sites, then the more conservative M2MAD method should be used to minimize the risk of Type II errors.

When applied to a regional dataset and paired with Mann-Kendall trend analysis, the NRV thresholds provide a robust approach for assessing cumulative effects in freshwater ecosystems. This quantitative approach enables practitioners to differentiate among sites impacted by point-source pollution, ambient conditions, and their combined effects. The NRV method remains effective when reference site data represent the natural variation at the assessed site, regardless of temporal trends and historical impacts. We suggest that the NRV method has applications for identifying sites impacted by cumulative effects, understanding project-level impacts, and setting appropriate remediation targets that account for changes in ambient conditions.

4.6 References

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Chapter 5

A Cumulative Effects Assessment Approach to Urban Water Body Restoration

Kidd, J. A., Courtenay, S. C., Annable, W., Epstein, G., Cott, P., Swanson, H. A Cumulative Effects Assessment approach to Urban Water Body Restoration. Prepared as a knowledge mobilization thesis chapter.

5.1 Abstract

Urban water bodies provide critically important ecosystem services with significant socio-economic benefits for high-density populations in areas where natural infrastructure can be sparse. These ecosystem services are, however, often impaired by complex influences of urban landscapes, and it is increasingly clear that the cumulative effects must be considered to successfully restore urban water bodies. Environmental managers, stewards and researchers have identified several criteria for success in urban water body restoration that closely resemble foundational elements of effective Cumulative Effects Assessments (CEAs), including transdisciplinary collaboration, meaningful community engagement, open data, long-term monitoring, regional spatial scope, a strategic approach, and sustainability assessment. We use here a case study of a conventional fish habitat restoration project for an urban lake (located in Yellowknife, Northwest Territories, Canada) that has been impacted by cumulative effects of urban development and historical mining activities. We illustrate how a CEA approach to the restoration of this lake could theoretically achieve sustainable outcomes. Our proposed CEA approach invites Indigenous people who are holders of Aboriginal and treaty rights (rights holders) and local residents to actively participate from inception, with project decisions made in collaboration with rights holders, stakeholders, and experts of multiple scientific disciplines. Project decision-making and monitoring occur at the watershed scale to understand both the cumulative effects impacting the water body and those created by its restoration. Monitoring data are collected over the long-term to capture natural variability and the water body's recovery. A strategic approach sets restoration objectives that align with environmental and socio-economic objectives for the watershed. The sustainability of candidate restoration measures is assessed to select the most cost-effective measure that will maximize the positive impacts of the project. Our proposed CEA approach to urban water body restoration should be further explored and validated to test our assumptions of its potential to yield more sustainable outcomes than conventional approaches. Ultimately, this study offers restoration practitioners and decision-makers ideas for consideration when developing more holistic approaches for urban water body restoration.

5.2 Introduction

In the context of amplifying cumulative effects of climate change and urbanization, effective restoration of urban water bodies (e.g., lakes, rivers, and wetlands) requires a new approach (Poikane et al., 2024). Urban water bodies are water bodies that are surrounded by an urban environment

(Persson, 2012). Urban environments tend to have a combination of residential dwellings, commercial operations, and infrastructure that exert a multitude of accumulating and interacting effects on nearby aquatic environments (Hychka & Druschke, 2017). Globally, scientists are calling for immediate action to address a lack of progress towards effective restoration as restoring degraded freshwater ecosystems and other critical natural infrastructure is a vitally important component of climate change mitigation and adaptation (Abell et al., 2022; Poikane et al., 2024; Tammeorg et al., 2023; United Nations Environment Programme [UNEP], 2022). Restoration researchers and practitioners are more frequently recognizing the need to consider cumulative effects as water bodies are rarely subjected to a single pressure (Dey et al., 2021; Hughes et al., 2014; Poikane et al., 2024). Cumulative effects are *“environmental changes caused by multiple interactions among human activities and natural processes that accumulate across space and time”* (Canadian Council of Ministers of the Environment [CCME], 2014). A limited understanding of the complex anthropogenic and natural pressures and their interacting effects (both spatially and temporally) can inhibit the success of restoration projects (Poikane et al., 2024). The cumulative effects—including those from environmental and socio-economic influences—that led to the degradation of a water body and could impede the success of the restoration project need to be understood to select appropriate restoration measures (Hughes et al., 2014; Hychka & Druschke, 2017; Poikane et al., 2024). As such, we explored if learnings from the study of Cumulative Effects Assessments (CEA) could be applied to improve restoration project success.

The CEA literature offers valuable insights for refining restoration approaches for urban water bodies that have been degraded by synergistic, cumulative effects. CEA is a decision support tool that helps inform sustainable development decision-making by evaluating past, present, and future interactions of multiple stressors, and by providing strategies that will manage and/or mitigate cumulative effects (Bristow et al., 2025; Chilima et al., 2013; Dubé et al., 2006; Duinker & Greig, 2006). During Impact Assessments, project-level CEA assesses the cumulative effects of a proposed project—along with other past, current, and proposed projects (Duinker & Greig, 2006; Foley et al., 2017; Lerner, 2018; Seitz et al., 2011). The less common, but more effective watershed-level CEA is a strategic assessment that assesses cumulative effects of existing or proposed plans, developments, land-use strategies, and management approaches at the scale of an entire watershed (Chilima et al., 2013; Johnson et al., 2011; Lerner, 2018). Watershed-level CEA is typically associated with

watershed planning and integrated watershed management (Dubé et al., 2006; Duinker & Greig, 2006; Johnson et al., 2011).

Not all CEAs are created equal, and decades of research have been conducted to define what constitutes an effective CEA (Arnold et al., 2022; Duinker & Greig, 2006; Foley et al., 2017; Jones, 2016). As CEA researchers who specialize in freshwater ecosystems, we observed that long-standing recommendations for CEA improvement were emerging in the restoration literature for freshwater environments. To our knowledge, however, no study has combined all of these recommendations into a comprehensive approach that can guide restoration efforts.

The potential for the application of a CEA approach to urban water body restoration became apparent while researching Frame Lake—an urban lake in Yellowknife, Northwest Territories that is impacted by the cumulative effects of urban development and historical mining. Restoration measures are currently underway in Frame Lake to meet the requirements of a conventional habitat offsetting project led by a mining company and regulated by Fisheries and Oceans Canada (DFO). The current Frame Lake restoration project involves installing a mechanical aerator to improve overwinter dissolved oxygen concentrations to make the lake once again suitable as fish habitat. However, it is unclear if the aerator is a sustainable solution and it will not necessarily address the arsenic contamination in the lake that prevents people from returning to the lake for water-based recreational activities.

Our study objective was to explore the potential of a CEA approach to urban water body restoration for achieving more sustainable outcomes than conventional approaches. This study does not present a definitive approach, but rather, offers a potential approach, illustrated by a case study, to initiate further discussion and research into more holistic approaches to freshwater ecosystem restoration. In this study, we use Frame Lake as a case study to demonstrate how our proposed CEA approach could theoretically achieve more sustainable outcomes than conventional restoration approaches. We first describe how we developed the CEA approach and then describe how it can be generally applied for urban water body restoration. We then present the Frame Lake case study, including background details of the lake, description of the current restoration project, and theoretical application of the CEA approach to expand restoration efforts for Frame Lake. Finally, we conclude with our proposed path forward for further development and application of the CEA approach.

5.3 Methods

5.3.1 Development of a Cumulative Effects Assessment Approach for Urban Water Body Restoration

In November 2022, a non-systematic review of the CEA literature was completed to prepare an essay in response to the PhD comprehensive examination question: *How can the practice of cumulative effects assessment (CEA) be improved in Canada to support contributions to sustainability through better understanding and decision-making affecting freshwater ecosystems?* This review included 56 sources from the CEA and Impact Assessment academic and grey literature. The result of the review was a summary of the high-level elements that are recommended for effective CEAs and applicable across all assessments (list of literature sources are available in Appendix D, External Resources D.1). These foundational elements are not specific methods for measuring and evaluating cumulative effects—which need to be defined on an assessment-specific basis—but rather are core attributes that any CEA must incorporate to be effective, regardless of context (Figure 5.1).

The foundational elements we identified for effective CEA include meaningful engagement (that goes beyond standard engagement practices) via creation of opportunities for community members—and particularly Indigenous peoples—to be actively involved from the beginning, and influence and inform decisions (Arnold et al., 2019; Pfeffer, 2022; Sinclair et al., 2017; Udofia et al., 2015). A collaborative, transdisciplinary process is needed that integrates different knowledge systems (including scientific, Indigenous, and local). Knowledge from Indigenous people who are holders of Aboriginal and treaty rights (rights holders), stakeholders, and subject matter experts from various disciplines are all needed to gain a holistic understanding of environmental and socio-economic conditions (Greig & Duinker, 2011; Jones, 2016). Effective CEA also requires long-term, regional monitoring data to accurately characterize baseline conditions, rather than the short-term, project footprint monitoring that is more commonly available and used (Arnold et al., 2019; Cronmiller & Noble, 2018; Dubé et al., 2013; Seitz et al., 2011). Monitoring data need to be openly accessible, so that project-level and watershed assessments can inform each other (Jones, 2016; Sheelanere et al., 2013). Long-term regional data are also required if practitioners of CEAs are to undertake a strategic approach that evaluates multiple scenarios and defines desirable future conditions (Johnson et al., 2011; Noble, 2008). Strategic approaches must be accompanied by a sustainability-based decision-making process that considers biophysical and socio-economic effects

to avoid, minimize, restore, and offset unsustainable outcomes, and to achieve net environmental gains for those who will be most affected by the resource management decisions (Gibson, 2006; Gibson et al., 2020; Jones, 2016). While this list of foundational elements is well supported in the CEA literature, it is not an exhaustive list because our search and synthesis of the literature was not systematic and we could have missed other important elements.

While reviewing the freshwater ecosystem restoration literature for the Frame Lake study, we noted that some restoration scholars have independently identified similar elements as necessary for effective freshwater ecosystem restoration. These elements include meaningful community engagement (e.g., Pradhananga et al., 2019), transdisciplinary collaboration (e.g., Hychka & Druschke, 2017), long-term monitoring (e.g., Poikane et al., 2024), regional spatial scope (Shackelford et al., 2021), open data (Piczak et al., 2022), strategic approach for setting restoration objectives (e.g., Abell et al., 2022), and sustainability assessment of restoration measures (Tammeorg et al., 2023). It is important to note that this review was focused on recent articles (i.e., since 2020) and was not completed in a systematic manner.

We propose a holistic CEA approach for urban water body restoration that incorporates the foundational CEA elements that we have identified (Figure 5.1). The CEA approach is well-suited to urban landscapes, which are subject to multiple stressors and which support numerous stakeholders with diverse interests. Urban restoration projects generally benefit relatively large populations, which should justify the increased public spending needed to achieve a more holistic approach. Increasing urban community engagement in restoration also builds public support for restoration projects beyond city limits.

To explore how our proposed CEA approach may achieve more sustainable outcomes for urban water body restoration projects, we theoretically applied it to Frame Lake as a case study. We completed a desktop assessment to search in the academic and grey literature for information on how Frame Lake became degraded, proposed methods to restore Frame Lake, previous Frame Lake restoration initiatives, the current Frame Lake restoration project, past and present public perspectives and uses of Frame Lake, and environmental and socio-economic objectives for the broader region.

5.3.2 Limitations

This study could have benefited from a systematic review of the CEA literature. It is possible that our non-systematic review of the CEA literature missed other foundational elements recommended for

effective CEA. However, all of the elements that we have considered in this study as foundational are recommended by multiple sources. Thus, we position our list as a non-exhaustive one because while we maintain these elements are important for effective CEA, we acknowledge there are others we may have missed. We recommend future work complete a systematic review of the CEA literature to yield a more comprehensive assessment of the foundational elements needed for effective CEA.

Our review of the restoration literature was shallower than our review of the CEA literature. We completed a more targeted review that sought recent articles and articles that might specifically discuss our proposed foundational elements (e.g., meaningful community engagement and sustainability assessment). While this search provided us with evidence that these elements are indeed called for in the restoration literature, it was biased towards our proposed elements and would have missed others that may be considered even more important or alternatives. Thus, the CEA elements we identify in this study are not necessarily common themes but are emergent in the restoration literature, and a more systematic search would be required to determine how common these themes are and if some researchers may be refuting rather than supporting their application for urban water body restoration. Future work should complete a systematic review of the urban water body restoration literature to identify a more complete list of recommended improvements for restoration projects to determine if the CEA approach addresses the recommendations, if it should be expanded, or if some elements should be replaced with alternatives.

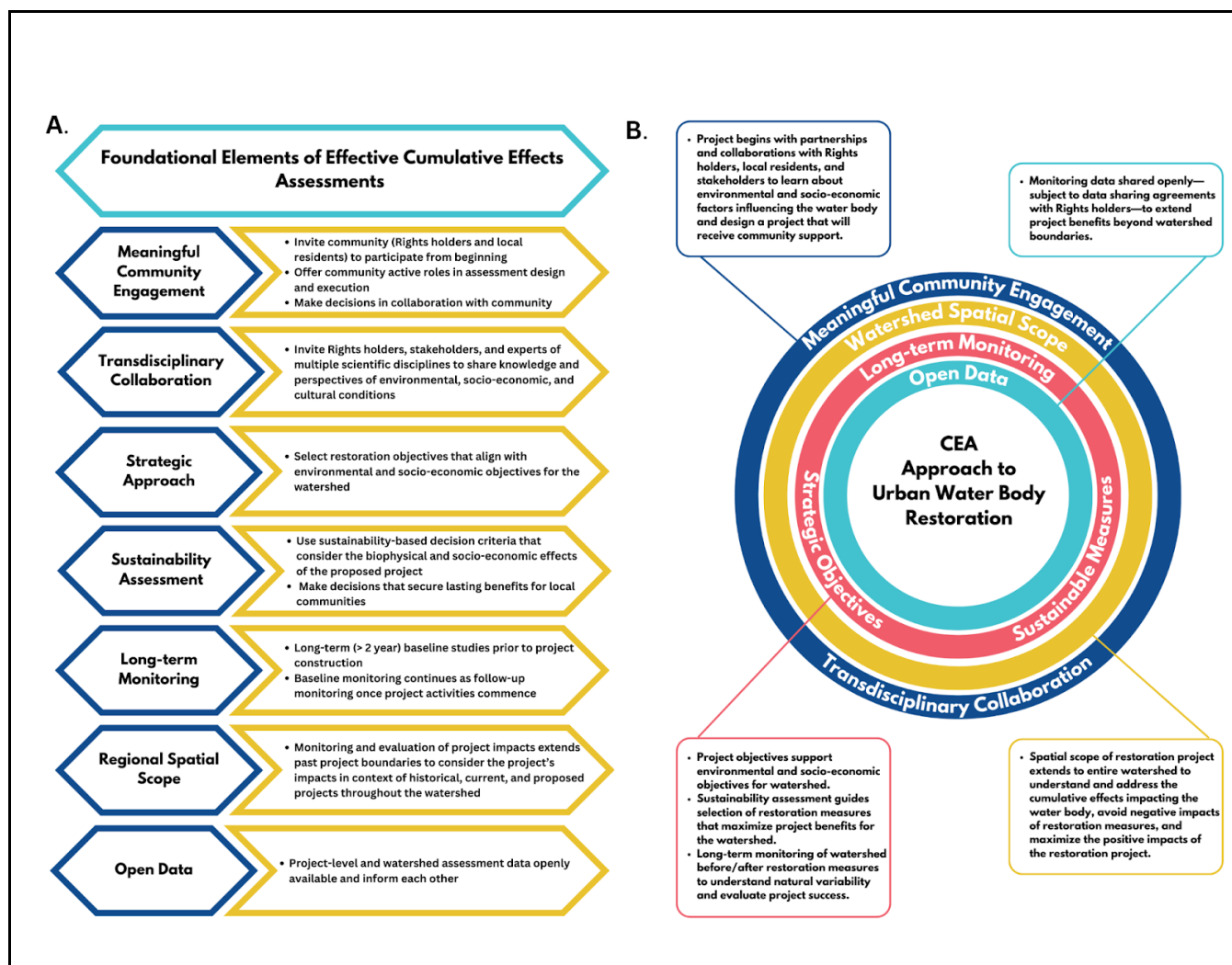


Figure 5.1: Foundational elements and how they can be achieved in effective Cumulative Effects Assessments (CEAs), and **B:** Proposed CEA approach to urban water body restoration that incorporates foundational elements of effective CEA.

5.4 Cumulative Effects Assessment Approach to Urban Water Body Restoration

This section defines the foundational elements of effective CEAs in the context of urban water body restoration and synthesizes how the restoration literature has highlighted the importance of each element. Learnings from the CEA and Impact assessment literature are also offered to support the implementation of these elements into restoration practices.

5.4.1.1 Meaningful Community Engagement

Restoration project managers can move past the traditional view of community engagement as public education and towards a more meaningful form of engagement that begins early in the project and creates opportunities for community members to actively participate, and influence and inform decisions (DFO, 2023; Hychka & Druschke, 2017; McGaughey et al., 2022; Pradhananga et al., 2019; Scoggins et al., 2021; Tammeorg et al., 2023). Unfortunately, in many cases, restoration project managers inform and consult the local community after restoration measures have already been selected, which is less collaborative and according to Arnstein's (1969) ladder of participation, could even be considered a tokenistic form of engagement (Klein et al., 2022; Perera et al., 2023). In contrast, meaningful community engagement involves partnerships and delegates some decision-making authority over project outcomes to the community (Arnstein, 1969; Klein et al., 2022; Perera et al., 2023). This type of engagement is particularly relevant for Indigenous communities, who have often found themselves excluded from environmental decision-making processes, including restoration initiatives (Arsenault et al., 2019; DFO, 2023; Eckert et al., 2020; Moran et al., 2019; Udofia et al., 2015).

Listening to community members through dialogues and discussions allows engagement to move beyond what could sometimes be considered a superficial box-ticking exercise (Klein et al., 2022; Perera et al., 2023; Sinclair et al., 2017). Incorporating knowledge, perspectives, and experiences of members of marginalized communities or groups will also help to ensure the project creates a space that benefits all (Klein et al., 2022). Listening allows restoration practitioners to mobilize multiple knowledges—not just western science—and focus on community goals (Klein et al., 2022; Pradhananga et al., 2019). Once the project vision and goals are defined with the community members, project managers can then work with the community to define which subsequent project activities they have the interest and capacity to participate in (Perera et al., 2023).

One opportunity for community members to actively participate in the project is through a community-based monitoring program. Community-based monitoring (CBM) can facilitate meaningful community engagement in restoration projects (Kanu et al., 2016). Kidd et al. (2024) found CBM programs have the capacity to collect the long-term regional data needed to inform baseline studies and CEAs. Thus, CBM can offer opportunities for early participation of community members and support the collection of data needed to monitor and assess the project's success.

Meaningful engagement with local community members benefits restoration projects by informing the project design phase with community knowledge, securing community cooperation and support throughout the project, and leading to decisions that support sustainable development (DFO, 2023; Moran et al., 2019; Perera et al., 2023). For example, Klein et al. (2022) observed members of the Muckleshoot Tribes disengage from restoration efforts for the Duwamish River in Seattle, Washington, when their opinions on the restoration measures were disregarded by project managers. As a result, the restoration measures were not carried forward because they did not address community priorities for the watershed (Klein et al., 2022). In contrast, restoration measures for the Klamath River at Tishánik were co-developed by restoration researchers and the Karuk Tribe, leading to culturally appropriate restoration measures that addressed community priorities, maintaining the community's support and participation throughout the project (Klein et al., 2022).

5.4.1.2 Transdisciplinary Collaboration

Transdisciplinary collaboration integrates both scientific knowledge from various disciplines and non-scientific knowledge and perspectives from rights holders and stakeholders. Similar to meaningful community engagement, transdisciplinary collaboration involves local community members; however, it also brings together local stakeholders, including businesses, non-profits, and government agencies to complete the picture of local perspectives on the project. Local knowledge and perspectives are bridged with disciplinary knowledge from experts of various scientific fields pertinent to the project, ensuring project decisions are informed by various types of knowledge that can support sustainable decision-making.

Collaborations with Indigenous peoples, government agencies, non-government organizations, academics, and the general public provide insights into local socio-economic conditions and values, and ecological knowledge beyond western science (Arnold et al., 2019; Ball et al., 2013; Jones, 2016). This knowledge is critical for designing restoration projects that incorporate

diverse knowledge and worldviews, are informed by knowledge of the various factors that will influence the recovery of the water body, and consider the perspectives and priorities of the local community (Goralnik et al., 2022; Hychka & Druschke, 2017; Moran et al., 2019; Pradhananga et al., 2019; Scoggins et al., 2021). Rights holders and stakeholders are more likely to support restoration projects that represent their perspectives and address their concerns (Cross & Chappell, 2022; Hughes et al., 2014; Hychka & Druschke, 2017; Murphy et al., 2022; Poikane et al., 2024; Pradhananga et al., 2019; Tammeorg et al., 2023), and this support is needed to secure funding and volunteer capacity, implement plans, and promote the behavioural changes that are needed for long-term project success and sustainability (Goralnik et al., 2022; McGaughey et al., 2022; Moran et al., 2019; Pradhananga et al., 2019). Thus, to maximize support for a project, it is essential to collaborate with rights holders and stakeholders who represent the diversity of public opinions, as it is possible that restoration measures may benefit one group while negatively affecting another (Cross & Chappell, 2022; DFO, 2023; Murphy et al., 2022; Pradhananga et al., 2019; Tammeorg et al., 2023).

5.4.1.3 Watershed Spatial Scope

Understanding and managing cumulative effects that influence water bodies requires at least a watershed-scale spatial scope (Chilima et al., 2013; Sheelanere et al., 2013). Typically, site-specific restoration measures are applied that do not account for watershed-scale influences and consequently fail to achieve the desired restoration outcomes (Hughes et al., 2014). A restored water body may return to degraded conditions if external influences (e.g., nutrient loading) continue due to unchanged land-use practices (Tammeorg et al., 2023). It is therefore prudent to approach restoration at the watershed scale as appropriate, where the root causes of degradation may be occurring (Hughes et al., 2014). As such, baseline and pre-restoration studies should assess the entire watershed to facilitate understanding of past and present cumulative effects on the waterbody, and to identify factors and ongoing stressors that could inhibit restoration (Hughes et al., 2014).

Ideally, restoration monitoring programs should also have a watershed-scale spatial scope to sufficiently assess the effectiveness of mitigation and restoration actions. The monitoring program should include other sites in the watershed that are impacted (i.e., undesirable conditions) and unimpacted (i.e., desirable conditions) to help practitioners set realistic recovery goals, and to facilitate monitoring of the rate of success of restoration measures (Gray et al., 2011; Harper & Quigley, 2005; Shackelford et al., 2021; Weber et al., 2018). In addition, the cumulative effects—

both positive and negative—of restoration measures on the watershed should be monitored to understand the overall impacts of the project and measures undertaken (Beck et al., 2019; Diefenderfer et al., 2021; Gray et al., 2011; Kondolf et al., 2008; Weber et al., 2018).

5.4.1.4 Long-Term Monitoring

To effectively measure the success of restoration measures, long-term monitoring is needed before and after restoration measures are implemented. Typical restoration projects take a short-term monitoring approach; data are often collected immediately prior to initiation of restoration measures and for a subsequent two years (Beck et al., 2019; Diefenderfer et al., 2021; Gray et al., 2011; Weber et al., 2018). Long-term monitoring is generally superior to typical one- or two-year baseline studies when defining natural variability (Arnold et al., 2019; Cronmiller & Noble, 2018; Dubé et al., 2013; Heino et al., 2020). An understanding of natural variability is useful when practitioners, stakeholders, rights holders, and managers are working collaboratively to select appropriate restoration measures and evaluate their success after implementation (Poikane et al., 2024). Effects of selected restoration measures should also be monitored for longer periods (i.e., > 5 years) to confirm that intended outcomes are achieved (DFO, 2023). Water bodies subject to cumulative effects realistically need decades to recover (Hughes et al., 2014; Poikane et al., 2024; Tammeorg et al., 2023). Thus, monitoring should be long-term, such that recovery and/or positive changes in water body metrics can be fully assessed, and to ensure that evaluation of efficacy is as fulsome and realistic as possible (Lyu et al., 2020).

The long-term maintenance of the monitoring program must be planned for during the program design phase to ensure the available funding and resources are sustainable. For example, the program can be designed as a community-based monitoring program. While community-based monitoring can facilitate meaningful engagement of community members in the project (Section 3.1), it can also be a cost-effective method for long-term monitoring (Gunn, 2021). Technological advancements in water quality monitoring are also making long-term monitoring more realistic (Droujko & Molnar, 2022; Rusnák et al., 2022; Salim et al., 2025).

5.4.1.5 Strategic Approach to Defining Restoration Objectives

A strategic approach to environmental decision-making considers the cumulative effects of multiple scenarios and selects the most desirable approach that does not conflict with regional goals to support

sustainable development and achieve desired environmental and socio-economic future conditions (Blakley & Russell, 2022; CCME, 2009; Chilima et al., 2013; Johnson et al., 2011; Lerner, 2018; Noble, 2008). Similarly, a strategic approach can be used when setting restoration objectives to ensure that they align with regional goals and desired future conditions for the watershed. Unlike conventional restoration projects that focus solely on biophysical conditions, a strategic approach integrates socio-economic, cultural, and political factors to balance human needs with ecosystem health (Beck et al., 2019; Speed et al., 2016). The United Nations Principles of Ecological Restoration state that restoration projects should be designed to achieve ecological, cultural, and socioeconomic objectives and goals that are situated in local and regional contexts (Food and Agriculture Organization [FAO] et al., 2023). As such, it is important to engage with stakeholders and rights holders to understand the costs and benefits of restoring water bodies, and to define a vision that describes the desired future state of the target water body and watershed (FAO et al., 2023; Hychka & Druschke, 2017; Poikane et al., 2024; Speed et al., 2016). Aligning restoration objectives, community objectives, and political objectives at a watershed scale contributes to long-term success of restoration projects via more social license, financial support, policies that protect restoration measures, and restoration measures that will work with future developments and growth (Abell et al., 2022; Hychka & Druschke, 2017; Poikane et al., 2024; Speed et al., 2016; Tammeorg et al., 2023).

5.4.1.6 Sustainability Assessment of Restoration Measures

Sustainability-based decision criteria strengthen restoration measure selection by evaluating environmental and socioeconomic impacts of multiple options (Tammeorg et al., 2023). Traditionally, subject matter experts inform rights holders and stakeholders of the restoration measures selected after decisions have been made and funding is secured, often without evidence of why the selected measure(s) are the best option, or what risks and benefits were considered (DFO, 2023). In contrast, a CEA approach would involve collaboration with rights holders and stakeholders to assess the sustainability and social license for multiple restoration options, and select the best option based on the evidence of how it will achieve sustainable outcomes (DFO, 2023; Kondolf et al., 2008; Tammeorg et al., 2023; Teichert et al., 2016).

The use of sustainability assessments of restoration measures is an emergent theme in the restoration literature (Tammeorg et al., 2023). It appears more common for studies to assess the sustainability of either existing restoration projects to learn about the application of that method for

other studies or evaluate additional measures that could improve project outcomes (Chardon et al., 2021; Goralnik et al., 2022; Kumar & Mizunoya, 2022). Tammeorg et al. (2023) assessed the sustainability of multiple measures before project initiation. Sustainability assessments consider positive and negative ecological, economic, and social consequences of restoration measures to maximize project benefits for the environment and for human well-being (Goralnik et al., 2022; Kumar & Mizunoya, 2022; Tammeorg et al., 2023). These assessments evaluate environmental footprints of restoration measures (i.e., environmental risks), including energy requirements and harmful byproducts (Tammeorg et al., 2023). The environmental footprint of restoration measures can be minimized by using renewable sources of energy, limiting chemical applications, and implementing nature-based solutions (Tammeorg et al., 2023). Managers should avoid restoration measures with net negative impacts when they stop or malfunction (Speed et al., 2016; Tammeorg et al., 2023). Potential co-benefits of restoration measures are also explored, such as reusing nutrients removed from lakes for fertilizer (Tammeorg et al., 2023). The longevity of the ecological and socio-economic positive impacts of the project are predicted (Chardon et al., 2021; Kumar & Mizunoya, 2022). The economic sustainability and cost effectiveness of the measure is considered, including whether or not the measure is long-lasting or if future measures (including funding) will be required to sustain restoration outcomes (Kumar & Mizunoya 2022; Tammeorg et al., 2023).

5.4.1.7 Open Data

There is growing acknowledgement that openly available data are needed to support environmental decision-making, including freshwater resource protection and restoration (Environment and Climate Change Canada, 2021; Jacob et al., 2018; Miller et al., 2022; Piczak et al., 2022). “*Sharing information is critical to the modern practice of science, particularly to inform and evaluate decisions made in the public interest*” (Jacob et al., 2018). Open data builds transparency and trust in restoration projects, supports public engagement, and fills data gaps, which allows for regional comparisons and adaptive management (Favaro & Olszynski, 2017; Piczak et al., 2022). Just as watershed and project-level CEAs should inform each other (Arnold et al., 2019; Ball et al., 2013; Foley et al., 2017; Johnson et al., 2011; Sheelanere et al., 2013), restoration projects should ideally share their data to allow other projects to build and improve on their work, and to generally advance the practice of water body restoration (FAO et al., 2023). Data collected by restoration projects can be shared on open digital platforms to increase transparency and to allow for data reuse, which can

maximize the positive effects of projects beyond original spatial and temporal scales and scopes (Piczak et al., 2022).

The societal benefits that could be gained by open data sharing should not outweigh potential harm to individuals or communities (Zipper et al., 2019). It is critical for restoration project managers to understand that all data should not be open by default—data privacy and Indigenous data sovereignty must always be considered (Wilson et al., 2024; Zipper et al., 2019). Restoration practitioners run the risk of unintentionally harming individuals and communities if they share sensitive data, which is particularly concerning when working with marginalized communities (Zipper et al., 2019). For example, sensitive data can include high-resolution spatial data, which can lower property values or increase insurance rates if they reveal environmental hazards (Zipper et al., 2019), which can be particularly concerning in urbanized environments where residences located near environmental contamination tends to be low-income housing (Sinnott et al., 2022). Meaningful community engagement can help project proponents work with local residents to identify potential risks of openly sharing project data and establish data protections that the community trusts and supports (Zipper et al., 2019). Project proponents must also understand and respect Indigenous data sovereignty, which stipulates that Indigenous governments and communities have jurisdiction over the collection and sharing of data collected by or about their peoples and land (Zipper et al., 2019). Thus, at the start of the project, managers should work with rights holders to create a data sharing agreement that outlines how data associated with the project will be shared and support Indigenous Data Governance principles, including OCAP (ownership, control, access, and possession) and CARE (collective benefit, authority to control, responsibility, and ethics) (First Nations Information Governance Centre, 2023; Jennings et al., 2023).

5.5 Case Study: Frame Lake

5.5.1 Background

Frame Lake is a small (84.4 ha) lake with a maximum depth of 6.5 m, which is fed from a 3.48 km² watershed and is located within the City of Yellowknife, Northwest Territories (Dirszowsky & Wilson, 2016; Menard et al., 2019; Figure 5.2). Frame Lake was originally known as Enaàti, and is located within the traditional territory of the Yellowknives Dene First Nation (Gavel et al., 2018).

Enaàti provided the Yellowknives Dene with a source of drinking water and as a place for fishing camps to fish for Lake Whitefish (*Coregonus clupeaformis*), Northern Pike (*Esox lucius*), and suckers (*Catostomus* spp.; Patterson et al., 2015). The Yellowknife Dene disbanded their fishing camp during the 1930s when gold mining began in the region (Gavel et al., 2018; Patterson et al., 2015). As settlers built the City of Yellowknife around the lake, they named it Frame Lake—after a miner and owner of a taxi company (Silke et al., 2010).

From the 1950s until the 1970s, Frame Lake was a popular destination for Yellowknife residents to fish, swim, and paddle (Gavel et al., 2018). McNiven Beach (Figure 2) was a community gathering and event space, and was equipped with a lifeguard, changing rooms, picnic benches, and diving board (Blake, 2021; Holden, 2024a; Mallon, 2015; Patterson et al., 2015). The City removed the recreational infrastructure in the late 1970s, after the lake’s popularity declined sharply when the fish population disappeared and it became dominated by leeches (*Hirudinea* spp.) and dense macrophyte mats (Dirszowsky & Wilson, 2016; Gavel et al., 2018; Mallon, 2015; Menard et al., 2019; Patterson et al., 2015). Children continued swimming in the lake into the 1990s, but they had to arm themselves with salt packets to ward off leeches (Blake, 2021).

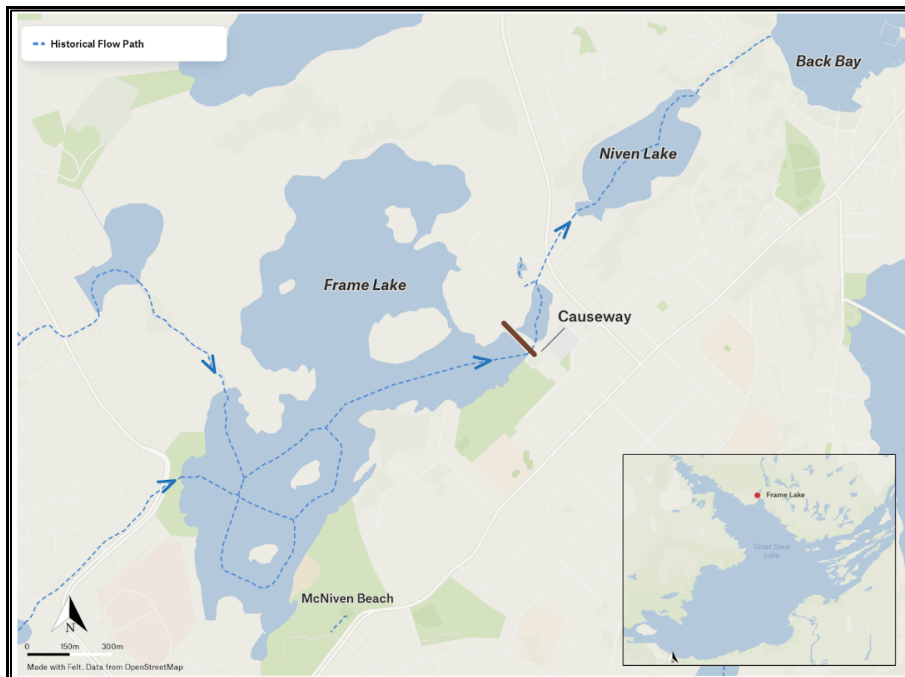


Figure 5.2. Site map of Frame Lake with water flow paths and direction indicated. Map inset box shows location of Frame Lake relative to Great Slave Lake, Northwest Territories, Canada. The base map is from Felt (2025), lake boundaries are from HydroSHEDS (2016), and water flow paths are from Natural Resources Canada (2017).

Frame Lake is currently referred to as a “*dead lake*”, and the waters are not safe to swim in (Blake, 2021; CBC, 2015). McNiven Beach has been degraded to a “*dusty patch of sand behind the pool*” (Mallon, 2015). The lake is eutrophic with black, foul-smelling sediment contaminated with arsenic at concentrations harmful to humans and aquatic life (Dirszowsky & Wilson, 2016; Gavel et al., 2018; Patterson et al., 2015). Since 2017, the Government of the Northwest Territories (GNWT) has maintained a public health advisory cautioning residents to not consume lake water and avoid fishing and swimming in Frame Lake (GNWT, 2024).

In 2015, the Frame Lake Rehabilitation Project—a collaboration between the GNWT, City of Yellowknife, Yellowknives Dene, Carleton University, and MakeWay (formerly Tides Canada)—received funding to investigate the cause of Frame Lake’s decline (CBC, 2015; MakeWay, 2024). The funding supported research that confirmed Frame Lake was degraded by the cumulative effects of multiple historical gold mines and urban development (Gavel et al., 2018). Hazardous arsenic levels stem from decades of aerial deposition from gold mine emissions and—likely—direct dumping of mine waste into the lake (Gavel et al., 2018; Patterson et al., 2015; SRK Consulting, 2007). While the gold mines discharged arsenic into the receiving environment, mine operations also accelerated the development, resulting in Yellowknife becoming the Northwest Territories’ largest urban centre (Silke et al., 2010). Eutrophic conditions in the lake developed as the surrounding landscape became urbanized and released nutrient-rich waters into the lake (Dirszowsky & Wilson, 2016; Gavel et al., 2018). Road construction redirected natural inflows away from the lake, diminishing its flushing capacity (Gavel et al., 2018). A causeway constructed in 1975 across the lake’s outflow further reduced flows, causing nutrients and sediment to accumulate (Environmental Monitoring Advisory Board [EMAB], 2021; Gavel et al., 2018; Patterson et al., 2015). The nutrient accumulation led to excessive macrophyte growth that depleted oxygen levels as dead plant material decomposed over winter (Gavel et al., 2018). Overwinter anoxia killed the remaining fish (Gavel et al., 2018; Patterson et al., 2015) and continues to spur the seasonal release of dissolved arsenic trioxide from sediment into overlying water (Palmer et al., 2021).

Despite its degraded condition, Frame Lake remains a focal point of Yellowknife, with the Heritage Centre and Legislative Building located on its shores, and City Hall, a swimming pool, hospital, and museum overlooking the lake (Neudorf, 2023). A “*much-loved, much-jogged trail system*” winds 5.5 km around the lake, offering a conduit for commuters between uptown and downtown Yellowknife (Mallon, 2015; Neudorf, 2023). As the backdrop of a typical day in the life of

a Yellowknifer, one would assume the lake’s degraded state would be alarming. Yet, efforts to restore the lake to a healthy ecologically functioning system are just beginning decades after fish disappeared. Below, we detail the restoration efforts that are currently underway to restore fish habitat, and conclude with a proposed plan that takes a cumulative effects approach to promote further efforts that could support Frame Lake becoming once again a place for people to gather and play during the long summer days.

5.5.2 Current Frame Lake Restoration Project

In 2021, the federal Department of Fisheries and Oceans (DFO) approved a mining company’s (i.e., project proponent’s) plan to include Frame Lake in its Fish Habitat Compensation Program to offset lost lake habitat from a mining development located 300 km north of Yellowknife (EMAB, 2021; Golder, 2022). The idea to include Frame Lake fish habitat restoration as part of this compensation program was developed and discussed with personnel of the GNWT who are based in Yellowknife and were involved with the initial Frame Lake Rehabilitation Project. The project proponent’s Frame Lake project (hereafter the project) has two phases: 1) aerator installation and monitoring, and—if sufficient dissolved oxygen is sustained for two years—2) fish reintroduction and monitoring for two years (Golder, 2022). Phase 1 is posed as a research project that aims to investigate if an aerator can maintain dissolved oxygen concentrations that can sustain fish in a subarctic lake (Golder, 2022). The project proponent will receive some habitat unit credits for the aerator installation regardless of its success because it will fulfil the objective of contributing to the body of knowledge of aerator efficacy in subarctic lakes (Golder, 2022).

The project proponent installed the aerator in Frame Lake in June 2024 (Holden, 2024b). Once the 4-year project ends, the company’s obligations, in accordance with their *Fisheries Act* Authorization, will be fulfilled and it will pass the responsibility of maintaining the aerator to a local organization (EMAB, 2021; Holden, 2024a).

5.5.3 Cumulative Effects Assessment Approach to Restoring Frame Lake

A holistic approach to restoring Frame Lake could have an outsized return on investment due to the number of people who stand to benefit. “*We’ve got a lake in the middle of the only urban centre in the territory, with half the territory’s population seeing it almost every day*” (Mallon, 2015). The efforts spent so far by the project proponent are not wasted but rather can be a springboard for a regional

restoration initiative that returns both fish and people to Frame Lake and other nearby lakes contaminated by historical mining (Figure 5.3). First, if the project successfully reintroduces fish as an indication of a healthy functioning ecosystem, it will change the public’s perception that the lake is beyond repair, which is one of the biggest barriers to urban lake restoration (Hychka & Druschke, 2017). Second, the lake-specific project can support a watershed-scale restoration initiative by demonstrating initial success, building partnerships and relationships, and prompting the local community to value urban lakes (Hychka & Druschke, 2017). Below, we describe how a CEA approach could enhance the current restoration project to maximize positive outcomes of restoring regional water quality (Figure 5.4; Table 5.1).

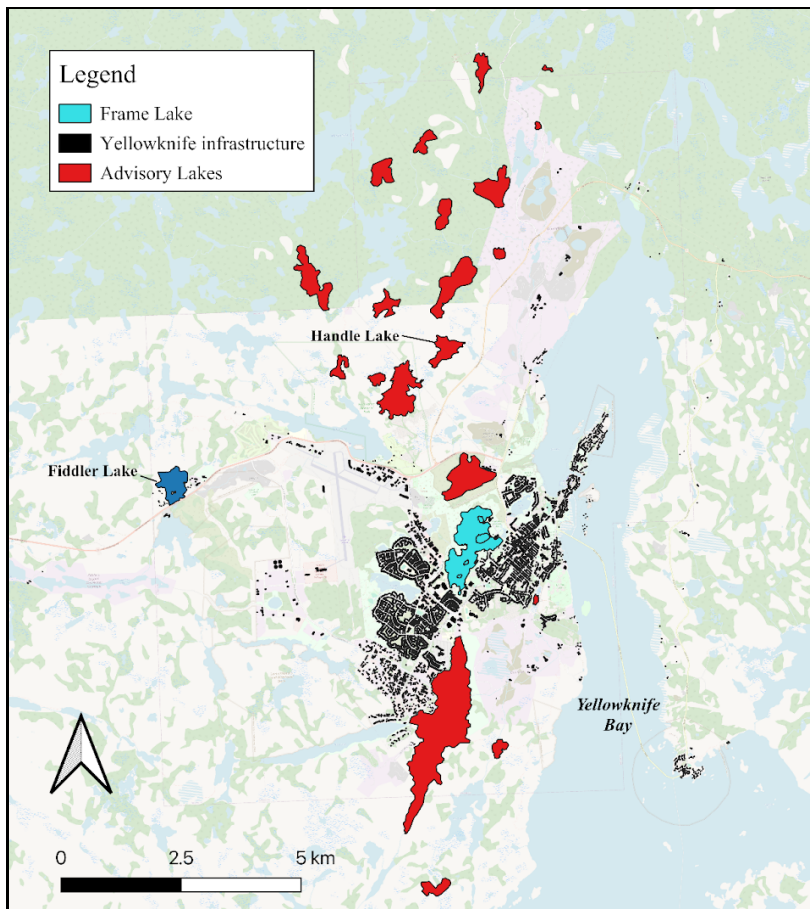


Figure 5.3. Map of lakes with arsenic contamination from Con and Giant Mines, Yellowknife, Northwest Territories, Canada. Advisory lakes are the other lakes in the region with government advisories cautioning against water-based activities and resource harvesting due to elevated arsenic levels. Black dots signify city infrastructure. Fiddler Lake (unimpacted by arsenic) and Handle Lake (impacted by arsenic) have been used as reference lakes for Frame Lake by the Aurora Research Institute. Map created using QGIS version 3.32 (QGIS Development Team, 2025), base map data from OpenStreetMap contributors (2025), the advisory lakes are from the GNWT (2024), and the buildings are from Daylight Map Distribution (2023).

Table 5.1. Comparison of conventional urban water body restoration project approach to proposed Cumulative Effects Assessment (CEA) approach.

Project Element	Overview		Example: Frame Lake in Yellowknife, NT, Canada	
	Conventional Approach	CEA Approach	Frame Lake Habitat Compensation Project	CEA Approach to Frame Lake Restoration
Community Engagement	The project proponent informs the community of how it plans to restore the water body and provides periodic project updates.	The project proponent invites rights holders and local residents to actively participate in the design and execution of all project phases, and collaborate on all project decisions.	The project proponent presented its plan to restore fish habitat in Frame Lake using mechanical aeration to the Yellowknives Dene, and confirmed there were no major project objections.	The project proponent invites the Yellowknives Dene and Yellowknife residents to participate in a project that aims to restore Frame Lake. Regular community meetings are held to share knowledge, gather perspectives, and collaborate on project decisions.
Collaborations	The project proponent informs stakeholders of how it plans to restore the water body and provides periodic project updates.	The project proponent invites stakeholders and disciplinary experts to join collaborations with community members to inform project decisions.	The project proponent discussed restoring Frame Lake with the territorial government and presented its plan to restore fish habitat in Frame Lake. The plan included using mechanical aeration and maintain the aerator (and associated maintenance) for up to four years. Municipal leadership confirmed there were no major project objections. The plan was presented to and received approval from Fisheries and Oceans Canada. Project proponent funded academic researchers to study the impacts of aeration on Frame Lake.	The project proponent creates a working group of rights holders, Yellowknife residents, stakeholders, and researchers who gather local and disciplinary knowledge and perspectives on Frame Lake's restoration to inform project decisions.
Spatial Scope	Single water body	Watershed	Frame Lake	Frame Lake, reference lakes, other arsenic-impacted lakes in the watershed.
Monitoring	Short-term (<10 year) monitoring of recovery	Long-term (≥10 years) monitoring of recovery	2-year aerator monitoring, plus 2-year fish population monitoring	Community-based monitoring of lake(s) recovery planned for at least 10 years.
Project Objectives	Defined based on the project proponent's goals (e.g., regulator expectations, research goals, species/habitat conservation).	Defined based on the project proponent's goals and rights holder and stakeholder objectives for the water body and watershed.	Conduct research and restore fish habitat in Frame Lake to demonstrate the lake's capacity to support a healthy fish population, gain support for further restoration efforts, and support the project proponent in being granted habitat compensation credits that offset for habitat lost at its industrial site.	Restore Frame Lake to support a healthy fish population and allow residents and visitors to once again enjoy water-based activities in Frame Lake and other lakes in the watershed.
Restoration Measures	The project proponent selects the restoration measure, providing little justification or alternatives.	The project proponent collaborates with rights holders, stakeholders and experts to assess the sustainability of multiple restoration measures.	The project proponent concluded dredging contaminated sediment was not a feasible option for them and chose mechanical aeration to improve dissolved oxygen levels.	The working group selects a restoration measure(s) based on a sustainability assessment of numerous options, including dredging, aeration, phytoremediation, and flow alterations.

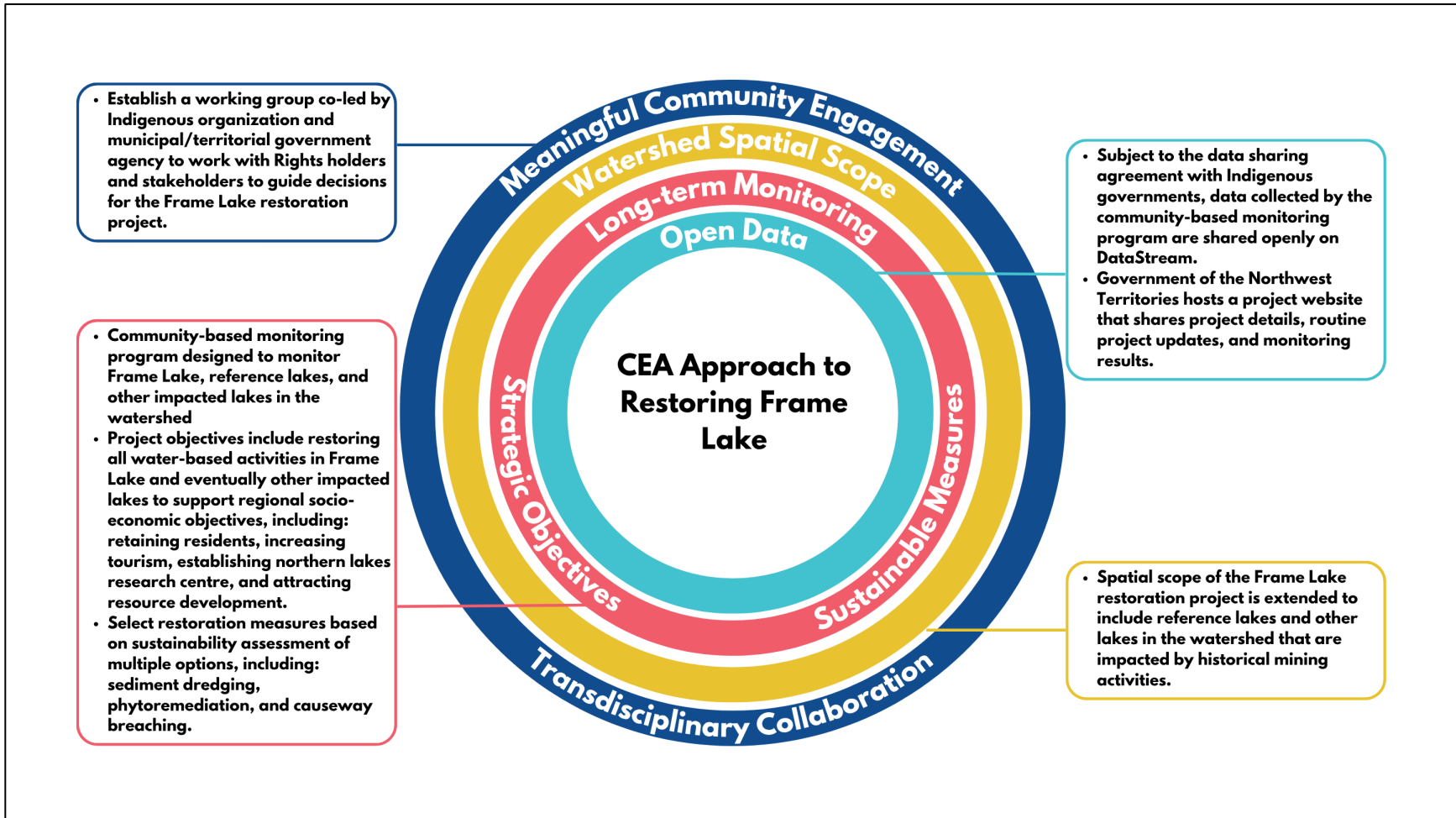


Figure 5.4. Cumulative Effects Assessment (CEA) approach to restoring Frame Lake.

5.5.3.1 Meaningful Community Engagement

Although the project proponent has communicated the goals of the project to various stakeholders and rights holders, community members do not have a strong and active role in the current project. The lack of community participation could be due to a lack of interest or capacity and not a lack of efforts of project managers to include them.

Community interest and participation could be gained with a community-based monitoring (CBM) program that is initiated to monitor long-term effects of the aerator, any future restoration measures, and offer community members a way to take ownership of stewardship initiatives. Here, we propose a CBM program for Frame Lake based on CBM project characteristics identified by Kidd et al. (2024) that were associated with an exceptional capacity to collect environmental data that informs CEAs. The following includes examples of organizations that may be interested in supporting a CBM for Frame Lake but are not organizations that have already committed to or shown interest in doing so. The GNWT could be a candidate for a partner organization that provides long-term funding and in-kind support, in addition to NGOs and the private sector. Funding could be allocated to a local research organization, such as the Aurora Research Institute (ARI) to develop training materials and facilitate community members in following standardized data collection protocols. ARI is a research institute in Yellowknife that generates and shares knowledge in the Northwest Territories that aims to expand the territory's research capacity through strategic partnerships (ARI, 2024). Involving a local research institute is important for legacy knowledge-transfer as the data will be collected and used by the community, prompting the knowledge and skills gained through the project to stay within the community and support future community-based research. ARI is currently collaborating with researchers from Wilfrid Laurier University and York University to study Frame Lake. Data collection protocols would align with ARI's existing methods to ensure consistency and comparability across monitoring programs. The data could be managed in a publicly accessible database, such as the Mackenzie DataStream, which the GNWT already uses to openly share its NWT-wide Community-Based Water Quality Monitoring Program data or the Discovery Portal where data from research supported under the NWT Cumulative Impact Monitoring Program are archived. The local non-profit agency MakeWay (formerly Tides Canada and involved in the original Frame Lake Rehabilitation project) could act as the bridging organisation that coordinates the program and supports partnerships between the community members, academic researchers, and government partners.

5.5.3.2 Transdisciplinary Collaboration

Collaboration with rights holders and stakeholders would have likely led to broader objectives for the restoration of Frame Lake. The current project's objective of restoring fish habitat was defined by the project proponent's regulatory obligation to compensate for habitat destroyed in a lake that is located several hundred kilometers away. This objective was guided by the regulator's expectations that the project proponent must meet. However, the objective of restoring fish habitat was also an objective of the initial Frame Lake Rehabilitation Project, which was a collaborative effort between stakeholders and rights holders, and which aimed to both restore fish habitat and McNiven Beach as a recreational area, including a place for swimming (CBC, 2015; Patterson et al., 2015). The current project involved the type of community engagement that is traditionally required of restoration projects, which includes holding meetings with municipal leadership, notifying the community of its restoration plans, and checking for opposition before proceeding with the project (Blake, 2021; S. Sinclair, personal communication, Oct 13, 2022). Community members have expressed concern over the project proponent's plan to transfer the responsibility of the long-term aerator operation and maintenance to a local organization (EMAB, 2021; Holden, 2024a). Since a local organization has not yet committed to the long-term operation of the aerator, further community engagement and collaboration may be required to secure the long-term success of the current project and continue restoration efforts beyond fish habitat restoration.

For a watershed-scale restoration initiative, a working group could facilitate transdisciplinary collaboration throughout all project phases. This working group could be modelled after the Elk Valley Cumulative Effects Management Framework (EVCETF) working group that is co-led by the Ktunaxa Nation Council and British Columbia's Ministry of Natural Resources (EVCETF, 2018). Such a working group could be co-led by an Indigenous government or organization and a territorial government agency and bring together diverse perspectives and strive for consensus-based decisions to develop, guide, and oversee restoration measures. An early step would be hosting a workshop that brings together rights holders, academic institutions, and representatives from the private sector, non-profit agencies, and municipal and territorial government agencies to discuss expanding the scope of Frame Lake's restoration beyond the current project. Here, the group could work to confirm and more specifically scope the ecological services rights holders and stakeholders wish to see returned to regional lakes, establish objectives for a watershed-scale restoration project, and inform the selection of restoration measures.

5.5.3.3 Long-Term Monitoring

The current project, which is bound within a regulatory context, is taking a conventional project-level approach to data collection, whereby data were collected for one year prior to the initiation of restoration measures and will be collected for two subsequent years post installation (Beck et al., 2019; Diefenderfer et al., 2021; Gray et al., 2011; Weber et al., 2018). If the aerator is deemed successful at increasing dissolved oxygen concentrations under ice, dissolved oxygen will be monitored for an additional two years after fish are reintroduced. It is imperative that this monitoring continue to allow understanding of the long-term effects of aeration in Frame Lake, particularly to understand if the fish population will be healthy and self-sustaining in the long term, as well as to study the effects of aeration on the re-mobilization of arsenic. Further, long-term monitoring will contribute to the understanding of the true efficacy of aerators in subarctic lakes. There is tremendous opportunity with this initiative to demonstrate the efficacy of mechanical aeration in subarctic lakes, and a CEA approach could be used to design a long-term monitoring program (minimum 10 years) that monitors the recovery of Frame Lake to confirm intended outcomes are achieved, and to adaptively manage the project if necessary.

5.5.3.4 Watershed Spatial Scope

The current project's monitoring plan only includes monitoring Frame Lake. A CEA approach for Frame Lake's restoration would include reference lakes that are unimpacted and impacted by historical mining activities. Researchers at ARI are already using Fiddler Lake (unimpacted by historical arsenic contamination) and Handle Lake (impacted by historical arsenic contamination) as reference lakes when studying Frame Lake dissolved oxygen concentrations (Figure 5.3). Including reference lakes (which have been subject to the same environmental impacts as Frame Lake) in data collection activities after aerator installation would allow for a comparative study that differentiates the influence of the aerator from regional impacts of climate change's influence on ice and surface flow dynamics. A watershed monitoring program could be designed as a CBM led by an Indigenous organization, if capacity and interest allow. Such a CBM could collate and highlight existing traditional knowledge, including which lakes in the Yellowknife area were previously fish-bearing, and contemporary information on the current fish communities.

With increased public support for the restoration of Frame Lake, the spatial scope of the restoration measures could also be expanded to include the other 18 contaminated lakes in the

Yellowknife region. While the aerator is being monitored, alternative restoration techniques could be tested simultaneously in other impacted lakes. If the aerator is not successful, this approach would allow assessment of other restoration measures already locally tested and ready to deploy in Frame Lake.

5.5.3.5 Strategic Approach to Setting Restoration Objectives

The current project's objective of restoring fish habitat fulfills habitat offsetting commitments to the federal government for a mining development and is a component of the broader objective of returning both fish and people to Frame Lake. With a CEA approach, broader restoration objectives could be selected based on local environmental and socio-economic objectives to maximize the benefits of the project and garner the increased support and interest from rights holders and stakeholders that is needed to continue and expand restoration measures (Pradhananga et al., 2019).

Expanding the restoration objective to include returning water-based activities to Frame Lake and other impacted lakes in the watershed would support several local and regional socio-economic objectives. Returning water-based activities to Frame Lake would support Yellowknife's strategy for meeting its labour demands by attracting and retaining residents with recreation opportunities (Immigration, Refugees and Citizenship Canada, 2020). Returning canoeing, kayaking, paddle boarding, and fishing to Frame Lake would also fulfill the City's commitment to expand opportunities for these activities to attract and retain tourists to counteract the economic losses from impending mine closures in the territory (FWCO Management Consultants Ltd. [FWCO], 2020). A regional restoration initiative that tests multiple restoration techniques on multiple lakes could support Yellowknife's economic development strategy of becoming a centre for northern arctic research (FWCO, 2020). Yellowknife could take advantage of its access to numerous lakes and create a research facility that would increase the number of students and researchers travelling to and staying in Yellowknife. Yellowknife can then submit the restored lakes to DFO's new habitat bank program (DFO, 2023); this would allow industrial project proponents that are considering future developments in the territory to pay for the restoration and secure habitat credits. The habitat banking project could be of mutual benefit for the GNWT and the City of Yellowknife; both parties need a cost-effective way to restore many local lakes and attract economic development opportunities to the region.

5.5.3.6 Sustainability Assessment of Restoration Measures

The aerator selected for the project proponent's project is a method conventionally used to address anoxic conditions in lakes. The company also considered dredging, but concluded it would be less practical than aeration (Blake, 2021). Although aeration is a proven means to provide overwintering fish with critical oxygen, aeration is not without its limitation, and it is yet to be confirmed if it will be successful in Frame Lake. Mechanical aeration is not often considered a long-term sustainable restoration measure because it requires ongoing maintenance and uses a non-renewable power source (Tammeorg et al., 2023). Several studies have found that aeration can have limited success in improving lake conditions due to the nutrient inputs that continue in shallow lake areas that are not aerated (Tammeorg et al., 2023). In some lakes, aerators can also pose the risk of net negative impacts when they stop or malfunction, causing the immediate release of the large quantities of phosphorus that was trapped in the sediment by the oxygenated conditions (Speed et al., 2016; Tammeorg et al., 2023). However, it is possible to build on the momentum of the existing aeration-based restoration initiative.

With a CEA approach, rights holders and stakeholders would be presented with a detailed rationale of which restoration measure, among several considered, is the best option (DFO, 2023). Employing a CEA approach could consider other restoration measures previously recommended for Frame Lake. Sediment dredging has previously been recommended as an option to remove the arsenic contamination and organic matter that is depleting oxygen levels of the lake (Gavel et al., 2018; Mallon, 2015; Menard et al., 2019; Patterson et al., 2015). While the initial costs are high, and feasibility must be considered—including disposal of contaminated waste—it is a permanent solution that does not require perpetual funding. Phytoremediation has also been recommended to remove arsenic contamination from Frame Lake (Neudorf, 2023; Reynolds et al., 2023). Phytoremediation is a relatively inexpensive measure that removes contaminants from lakes using macrophytes (Neudorf, 2023). To enhance the sustainability of phytoremediation, Neudorf (2023) recommended achieving a co-benefit by incinerating the plant material and using the heat generated from the incineration as biofuel, and burying the contaminated ash at the Giant Mine site. However, phytoremediation has long-term costs associated with maintaining and removing plant material as arsenic continues to be released by disturbed sediment (Neudorf, 2023). Gavel et al. (2018) and Menard et al. (2019) recommended opening Frame Lake's causeway gates to increase water flow through the lake system, possibly alleviating eutrophic conditions that cause overwinter anoxic conditions, which result in the

mobilisation of contaminants from the sediment (Palmer et al., 2021). Any hydrological modifications would have to consider potential negative and positive impacts downstream to Niven Lake.

5.5.3.7 Open Data

The current project's monitoring data are not yet publicly shared or published. Consequently, the success of the aerator is currently unknown, and the community will have to wait for the mining company to disclose information. With an expanded CEA approach that establishes a long-term monitoring program, a data sharing agreement should be established with rights holders to identify what data can be shared and how it can be shared. Subject to the data sharing agreement, water quality data collected by the monitoring program could be potentially shared publicly on Mackenzie DataStream or similar open data archives. Alternatively, a project website could be hosted by a project partner to share the restoration project plan, project updates, and monitoring data. This website could also offer any scientific publications or technical reports that document past and current research conducted on arsenic-impacted lakes in the Yellowknife region.

5.6 Path Forward

We describe a CEA approach to restoration of a contaminated urban lake based on common elements recommended for effective CEA and emerging for freshwater ecosystem restoration. The list of elements we identified as being useful for urban lake restoration is not exhaustive. We recognize that our recommendations for the restoration of Frame Lake are to some degree case-specific and aspirational, and we acknowledge the positive progress made to date on restoring this water body. We encourage others to build on our work and carry out research projects that dive deeper into the opportunity for CEA to support more sustainable restoration projects.

Our assessment of the CEA approach being able to enhance the sustainable outcomes of the restoration of Frame Lake was theoretical and based on a desktop review of available academic and grey literature. To validate our proposed approach, we recommend applying it to Frame Lake, or a similar case, where the differences in project objectives, sustainability measures, and monitoring scope and scale can be documented and compared with the initial conventional approach to restoration.

Watershed CEA is complex and thus difficult to execute, which is why it remains relatively uncommon compared to its project-level counterpart (Bristow et al., 2025). We anticipate the more

complex, and thus resource-intensive, CEA approach to restoration may have little real-world uptake unless sufficient funding is made available. The CEA approach could be a means for DFO to improve the success of its Fish Habitat Compensation Program (FHCP). As part of efforts to modernize fish habitat offsetting, DFO is drafting guidelines for creating and managing habitat banks (DFO, 2023). The habitat banking program is being designed to allow proponents to receive habitat credits for habitat they can demonstrate they have successfully restored (DFO, 2023). These credits can then be used by the proponent to offset future habitat damage by one of their projects (DFO, 2023). The CEA approach, if further explored and validated, could be incorporated into these guidelines to help ensure restoration goals are achieved and the benefits of restoration projects are maximized. Sustainable financing may be another tool to accelerate the adoption of a CEA approach to restoration (Gulzhan et al., 2023). Freshwater restoration is likely to gain more attention, with growing interest from the private sector, in offsetting the environmental impacts of economic development (Thebaud et al., 2015).

Biodiversity credits are a relatively new mechanism for channeling private sector funds to restoration projects (Antonelli et al., 2024). To be effective, however, biodiversity credits must be designed to avoid the failures of carbon-credit markets, including insufficient evidence of project success, negative consequences to communities, and inadequate community engagement (Antonelli et al., 2024). Essentially, private sector compensation projects, whether on or offsite, should strive to achieve net positive cumulative effects. The recommendations for effective biodiversity credits align with several key facets of the CEA approach, including meaningful community engagement, long-term vision, project objectives that align with the objectives of rights holders and stakeholders, publicly available data, and projects that have lasting positive impacts (Antonelli et al., 2024). Thus, if the CEA approach is further explored and validated, organizations that regulate or offer guidance for the biodiversity credit market could encourage or mandate the CEA approach for restoration projects.

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Chapter 6

Discussion

This thesis is a compilation of research studies that assessed methods for gathering, generating, managing, and applying knowledge needed to inform Cumulative Effects Assessments (CEAs) of freshwater ecosystems. The primary objective of this research was to address long-standing criticisms of CEAs, including the lack of long-term regional data, insufficient community engagement, limited consideration of socio-economic factors, and absence of strategic and sustainability assessments. To achieve this objective, I explored if community-based monitoring can be used to collect long-term regional biophysical environmental data (Chapter 2); once collected, how data can be managed and stored so that they can inform various levels of assessment (Chapter 3); when long-term regional data are accessible and reusable, how they can be used to understand baseline conditions and differentiate impacted from unimpacted sites (Chapter 4); and, when impacted sites are identified, can restoration approaches be informed by the same types of knowledge recommended for CEAs to achieve more sustainable outcomes (Chapter 5). The following major conclusions were drawn from each of the studies included in this thesis (Chapters 2-5).

Chapter 2: Community-based monitoring (CBM) can help address the shortage of adequate baseline data that are typically used to support CEA's western science methodology and enhance environmental decision-making. We recommend that CEA practitioners and natural resource managers use CBM to collect long-term regional biophysical data. CBM projects that use training materials (e.g., manuals and videos) to describe standardized data collection methods, include partnerships with provincial/territorial levels of government that provide long-term project funding, manage and share data publicly in georeferenced databases, and have non-governmental bridging organizations that facilitate community engagement are likely to be the most successful and effective.

Chapter 3: To overcome reluctance regarding data sharing within the freshwater science sector, a culture change that embraces open data is needed. This culture change can be achieved through incentives and leadership that encourage open data sharing. Data literacy foundations should be offered in academia and continuously developed in the workplace to help freshwater scientists become proficient in data sharing practices and ensure data are reusable. A freshwater data standard should be developed in collaboration with freshwater stakeholders to offer clear guidance for data collection and data entry methods. Finally, the freshwater science sector needs simple and user-friendly digital tools that facilitate data discovery and access.

Chapter 4: For surface water quality baseline estimation, Natural Range of Variation (NRV) thresholds should ideally be calculated using only reference site data (i.e., sites known to be unimpacted by the impact of interest). To minimize the risk of Type I errors, the Tukey Inner Fence (TIF) method should be used when censored data comprise less than 25% of the dataset, whereas the median ± 2 median absolute deviation (M2MAD) method should be used when censored data comprise 25-50% of the dataset. Beyond 50% censored data, the NRV method should not be used to estimate baseline values. If there is uncertainty about which sites are reference sites, then the more conservative M2MAD method should be used to minimize the risk of Type II errors.

When paired with Mann-Kendall trend analysis and spatial assessment of regional concentrations, NRV thresholds provide a robust approach for assessing cumulative effects in freshwater ecosystems. This quantitative approach enables practitioners to differentiate among sites impacted by point-source pollution, ambient conditions, and their combined effects. The NRV method remains effective when reference site data represent the natural variation at the assessed site, regardless of temporal trends and historical impacts. The NRV method has applications for identifying sites impacted by cumulative effects, understanding project-level impacts, and setting appropriate remediation targets that account for changes in ambient conditions.

Chapter 5: Our proposed CEA approach to urban water body restoration invites rights holders and local residents to actively participate from inception, with project decisions made in collaboration with rights holders and local residents and informed by knowledge gathered from stakeholders and experts of multiple scientific disciplines. Project decision-making and monitoring occur at the watershed scale to understand both the cumulative effects impacting the water body and those created by its restoration. Monitoring data are collected over the long-term to capture natural variability and the water body's recovery. A strategic approach sets restoration objectives that align with environmental and socio-economic objectives for the watershed. The sustainability of candidate restoration measures is assessed to select the most cost-effective measure that will maximize the positive impacts of the project. This approach can be applied to address known deficiencies in restoration projects.

The studies in this thesis demonstrate that the knowledge that is foundational for effective CEAs is also useful for environmental decision-making processes in general. The community-based monitoring projects that clearly demonstrated the ability to collect data for CEA had various project

objectives extended beyond CEA, including aquatic ecosystem health assessments, assessing minimum needs harvesting levels for treaty rights; research of algal blooms; fish and wildlife health assessments; management of freshwater resources, including groundwater and lakes; watershed planning; and human health risks assessments (Chapter 2). In addition to supporting the integration of watershed and project-level CEA, achieving a culture of open data sharing in the freshwater science sector can maximise the impact of all monitoring activities and expedite the advances of freshwater resource protection and restoration practices (Chapter 3). Estimating the natural range of variation for surface water quality can be useful for watershed CEAs and project-level impact assessments, detecting impacts of climate change, and identifying priority water bodies for restoration (Chapter 4). Restoration of urban water bodies can be more sustainable if projects are informed by similar knowledge used and needed in effective CEA, including long-term regional environmental and socio-economic data, perspectives of rights holders and stakeholders, and insights from disciplinary experts from multiple fields (Chapter 5).

A theme that emerges from considering these four data chapters together is that the study and practice of CEA should advance beyond specialized assessments in Impact Assessment and watershed planning and become a general approach used in freshwater ecosystem protection and restoration. A common barrier to practitioners and government personnel practicing effective CEA is the need for clarification on what CEA is (Arnold et al., 2019). The literature has numerous cumulative effects assessment definitions, which confuse and mistakenly suggest cumulative effects are a particular class of effect when they are simply all stresses influencing a particular ecosystem component (Arnold et al., 2019; Blakley & Russell, 2022; Duinker & Greig, 2006; Sinclair et al., 2017). Myriad activities degrade water quality and quantity across watersheds, including instream activities, water withdrawals, wastewater discharges, and land uses within the drainage area (Sheelanere et al., 2013; Sinclair et al., 2017). Even activities outside a watershed can degrade freshwater habitats, such as atmospheric deposition of contaminants from far away industrial activities (Dastoor, 2021). In addition, effects from natural disturbances, such as floods, droughts, wildfires, and temperature changes, cumulate and interact with anthropogenic effects (Sheelanere et al., 2013; Sinclair et al., 2017). Thus, all anthropogenic activity and natural disturbance effects should be considered cumulative (Duinker & Greig, 2006). Therefore, it would be logical to take a CEA approach when considering decision-making—on any level—for freshwater resource sustainability.

This thesis advances the study of the information provision stage of decision-making for freshwater ecosystem protection and restoration by defining the types of information that should inform freshwater ecosystem decision-making and how that information can be obtained and stewarded. Frameworks are commonly recommended in the CEA and Impact Assessment literature to improve the practice of CEA (e.g., Dubé et al., 2006; Dubé et al., 2013; Noble, 2008; Seitz et al., 2011; Sheelanere et al., 2013; Sinclair et al., 2017). The knowledge needed for effective CEA that is described in this thesis is well established in the literature but assessments generally remain deficient, largely because the knowledge is beyond the capacity of individual projects to collect (Arnold et al., 2019; Ball et al., 2013; Dubé, 2003; Duinker & Greig, 2006; Jones, 2016; Seitz et al., 2011; Sinclair et al., 2017). Thus, CEA frameworks will continue to be unsuccessful because practitioners simply cannot access the information they are being directed to use. This issue is likely to persist for Impact Assessments as project timelines appear more likely to tighten rather than lengthen (Markusoff, 2025). Thus, a framework is likely not what is needed—at this point—to improve CEAs and freshwater decision-making. First, we need a paradigm shift that reestablishes how we fundamentally view data collection—not as a reactive process that simply informs assessment but a proactive process that defines assessments.

There needs to be a shift in where freshwater data collection and knowledge gathering (i.e., community knowledge and perspectives on freshwater management) fits into formal freshwater decision-making processes. The data must first be available, then, frameworks and regulations can be introduced to ensure these data are used as intended. Traditionally, the pursuit of data and knowledge is initiated once an assessment is underway. For example, baseline studies are considered the “first step” in CEAs (Ball et al., 2013; Dubé, 2003). Baseline studies should no longer be considered a pre-impact activity, but instead a continuous activity that monitors “ambient conditions” as climate change continues to alter natural variability. Continuous baseline data collection would lead to long-term and watershed-scale data being available when projects need them. Robust studies that consider cumulative effects can then become a reality.

While project-specific data will likely always be needed, baseline studies should be expanded to collect these data, rather than initiated by project proponents. Baseline studies should be initiated and led at the local level by communities most directly impacted by the resource management decisions in their watersheds. Monitoring programs may be considered more credible without direct oversight or management by a government regulator or industrial proponent (Cronmiller & Noble,

2018). Others have discussed how CEA led by project proponents is ineffective because project proponents are mostly interested in project approval rather than scientific rigour (e.g., Seitz et al., 2011), and the consultants who are hired by project proponents to conduct CEAs are not truly independent (Jacob, 2018). Expanding existing monitoring programs to include project footprints will also make project-level and regional data more comparable as they are collected using the same methods and procedures.

Numerous community-based monitoring programs across Canada are collecting long-term regional data for various purposes, including building robust baselines, understanding the condition of the local environment on which they depend, and monitoring for changes that they can mitigate before they become irreversible. These programs demonstrate that communities already understand the value of proactively collecting data. For example, the Lake Partner Program is a community-based monitoring program that has run for almost 30 years to monitor lake health throughout Ontario (Federation of Ontario Cottagers' Associations, n.d.). Of course, there will be areas that lack community members for CBM, such as remote unpopulated areas or where community members lack capacity or interest in CBM. In these areas, provincial/territorial governments may have to spend more resources on funding and coordinating third-party consultants or internal staff to collect monitoring data. If community-led data collection is promoted and supported, and those data guide formal decision-making processes, then perhaps environmental decision-making will also become localized.

The learnings from this thesis can be applied to design and implement a national approach to freshwater monitoring that will make long-term regional freshwater data and knowledge accessible. Fundamentally changing the way in which decisions are made for freshwater resource management will require a coordinated effort to change the way in which freshwater environments are monitored. To achieve this, an “all-hands-on-deck” approach that gives everyone a meaningful role is required. These roles and recommendations for future work are discussed below.

6.1 A National Approach to Freshwater Data and Knowledge Gathering

6.1.1 National Freshwater Data Standard

It is clear that a freshwater data standard is needed to ensure that freshwater data are managed and shared in a way that makes them reusable and comparable across studies. Interviews with technology

experts suggested that the federal government is well-positioned to lead the collaborative effort of developing a data standard. Fortunately, the newly formed Canada Water Agency (CWA) has made one of its early priorities the development of a National Freshwater Data Strategy (CWA, 2025). They have also already brought together stakeholders from the freshwater science sector to share input on the development of standards (CWA, 2025).

The CWA could also take on the role of coordinating updated national freshwater data collection standards. National freshwater data collection standards have already been developed by the Canadian Council Ministers of the Environment (CCME, 2011). However, some provinces and territories have their own freshwater sampling protocols (e.g., British Columbia Ministry of Environment, 2013). The federal, provincial, and territorial governments could collaborate to update the CCME guidelines so that they work across the country and are widely adopted. Such a national standard will be useful for further advancing the credibility and utility of data from community-based monitoring programs as groups can point to the standard they follow for data collection.

6.1.2 Centralized Data Platform

A centralized data platform is needed for freshwater data to be findable and accessible. The freshwater science sector would likely benefit from a hybrid platform that helps users find and access data from all of the fragmented data sources, and offers a place where new data can be stored. With all of the investment that has gone into creating open data platforms in the public and non-profit sectors (e.g., DataStream, Ontario Open Data Catalogue), it is unlikely that all data holders will be willing to transfer their data to a new platform. If the new platform is user-friendly and becomes popular, organizations may choose to migrate their data to the centralized platform over time and save on resources spent maintaining their own platform. The federal Canada Water Agency is a good candidate organization to coordinate and support the development of a centralized freshwater data platform.

6.1.3 Watershed Planning

Watershed plans are important for collating the available knowledge of current conditions and defining objectives for future conditions that can guide monitoring and decision-making. In addition to baseline biophysical data, an understanding of the perspectives of rights holders and stakeholders, and socio-economic conditions must be gained. Collecting this type of knowledge was beyond the

scope of this thesis. Future research should explore how to ensure that watershed plans have some degree of coordination, so no matter the local values or concerns, there is an underlying suite of components that is being monitored in a standardized way that is comparable across watersheds. Proactively developing watershed plans will ensure that knowledge needed for watershed-scale and project-level decisions is already available, and reduce time and effort needed for individual assessments.

Provincial/territorial governments can be responsible for initiating, funding, and coordinating the development of watershed plans within their jurisdictions. All watersheds should be covered under a watershed plan; less populated areas may have a plan that covers an entire basin, whereas high density areas may have individual plans for small sub-watersheds. Indigenous governments will likely be involved in several plans that address multiple watersheds within their traditional territories. Existing watershed plans should undergo a gap analysis and be updated if necessary. Watershed plans should be regularly updated as new information becomes available and community priorities evolve. The federal government can collaborate with provincial/territorial governments, Indigenous leadership, and disciplinary experts to develop a clear and concise guidance document that outlines the expectations for each watershed plan.

While the methods used to collect freshwater data should be standard, each monitoring program must be tailored to the specific concerns and questions of the rights holders and stakeholders in each watershed. A working group should be established to guide the development of each watershed plan. Once established, the working group can be maintained to guide future decisions regarding freshwater resources, including impact assessments and restoration projects.

6.1.4 Watershed Monitoring

Once the data standard, data infrastructure, and watershed plans are established, then long-term monitoring programs can be initiated by the watershed working group. These monitoring programs can be designed as community-based monitoring programs that either employ community members or are conducted by non-profit organizations who coordinate volunteers. The provincial/territorial and municipal governments should fund monitoring programs as they will be benefactors of these data.

Watershed plans and associated monitoring can be used by government agencies to attract development and investment where it is desired. While site-specific data will inevitably be required, the watershed-scale monitoring data will help illuminate areas that should be avoided for

development and identify candidate reference sites. When a project is proposed, the monitoring program can be expanded to cover the area that is being considered for development. The project proponent can then fund the expanded section of the program. This proposed structure is not meant to alleviate the costs associated with baseline data collection for project proponents, but to reduce the amount of time needed for baseline data collection for each individual project and to improve the robustness and credibility of baseline data. Others have also recommended project proponents help to fund watershed CEAs that can be used to inform their projects-level assessments (e.g., Seitz et al., 2011). Ultimately, the intention is to change the process from one led by project proponents to one that is ongoing and invites project proponents to have a seat at tables that are headed by local communities.

6.1.5 Integrating Project-Level and Watershed Decision-Making

Once established, the watershed planning and monitoring could then fit into a framework for CEA. Numerous CEA researchers and practitioners have identified the need for project-level CEA to be informed by and integrated with watershed CEA (e.g., Arnold et al., 2019; Dubé et al., 2006; Duinker & Greig, 2006; Noble, 2008; Seitz et al., 2011; Sheelanere et al., 2013; Sinclair et al., 2017). The watershed plans could guide local decision-making for project approvals that are integrated with provincial/territorial and federal Impact Assessment processes. Figure 6.1 illustrates how such an integration could look and change current Impact Assessment processes.

Early in the project inception phase, a project proponent can review the watershed plan associated with the location where they wish to operate. Watershed plans would offer project proponents immediate insight into the objectives of the local community, thereby helping them design their project in a way that would likely be broadly supported.

The proponent can then submit their project description to the watershed working group for consideration in the watershed CEA—which would be revised and updated annually. Regular updates will avoid the watershed CEA being a “one-off” assessment and remain an important part of the watershed planning process (Dubé et al., 2013; Noble, 2008). Other CEA researchers and practitioners have recommended that watershed CEA be the responsibility of governments, rather than project proponents, and be implemented within integrated resource management (including watershed) planning, which should take a strategic approach (Dubé et al., 2013; Duinker & Greig, 2006; Jones, 2016; Noble, 2008; Seitz et al., 2011; Sheelanere et al., 2013). However, in this

proposed framework, the CEA would be the responsibility of the collaborative transdisciplinary working group, rather than a single government agency.

The working group would use the findings of the watershed CEA to update the watershed plan and assess proposed projects based on whether or not the predicted negative and positive effects of the project align with the objectives of the watershed plan. Government regulators can then use these local project-level decisions to inform formal project decisions. Projects should not be approved if the working groups object to them. Projects that receive approval from the working group associated with the watershed where the project is proposed should also require approval from other working groups that represent nearby or downstream watersheds that could also be impacted by project activities. In addition, feedback from territorial/provincial and federal government agencies should be sought to ensure the proposed project does not conflict with broader regional or national objectives. Such a process has the potential to prompt more robust assessments that inform environmental decision-making, and transition decision-making power to those who stand to be most impacted by the outcomes of the decisions.

6.1.6 Governance

This approach to watershed planning and management involves collaborative (i.e., bottom-up approaches) that ensure the local context is considered in environmental decision-making. Top-down approaches to watershed management involve high-level (e.g., federal or state) government agencies developing a watershed plan and then informing the local community of the plan (Koontz & Newig, 2014). The watershed planning literature has been recommending and documenting a shift toward bottom-up approaches that involve collaborative processes with local stakeholders that focus watershed planning and management on local objectives (Koontz & Newig, 2014; Mika et al., 2019; Vollmer et al., 2023). However, even in bottom-up governance approaches to watershed management, there are still roles for higher levels of government (Koontz & Newig, 2014; Vollmer et al., 2023).

In the approach described here, the national and provincial/territorial governments play supporting roles in the provision of long-term funding and coordination of watershed planning across the country. The influence and participation of these higher levels of government are required to ensure watershed plans are developed in a manner that is consistent—at least at a high level—to maximize the benefits of data comparisons across watersheds. Further, standardized tools and processes developed by higher levels of government can make the local efforts more effective and

efficient by reducing the need to duplicate efforts. Finally, buy-in and support of the process by higher levels of government are required to ensure the watershed plans actually inform decisions governed by federal and provincial/territorial agencies.

When initiating and conducting watershed plans, it is critical that it is the local governments, rights holders, and stakeholders who are empowered to develop and manage their own watershed plans as they deem appropriate to address their local context. In the approach described here, it is the working group comprised of local rights holders, stakeholders, and government agencies that design and implement the watershed plan and monitoring program. Thus, as previously recommended for holistic watershed management, the decisions and responsibilities associated with each watershed plan will be controlled by the lowest practical level of governance and management and supported by participatory and collaborative processes with rights holders and stakeholders (Vollmer et al., 2023).

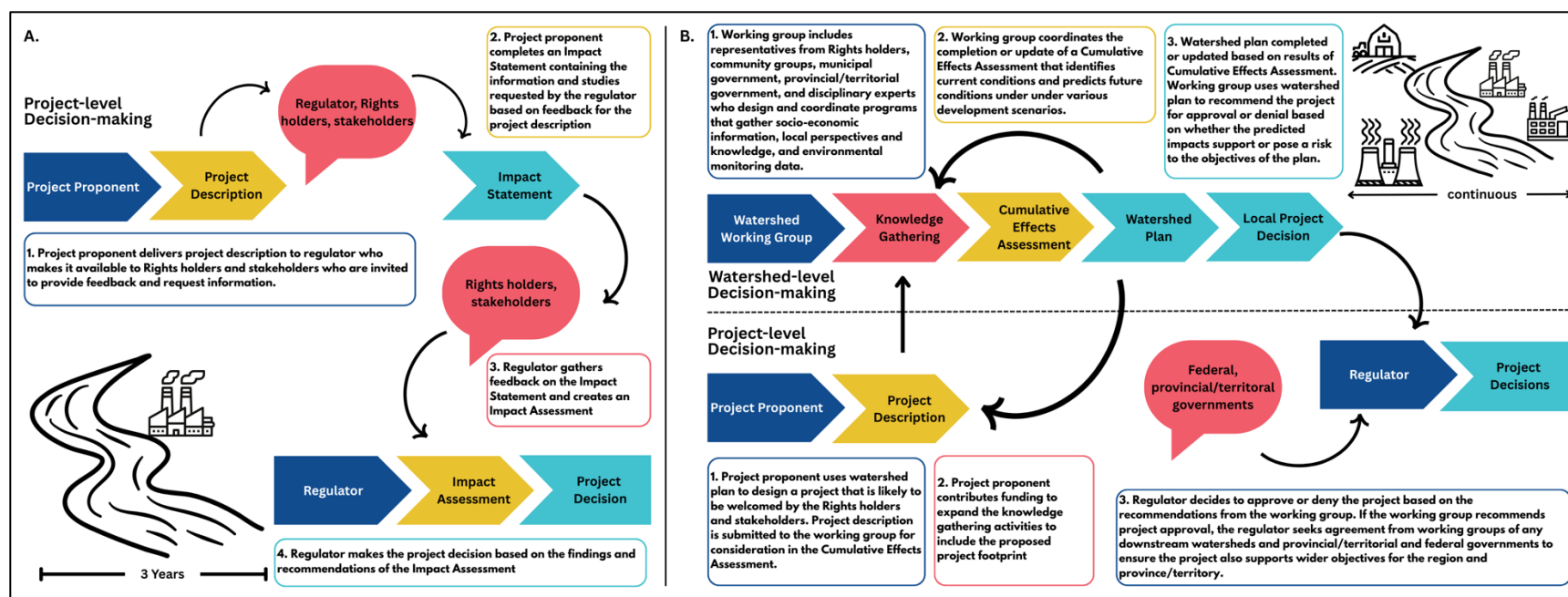


Figure 6.1. A: Illustration of the current federal Canadian Impact Assessment process (Impact Assessment Agency of Canada, 2025) that is led by project proponents and informed by monitoring of project footprints for up to three years. B: Illustration of how the Cumulative Effects Assessment process that is led by watershed working groups and informed by continuous monitoring across the watershed can be used to support project-level decision-making.

6.2 Future Research

Further research is needed to understand if community-based monitoring is a suitable approach for collecting all the information needed for CEA—not just the biophysical data collected using western science methods. This information includes local and Indigenous knowledge, which is essential for CEAs to have a holistic view of environmental and socio-economic conditions. Such a research study could explore how community-based monitoring and community-led research projects have used approaches beyond western science methodology to gain an understanding of past and present environmental and socio-economic conditions, and community perspectives on watershed planning. This research could support the development of guidance for future community-based monitoring programs that aim to support environmental decision-making.

Research is needed to develop and test data collection and monitoring methods that are cost-effective and easy-to-use to support community-based monitoring and wider-scale long-term monitoring initiatives. A review of current methods can be completed by searching the grey literature for standardized monitoring procedures and the academic literature for novel approaches. Interviews of practitioners can complete the picture of conventional practices. A workshop can then be hosted that presents current monitoring approaches to freshwater scientists, community groups, engineers, and software developers who can then brainstorm together on how to make the conventional approaches more user friendly and cost-effective.

A research project is needed to develop and test data analysis methods that can be standardized and widely accessible. For example, I created an R package on behalf of the Government of the Northwest Territories who wanted government personnel and practitioners to be able to use the Natural Range of Variation calculations. However, those who are unfamiliar with R programming may be hesitant to use the R package. An alternative approach that could be tested would be to build a webpage that is designed to allow users to upload their data and run the NRV calculations by simply clicking a button, which would execute the R code for the user in the backend of the webpage. This webpage would not only make it easier for practitioners to analyse their data but also community members who could be empowered to analyze the data they collect. A research project could be designed as a case study that works with freshwater scientists, user experience experts, software developers, and community monitors to develop and test a system that allows community members to manage and analyze their own data. Possible long-term community-based monitoring programs that could be considered for the case study include the Indigenous Observations

Network, NWT-wide Community Based Water Quality Monitoring Program, or the Lake Partner Program.

A research project is also needed to explore sustainable funding models for long-term watershed monitoring. Previous studies have identified funding as a key limitation to watershed CEA (e.g., Chilima et al., 2013). Future research could investigate sustainable (i.e., green) financing solutions (e.g., green bonds, biodiversity credits) that could help to alleviate the financial burden of watershed monitoring for the public service.

Most importantly, future research is needed to demonstrate the value of effective environmental decision-making for the private and public sectors and the public. The results of the 2025 Canadian federal election showed that a large proportion of the population voted for a party that framed Impact Assessments as “anti-development.” During his campaign to become the prime minister of Canada, Mr. Pierre Poilievre outlined his plan to change federal legislation to expedite approval processes for resource development projects, stating “*We will unleash the production of our resources for our own benefit*” (Sarfraz, 2025). While concerns about the time and effort required for environmentally sustainable Impact Assessment are understandable, so too is the incentive to avoid the resource development mistakes of the past that led to long-term costs far outweighing the short-term benefits. For example, Giant Mine, which operated from 1948 to 2004, requires significant remediation to contain legacy arsenic contamination, costing Canadian taxpayers upfront \$1 billion along with perpetual care costing of \$2 million annually—forever (O’Reilly, 2015; Gavel et al., 2018; FWCO, 2020). A research study is needed to quantify the environmental and socio-economic costs of previous projects that were approved without robust assessments and/or decision-making practices. Ultimately, the changes I have proposed in this chapter are only realistic if the public, policy makers, and private sector understand and appreciate the importance and value of effective environmental assessments, which are not meant to block development but facilitate wise choices that actually achieve net positive outcomes now and into the future.

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Appendix A
Supplemental Materials for Chapter 2

Appendix A External Resources

The following supplementary materials are available in the GitHub repository:

<https://github.com/J2Kidd/ThesisSupplMaterials>

External Resource A.1: Master Community-based Monitoring Project List (Excel File)

External Resource A.2: Community-based Monitoring Project Inventory (Excel File)

External Resource A.3: Community-based Monitoring Project Scores and Characteristics (Excel File)

Appendix A Tables

Table A.1 Valued Ecosystem Components (VEC) and environmental indicators monitored in the evaluated community-based monitoring (CBM) projects.

VEC	Indicator	Example Methods	Example Parameters	Project Count (Total 40)
Surface Water Quality	In-situ water quality	Hand-held meter Sondes/Data logger Secchi Disk	Temperature, EC, DO, pH, Turbidity Water clarity	10
	Water Chemistry	Grab sample	Nutrients, metals	12
	Sediment Chemistry	Grab sample		2
Wildlife Species	Condition	Observations Tissue samples	Abnormalities Mercury, PCBs	10
	Movement	Observations	Movement patterns	2
	Population Structure	Observations	Age, sex	6
	Presence/Abundance & Distribution	Observations		5
	Traditional Use Species	Observations	Number of species harvested	8
Wildlife Habitat Quantity	Habitat Availability & Suitability	Observations	Habitat range, habitat use	2
Fish and Fish Habitat (include shellfish)	Movement	Observation	Migration timing	3
	Population Structure	Measurements Samples	Length, weight, sex, fecundity, age	4
	Fish Condition	Observations Tissue samples	Abnormalities Mercury, metals, hydrocarbons	7
	Abundance, Presence & Distribution	Observations	Catch effort, species identification	5
	Fish Habitat	Samples	Benthic invertebrate community	3
	Traditional Use Species	Observations	Number of species harvested	7
Cryosphere	Snow Temperature	Measurement		2
	Snow Depth	Measurement		5
	Ice Thickness	Measurement		6
Surface Water Quantity	Water depth	Measurement		1
	Water Flow	Measurement		4
Groundwater Quantity	Water level	Measurement		1
	Water Level	Data Logger		2
Groundwater Quality	Water Chemistry	Grab sample		1
	Water Temperature	Measurement		1
Climate Change	Weather	Observations Weather Stations	Wind direction, wind speed, air temperature, humidity	5
Air Quality	Air Chemistry	Meter	Radon gas levels	1
	Odorous Emissions	Observations		1
Noise	Sound level	Sound recording meter		1
Vegetation Habitat Quality	Vegetation Health	Tissue samples		2
Plant Species Distribution	Presence/Distribution	Observations	Seasonal abundances	3
	Traditional Use Species	Observations	Number of species harvested, harvest locations	2

Document A.1

Standardized E-mail

[Salutations]

From Environment and Climate Change Canada (ECCC) personnel

(salutation of your choice)

We are creating an inventory of community-based monitoring programs that monitor environmental change. For this study, we define community-based monitoring programs as programs in which the data are primarily collected by local people, who may have received training/guidance from professional researchers, and the data are used by either the local community and researchers, or just the local community. Please let us know if you are aware of any projects or programs that fit this description and could direct us to a source for further information (e.g., program website, reports, journal articles, program manager). Canadian programs are the focus of the study, but notable international examples are of interest as well.

Thank you for your time.

(insert signature)

From Jess Kidd

(Good morning/afternoon)

I am currently working with Environment and Climate Change Canada to create an inventory of community-based monitoring programs that monitor environmental change. For this study, we define community-based monitoring programs as programs in which the data are primarily collected by local people, who may have received training/guidance from professional researchers, and the data are used by either the local community and researchers, or just the local community. Please let me know if you are aware of any projects or programs that fit this description and could provide a source for further information (e.g., program website, reports, journal articles, program manager). Canadian programs are the focus of the study, but notable international examples are of interest as well.

Thank you for your time.

(insert signature)

Document A.2

Project Attribute Description and Scoring Rationale

1. Data Collection Protocols

This criterion scored the projects based on whether rigorous and repeatable data collection protocols were consistently used and reported. Data collection methods should be standardized to collect defensible data that can inform western science approaches to regional CEA (Gérin-Lajoie et al., 2018; Hunsberger et al., 2005; McKay & Johnson, 2017a). Standardized monitoring methods are essential to compare datasets across space and time, evaluate trends, and understand regional conditions to support sustainable development (Miller et al., 2022). Standardized monitoring protocols would open possibilities for the centrally managed public data repositories needed to support regional CEA (Ball et al., 2013; Environment and Climate Change Canada [ECCC], 2016; Foley et al., 2017; Miller et al., 2022; Sheelanere et al., 2013). Successful project-level and regional CEA integration requires standardized long-term monitoring methods (Arnold et al., 2019; Dubé et al., 2006; Foley et al., 2017). McKay and Johnson (2017b) found that government and industry representatives believed the effectiveness of CBM projects depended on rigorous, robust, and defensible methods. Furthermore, standardized monitoring approaches facilitate earlier detection of environmental effects and can improve adaptive management (Roach & Walker, 2017).

The purpose of this criterion was to score the projects based on whether rigorous and repeatable data collection protocols were consistently used and reported. The scores were categorized as:

1. No explicit data collection protocol reported or referenced. No indication a protocol exists for community members.
2. An indication a protocol exists, but no other details. An indication of protocols includes mention of monitor training but lacks a description of the training.
3. A protocol clearly exists, and some description of what it entails is provided. This includes statements that monitors are trained to use standardized protocols, including monitoring forms, but the protocol itself is not mentioned or described. Or there is evidence the protocol has not been consistently used throughout the project.
4. It is clear that project participants follow a set protocol that is described to repeatedly collect data, but the protocol itself is not available.

5. Project participants follow a set protocol to repeatedly collect data, and the protocol itself is easily accessible. This includes reference to standardized protocols and the source or citation for that protocol.

2. Project Duration

This criterion defined the number of years the project has been collecting monitoring data. Cumulative effects monitoring, assessment, and management are long-term processes (ECCC, 2016; Hegmann et al., 1999). Long-term monitoring data are needed to inform robust baseline studies that better define natural variability, identify deviations from that variability, and produce more accurate impact prediction models (Dubé et al., 2013, Duinker & Greig 2006, ECCC, 2016; Roach & Walker, 2017). Long-term monitoring before and after developments also helps identify when and where mitigative measures are needed and supports adaptive management (Dubé et al. 2013; Duinker & Greig, 2006; ECCC 2016; Roach & Walker 2017). The duration of a CBM project is also an indicator of its success in holding the interest of participants and funding agencies.

The total number of years did not include the time during which the project was designed or any years when the project was on hold (i.e., we only included years when data were collected in the total duration calculation). We did not include 2020 in the duration calculation for ongoing projects, as the sampling period for all projects would not have occurred by the time we completed our study. The duration of projects in the inventory ranged from 1 to 29 years, with a median of 8 years (Figure 1). We used data from an initial project inventory to generate a typical range of project duration. We divided this range into four equal-sized categories, with an additional category representing exceptionally long projects. The scores were categorized as:

1. 1–5 years
2. 6–10 years
3. 11–15 years
4. 16–20 years
5. >20 years

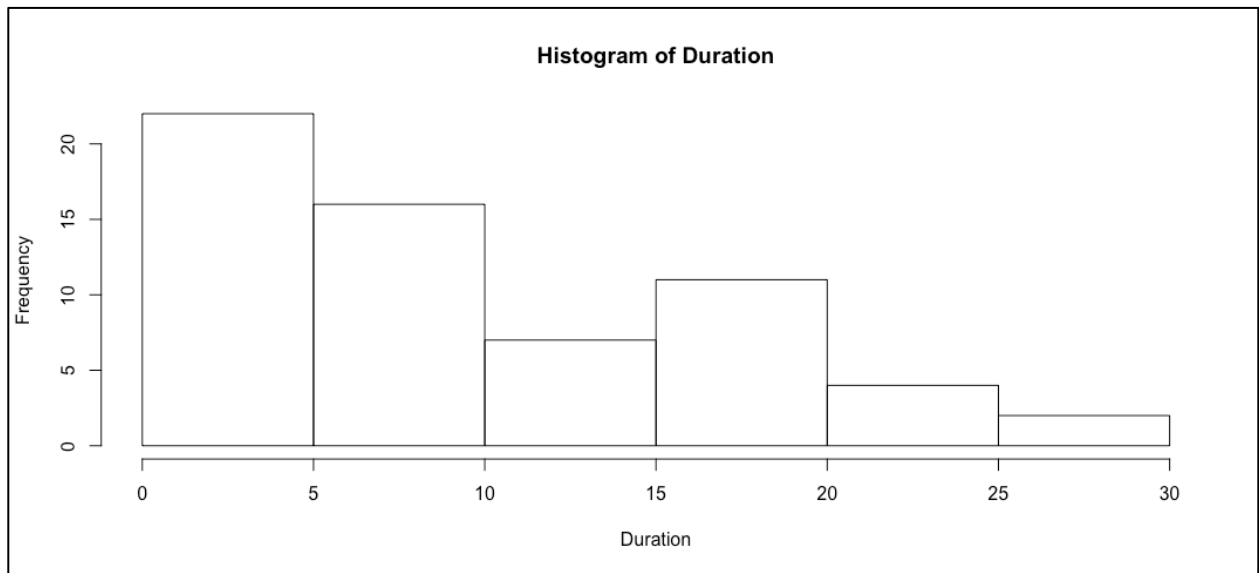


Figure 1. Histogram of the project duration of the 62 projects in the project inventory.

3. Spatial Scale

This criterion scored the project based on the project's reported study area size. Scholars widely agree that effective CEA requires a regional approach (Arnold et al., 2019; Chilima et al., 2013; Dubé et al., 2006; Dubé et al., 2013; Duinker & Greig, 2006; Gibson et al., 2020; Foley et al., 2017; Johnson et al., 2011; Jones, 2016, Noble, 2008). Thus, it is important to identify projects that are monitoring at a larger spatial scale. CBM projects that monitor larger spatial scales also demonstrate greater logistical complexity in coordinating monitoring efforts across a larger area.

For projects that monitored harvesting data and did not define a study area size, we estimated a 100 km radius (i.e., 31,416 km²) for each community that participated. The size of study areas monitored by the projects in the inventory ranged from 5 to 1,100,000 km², with a median of 3,939 km². (Figure 2). The scores were categorized as:

1. Study area <500 km²
2. Study area <5,000 km²
3. Study area <50,000 km²
4. Study area <500,000 km²
5. Study area >500,000 km²

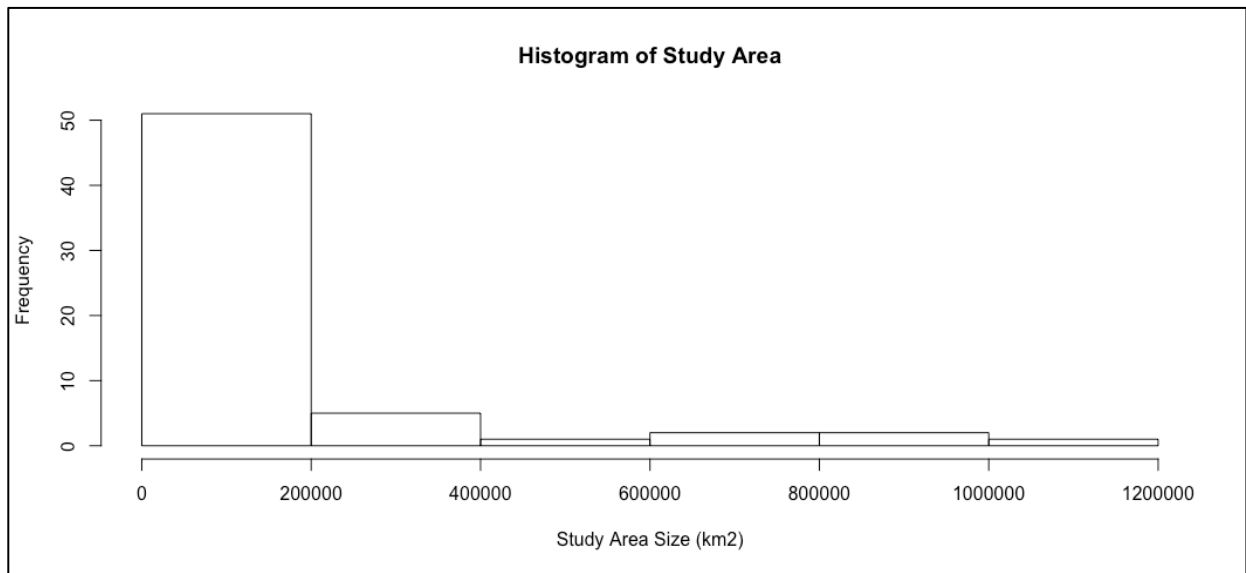


Figure 2. Histogram of the study area sizes of the 62 projects in the project inventory.

4. Project Participants

Cumulative effects monitoring, assessment, and management require coordination of activities among multiple participants (ECCC, 2016). CBM projects demonstrating coordination success, particularly the capacity to coordinate numerous communities, are valuable models. This criterion scored the projects based on the number of communities or the number of non-profit groups that routinely participated in the project and was meant to help understand the scope of the logistics and coordination required to operate the project. This criterion was also meant to reflect how many communities/groups can be expected to be involved in one project. We scored some projects based on their number of volunteers because the number of communities or non-profit groups was not provided.

The number of communities or non-profit organizations participating in projects in the inventory ranged from 1 to 35, with a median of 2 (Figure 3). We used data from an initial project inventory to generate a typical range of community participants. We used this range to define three equal-sized categories above 1, with an additional category representing abnormally large participant numbers. Some projects were scored based on their number of volunteers, because the number of communities or non-profit groups were not provided. and the number of volunteers ranged from 5 to 600 (Figure 4). The scores were categorized as:

1. 1 community/non-profit
2. 2–4 communities/non-profits
3. 5–7 communities/non-profits
4. 8–10 communities/non-profits
5. >10 communities/non-profits

OR

1. <10 volunteers
2. <100 volunteers
3. >100 volunteers

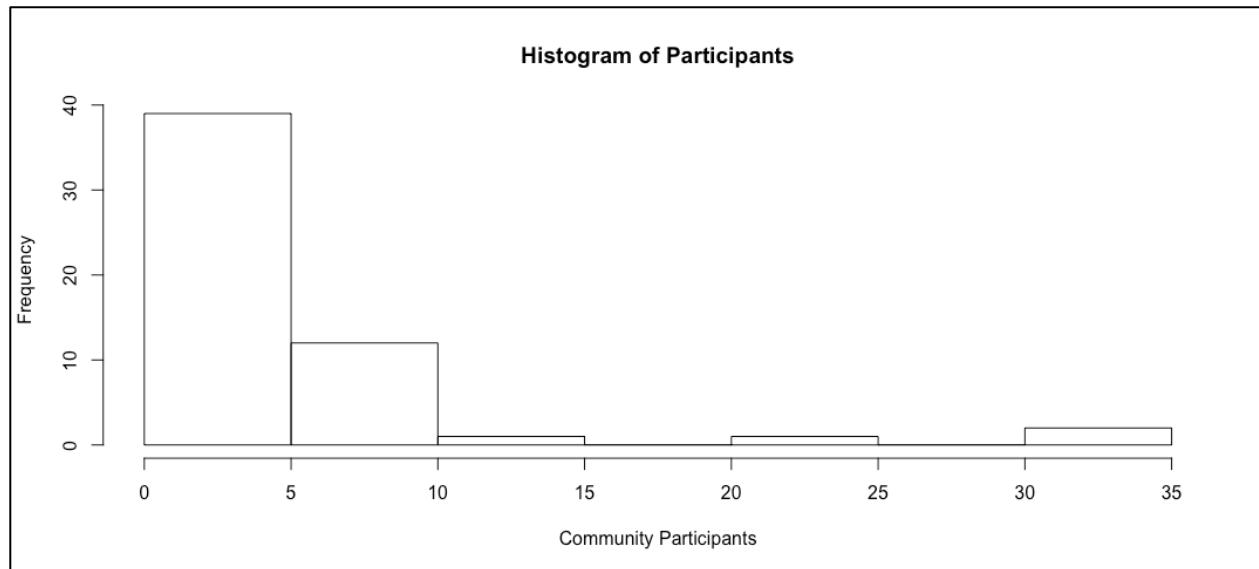


Figure 3. Histogram of the number of community participants of the 62 projects in the project inventory.

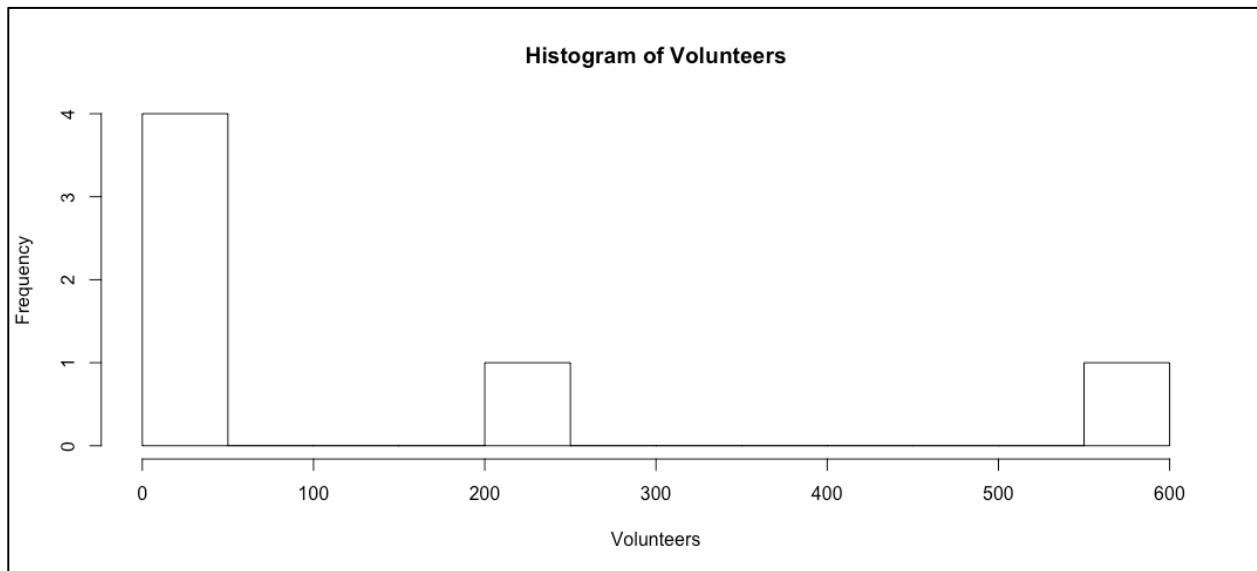


Figure 4. Histogram of the number of volunteer participants of the 62 projects in the project inventory.

5. Data Management and Communication

This criterion scored the projects based on data management and protocols that clearly articulated data handling and management procedures for analysis and regularly communicated results. Data management is critical to effective cumulative effects monitoring (ECCC, 2016). Data management systems can improve the integrity of monitoring projects and facilitate effective communication of data to partners, rights holders, stakeholders, and the public. Data management systems and communication are also essential when data from cumulative effects monitoring are used to develop management actions or responses (ECCC, 2016; Kipp et al., 2019; McKay & Johnson 2017a). The score categories were confined to three scores, as we found only three explicit variations in data management. The scores were categorized as:

1. No explicit indication that data are managed and stored using any particular technique.
An indication that data are stored, but no other details.
3. Where and how data are managed is clear, but it is not clear whether data can or have ever been analyzed. Data may be available through a database but no indication of data analysis and results being communicated through reports or outreach materials. This includes when results are communicated in peer-reviewed publications (i.e., results withheld for publications or thesis).
5. It is clear that data are analyzed, and results have been communicated in reports or outreach material to the community.

6. Monitoring frequency

This score was based on the frequency of data collection for the indicators routinely monitored by the project. If project-specific frequencies varied among indicators or variables, we used the most frequent sampling for the scoring. We used this scoring criterion to understand if data collection protocols included consistent data collection and if the data could capture temporal variability. In addition, this criterion helped identify projects that required greater involvement and commitment by project coordinators and participants throughout the year (i.e., does the project only operate during one month of the year, or does sampling occur throughout the year).

Some monitoring parameters only need to be sampled annually; however, monthly monitoring is recommended for other variables to understand seasonal variability clearly. As such, programs demonstrating the capacity to collect monitoring data throughout the year are particularly valuable and applicable to CEA. One of the purported benefits of CBM is more robust datasets that include data collected throughout the year (Gérin-Lajoie et al., 2018). Regardless of timing, samples should be repeatedly collected during specific times of the year to allow robust trend analysis (Carlsson et al., 2015). The scores were categorized as:

1. Opportunistic (i.e. inconsistent sampling periods)
2. Annual (i.e. 1x per year)
3. Biannual (i.e. $\geq 2x$ per year)
4. Seasonal (i.e. $\geq 4x$ per year)
5. Monthly (i.e. $\geq 12x$ per year)

7. Data Application

The purpose of this criterion was to rank the projects based on whether the data were used to inform decisions. Cumulative effects data are meant to be used in environmental policy, management, and decision-making (ECCC, 2016; Kipp et al., 2019). The hope for CBM is that decision-makers will respect and use the data to inform decisions (McKay & Johnson 2017a; Theobal et al., 2015). Some view CBM as an avenue for communicating with communities, while others see it as a data source to inform decisions (Kanu et al., 2016; McKay & Johnson, 2017a). Hence, it is important to identify whether the data were actually used to inform decisions. For example, the Indigenous Observation Network's data directly informed the Yukon River Watershed Plan (Living Lakes Canada, 2020), so it received a Data Application score of 5. The scores were categorized as:

1. No mention of objective for data, or acknowledgement that decision-makers do not consider the data.
2. The stated objective is to monitor change, but no mention of the decisions that will be informed by this monitoring data (e.g., caribou populations are monitored to document if populations are declining overtime). This ranking defines those projects that state the purpose of their data, but does not define who is supposed to use the data to make decisions (e.g., we collected water samples to identify phosphorous hotspots. No information is provided as to who will use this information, or how identifying phosphorous hotspots will inform decisions)
3. The objective for the data is to inform decision-makers, but no details are provided as to how decision-makers will use the data (e.g., caribou populations are monitored to inform the resource management board). This ranking defines projects that state the proposed objective for the data and who the data is meant to be used by, but doesn't provide a clear indication of how that data can be used to inform decisions (just because they send their data to an industrial proponent, doesn't mean they consider it).
4. Details for how decision makers can use the data and what decisions will be informed by the data are provided (e.g., caribou populations are monitored to inform resource management board's decision for the number of caribou tags to release each year). This ranking defines projects that clearly describe the objective for the data and how that objective will be fulfilled. So, who the data is used to make decisions, and what decisions do they use the data for?
5. Evidence is provided that decision-makers consider the data and have used it to inform decisions (e.g., in 2015, the resource management board reduced the number of caribou tags after reviewing

the project data that revealed a sustained downward trend in caribou abundances), or evidence is provided that the data has been incorporated into a decision-making process/framework (e.g., land use and management plans).

8. Data Availability

This scoring criterion was meant to define the availability of data in a form that can be analyzed and interpreted by those not directly associated with the project (e.g., project database or technical reports that present data tables). Effective regional CEA requires project-level and regional monitoring data to be available to government agencies, project proponents, rights holders, and stakeholders across the region (Ball et al., 2013; Dubé et al., 2013; Foley et al., 2017; Johnson et al., 2011; Miller et al., 2022; Sheelanere et al., 2013). ECCC (2016) describes the importance of publicly sharing cumulative effects data for management actions and decision-making. Effective data communication is especially critical when data are meant to be used to develop management actions or responses (ECCC, 2016; Kipp et al., 2019; Moyer et al., 2008). The scores were categorized as:

1. No mention of data being available for use by anyone. Also includes projects where the data do not appear to be directly available to the community.
2. Data are available to the community only.
3. Data are available to the community and project partners, or when data are only made available through scientific publications.
4. Data are available to the public, but only by request, or there is no evidence of the project data being readily available online. Or, the data are publicly available, but available data are not up to date (i.e. publicly available data is older than 2018).
5. 2018 and older data are readily available to the public.

Document A.3

Description of Project Characteristics

Below is a description of each project characteristic (i.e., explanatory variable) that was evaluated for each project.

1. Land Claim Structure

The land claim structure for each project was determined using the Government of Canada's (GC's) Pre-1975 Treaties (GC, 2019a) and Post-1975 Treaties (GC, 2019b) datasets, which define the boundaries of historical treaties and modern land claims. The study areas were located on the GC's Open Maps Data Viewer to identify the land claim structure(s) for each project. This characteristic will help to understand whether the establishment of co-management structures through modern land claims have had an impact in supporting CBM projects, or if any particular land claim structure is associated with higher scoring CBM projects. This characteristic was identified for both Indigenous and non-Indigenous projects. The land claim structure categories were:

- Unceded
- Modern Land Claim
- Pre-1975 Treaty
- Peace & Friendship Treaty

2. Data Collection Methods

The general methods used to routinely collect monitoring data were identified for each project. Data collection methods will help to illustrate the capacity for CBM projects to collect various types of data, including qualitative and quantitative data. Quantitative methods increase the range of application of CBM data and increase the interest of funding agencies (Gofman, 2010).

In addition, this project characteristic will help to understand if certain methods are employed more often to monitor certain VECs and indicators. The data collection method categories were:

- **Interviews:** data were collected through interviews or surveys that document/record the observations of others.
- **Observations:** data were collected directly by monitors who document/record their observations while in the field.
- **Measurements:** data are collected by recording measurements in the field by community members. Measurements can be manual measurements by a person or electronic recordings (e.g., air and

water quality devices). These do not include measurements made by professional researchers or laboratory technicians on the samples collected by the community members.

- **Sample Collection:** data were collected by a sample being removed from the field and further evaluated elsewhere.

3. Paid Monitors

Compensating community members for their time has been identified as a key element in the success of CBM projects (Johnson et al., 2016; Kouril et al., 2015; Parlee et al., 2017). It was identified (Yes or No) if the community members were compensated for participating in monitoring activities.

4. Use of Indigenous Knowledge

For the purpose of this study, Indigenous Knowledge (IK) refers to both traditional and contemporary knowledge held by Indigenous community members. ECCC recognizes IK as a critical component of CEE monitoring (ECCC, 2016). Incorporating IK into monitoring activities has been identified as a key element of CBM project success (Gofman, 2010; Johnson et al., 2016; Kouril et al., 2015, McKay & Johnson, 2017b, Parlee et al., 2017). Industry proponents have also identified the access to IK would be a benefit of CBM, as they do not have the tools to collect IK (McKay & Johnson, 2017a).

It was identified (Yes or No) if the project **explicitly** described incorporating Indigenous Knowledge (i.e., traditional knowledge, local knowledge) into the project design, data collection, or data analysis and interpretation.

5. Routine Training Frequency

Routine training has been suggested as a successful component of CBM projects (Carlsson et al., 2015). The objective was to identify the typical training effort required to maintain the project, and if training was a routine component of the project coordination and execution. Training frequency was assessed based on the active training (e.g., field training, classroom sessions) conducted for the project; the frequency of passive training, such as training manual or video review, was not assumed.

It was identified (Yes or No) if the project described community member training occurring on a routine basis (e.g., annual, every field season).

6. Trainer

It was identified who typically delivers the training to the community members to understand which project partner typically conducts the training. The trainer categories included:

- **Government:** staff/personnel from a government agency (federal, provincial/territorial, co-management/local resource management board, regional/municipal/Indigenous)
- **Community:** members of the community (e.g., elders) provide training
- **Academic:** researcher or instructor from a post-secondary institution
- **Consultant:** scientists/technicians from an independent consulting company provides the training
- **Non-profit:** non-government organization that is not operated as a for-profit business. Can be a research network or institute.
- **Project alumni:** community members who participate in the project and begin to train other community members once they have gained experience.

7. Training Techniques

CBM projects involve various methods to facilitate collaboration between community members and scientists (Gérin-Lajoie et al., 2018). Training and collaboration opportunities have been identified as a key element for CBM project success (Johnson et al., 2016; Kouril et al., 2015). Training techniques included:

- **Remote training:**
 - Training manual
 - Training video
 - Online course
 - Remote presentation
- **In-person training:**
 - Field training
 - Meetings/workshops

- Land camps
- Classroom

8. Intergenerational Engagement

Previous studies have suggested that elder and youth engagement activities are key project characteristics for successful CBM projects, because it increases the level of interest and involvement from the community (Gérin-Lajoie et al., 2018; Knopp et al., 2013).

It was identified (Yes or No) if the project included youth and/or elder engagement activities.

9. Data Objective

CEE data is meant to be used to inform management actions and decisions (ECCC, 2016). Appropriate responses to environmental change require data that can inform policy and decision-making (Kipp et al., 2019). Linking data to decision making has been identified as a key characteristic of successful CBM projects (Kouril et al., 2015; McKay & Johnson, 2017b; Parlee et al., 2017). This identified the proposed uses for the data collected by the project. Only the objectives that were explicitly described in the project description were recorded. The categories for data application were:

- **Baseline:** the objective is to collect baseline data to understand the conditions of the study area prior to a proposed project, or to understand the natural variability of the area to understand future changes from various anthropogenic impacts
- **Cumulative Environmental Effects:** the objective is to collect data to understand/monitor the effects of multiple anthropogenic influences
- **Industrial Compliance:** the objective is to collect data to monitor the impacts of a specific industrial project's operations and/or monitor the effectiveness of mitigative measures in place by the industrial proponent.
- **Conservation:** the objective of the data is to apply it to conservation initiatives
- **Treaty/Harvesting Rights:** the objective is for the data to be used to protect or inform treaty and/or harvesting rights
- **Research:** the objective of the data collection is to answer a research question

- **Resource Management:** the objective of the data collection is to inform either fish and wildlife management decisions, general resource management decisions, or land use and watershed planning
- **Human Health and Safety:** the data are collected to prevent or assess risks to human safety and/or safety (i.e., prevent physical injury or illness). For example, ice thickness is monitored to inform the community of where it is safe to travel, or moose tissue samples collected to monitor human health concerns of mercury poisoning

10. Data Communication

Sharing monitoring results to partners, stakeholders and the public is a critical step of CEE monitoring (ECCC, 2016). The distribution of project results to community members is a key element to a successful CBM project (Eamer, 2011; Gofman, 2010; Johnson et al., 2016; McKay & Johnson; 2017b). However, communicating project results back to the community members who collect the data has been identified as a difficult task and there is a need to improve how results are communicated and make the accessible to the local community (Noble & Birk, 2011). There are various communication techniques used within and across CBM projects (Eamer, 2011). As such, we wanted to investigate the various data communication techniques and see which were common amongst the highest scoring projects. Data communication methods included:

- **Online tools:**
 - Database: the data are available for access through an online database. Note: this is different from the data simply being managed/stored in a database.
 - Georeferenced database: the data are presented in a georeferenced format, where people can view and locate data based on the sampling site location
- **Science Communications**
 - Peer-reviewed publication, including theses
 - Conference presentation
- **Reports:** documents created to present the findings of the project. These reports are meant to present the project findings to various stakeholders.
 - Routine: data are communicated in a report as a routine component of the project (e.g., once a year through an annual report)

- Non-routine: report the details the findings of the project either at the end of the project or after the project initiation (i.e., pilot phase).
- **Community outreach materials:** Community Outreach Materials: Materials created to communicate project findings to the community. Materials created to communicate project findings to the community (e.g., brochures, plain language report, visuals, report cards, data summaries, and newsletters).

11. Data Collection Technology

The use of innovative technology has been recommended to improve CBM projects (Kipp et al., 2019; Kouril et al., 2015). Previous studies have concluded that the design of a project-specific app would provide benefit to the program. For example, Thompson et al. (2019) received feedback from program participants that a digital app designed around the logbooks they were using to gain information from harvesters would improve future participation. The purpose of this criterion was to understand if technology is helping advance projects, and identify the technology and/or equipment used by the community members to collect data. The data collection technology categories were:

- **App/software:** An application or software installed on a computer/IPAD that is used in the field to record observations and enter field data
- **Data recording device:** any device that is used to record observations or measurements (e.g., wildlife cameras, water quality meters, air quality monitors)

12. Data Management Technology

Data management is a critical component of any monitoring program. Thus, it is important to understand what projects are currently doing to manage their data effectively. In particular, it will be valuable to understand if certain data management technologies are related to higher scoring projects. Hunsberger et al. (2005) recommended CBM monitoring data should be stored in a searchable digital database, which can help to reveal relationships between the environment and human activities. Ultimately, it will be interesting to see how data are managed for projects that effectively communicate their data to the community and project partners. Categories of data management technology included:

- Project-specific database
- Third-party database (i.e., network or open-source database)

13. Funding Sources

Long-term sustainable funding is critical to ensure the long-term success of CBM projects (Carlsson et al., 2015; Gérin-Lajoie et al., 2018; Johnson et al., 2016; Kouril et al., 2015; McKay & Johnson, 2017b). The purpose of this criterion was to identify the various funding sources for CBM projects, and understand the typical number of different sources for each project. Funding sources included any source of monetary funds for the project design or operation. Funding sources did not include in-kind support. Categories of funding sources included:

- Public
 - Federal (non-Canadian) government
 - Federal government
 - Provincial/Territorial government
 - Municipal/Regional/Indigenous government
 - Crown corporation
 - Co-management/Local resource management boards
- Private
 - Community: individual members/citizens from the community
 - Industry
 - Academic: post-secondary institution
 - Indigenous: organizations with an Indigenous focus
 - Non-Profit (e.g., NGO, Foundation)

14. Project Partners

Multiple partnerships have been identified as fundamental to the success of CBM projects (Carlson & Cohen, 2018; Eamer, 2011; Kouril, 2015; McKay & Johnson, 2017b). Project partners are similar to funding sources, but do not necessarily provide monetary support to the project. Project partners may instead provide training, study design guidance, data management and analysis support, or use the data collected by the project. Similar categories to funding sources were used.

15. Bridging Organization

The purpose of this criterion was to identify if bridging organizations act as liaisons between the community and researchers and/or government agencies. Bridging organizations are believed to be useful in providing a project coordinator communities trust and help build relationships between other project partners (Wilson et al., 2018). It is important for the project to be administered by a local agency, such as a renewable resource board, to ensure ongoing community engagement (Carlsson et al., 2015; Little et al., 2015). Projects should partner with a local agency to make it meaningful locally (Gofman, 2010). It will be valuable to understand if the higher scoring projects appear to be using bridging organizations to understand if these are indeed key elements to consider for future CBM projects.

The bridging organization was scored as a “1” if the bridging organization was a non-profit agency, co-management board, or consultant, and scored “0” if the bridging organization were a government agency or academic.

16. Community Involvement

It is important in CBM for community members to be treated as knowledge holders and included in the project design, and analysis and interpretation of results (Wilson et al., 2018). Projects should be co-designed with the community (Mahoney et al., 2009). Using local knowledge to inform sampling station placement is important (Mahoney et al., 2019). It has also been suggested that scientists need to transfer data collection and management skills to the community members to make the CBM sustainable (Thompson et al., 2019). The purpose of this criterion was to understand the project components that the community members are involved in, in addition to data collection. The project components included:

- Project design
- Data management
- Data analysis and interpretation
- Data reporting

Document A.4

Cross-Validation Results and Interrater Agreement Analysis

Cross Validation No. 1

The following clarifications and changes were made to the data dictionary based on the authors discussion of the cross-validation results:

- We removed the VECs/Indicators from the project scoring as there were too severe of a disagreement among the authors.
- Project Duration: clarified if the project were only hold during the project timeframe, those years would be subtracted from the project duration calculation
- Spatial Scale: If a project does not have a defined study area, then it will be assumed that each community has a 100 km radius in which harvester travel on the land, which will contribute 31,416 km² to the study area size.
- Project Participants: We will count the number of non-profit organizations involved in volunteer-based projects if individual communities are not mentioned. Both the number of groups and the number of volunteers will be tracked.
- Redefined the Data Application criterion.
- Clarified for Data Availability that a score of 3 applies to projects where data are published publicly, but only in scientific manuscripts.
- Clarified for Monitoring Frequency that a score of 1 should be assigned to projects that do not sample at routine times each year.
- Refined project personnel position to include only positions, other than monitors, that community members hold.
- The use of IK will only be documented if the project explicitly mentions its use
- The data objectives of mitigation and compliance were combined into “compliance”
- Watershed and land use planning objectives were combined into “planning”
- Training Frequency and Trainer project characteristics were added

Cross Validation No. 2

We completed an interrater agreement analysis individually for all project attributes and characteristics using the following scripts in R:

Calculating Interrater Agreement

Script for Project Scores

```
>protocol_3<-matrix(c(
+ 5,3,5,4,3,5,5,2,4,3,
+ 5,3,5,4,2,5,1,1,4,5,
+ 5,5,5,5,4,5,5,1,4,3), byrow = TRUE, nrow=3)
>kripp.alpha(protocol_3,"ordinal")
```

Script for Project Characteristics

```
meeting<-matrix(c(
0,1,0,0,1,0,0,1,0,0,
1,0,0,1,1,1,1,1,1,1,
0,0,1,1,1,0,1,1,1), byrow = TRUE, nrow=3)
```

```
kripp.alpha(meeting)
```

We closely evaluated all interrater agreement scores <0.4 and evaluated how the methods could be improved to increase their repeatability. There was some confusion over the definition of several project characteristics. Once the confusion was cleared, the data dictionary was refined to ensure the description clearly described the intention for the project characteristic. These project characteristics included:

- **Data Management and Communication:** was the only scoring criterion that had a repeatability of 0.3. As a result, the scale for this scoring criterion was reduced from 1 through 5, to 1, 3, 5. All ratings of 2 were reduced to a 1, and all ratings of 4 were increased to a 5. This resulted in a repeatability measure of 0.5. The data dictionary was updated to reflect the new scale.
- **Data Collection Methods** – there was confusion over what constituted a measurement (e.g., laboratory analysis vs community members measuring the length of a fish). It was clarified in the data dictionary that “measurements” referred only to measurements made by community members to collect data.

- **The Elder and Youth Engagement:** categories were changed to stand-alone categories from their original placement under both the Training and Data Communication sections. These had an interrater agreement of 0.8 and 0.9
- **Training Frequency:** re-categorized from Unknown, Infrequent, Annual, and Sampling Event to Infrequent and Routine. This resulted in interrater agreements of 0.4 and 0.5.
- **Field Training:** there was confusion over what constitutes field training. It was clarified in the data dictionary that field training was any time a trainer was physically present in the community and provided hands-on training for the data collection, outside of a classroom setting. So, workshops where the monitors would go with a trainer and collect water samples from a river is considered field training.
- **Data objective:** the three Resource Management Categories (Fish and Wildlife management, Resource Management, Planning) were combined
- **Reports:** The categories for reports was changed from Annual, Sub-annual, and Project Summary to Routine and Non-routine. This resulted in both categories having an interrater agreement of 0.5.
- **Outreach material:** all outreach material categories (annual brochure, plain language report, report card, data summaries, newsletter) were combined and had a score of 0.8.
- **Funding:** there was confusion over what constitutes a funding source. It was clarified that only direct funding should be considered, and any in-kind funding should be categorized as a project partner. In addition, it was re-iterated that only explicit mention of funding should be considered. It was also clarified that funding sources could be searched online to clarify what category they should be placed under. Non-profit and Foundation funding sources were combined.
- **Partners:** Some of the disagreement among the rates for the funding and partners was due to authors only using the available project information to identify the type of funder/partner and organization should be categorized as. It was clarified in the data dictionary that online search engines can be used to look up an organization to understand how they should be categorized.
- The bridging organizations category was changed from the name of the organization to a yes/no relating to if the organization for each sub-category was a non-profit, consulting company, or co-management organization (i.e., not an academic or government agency). For the analysis, the bridging organization as “1” if community liaison role was conducted by a co-management board, non-profit, or consultant. The project was scored “0” if no community liaison was indicated, or if

the community liaison was federal/provincial/territorial/regional/Indigenous government agency, or an academic. The rationale for this was to test the hypothesis from the literature that bridging organizations are recommended that act as a liaison between the community and the government and researchers.

There were several project characteristics that were determined to have the repeatability that was too low due to the subjectivity of the characteristic and a difference in the authors' interpretation of the project information. To improve repeatability, these characteristics were only recorded for a project if the project information **explicitly** described the presence of the characteristic. The full dataset was reviewed to ensure all of these characteristics corresponded to a comment with text taken directly from the project information, providing evidence for the presence of that characteristic. These characteristics were:

- **Use of Indigenous Knowledge:** (the three categories [project design, data collection, data analysis & interpretation] condensed into one category to further improve repeatability)
- **Data objectives:** were re-defined in the data dictionary to only include those objectives that were explicitly described as an objective of the project in the project information.
- **Data Management Technology:** had a low inter-rater agreement, in part, due to the authors not accessing online search engines to verify the type of databases being used. For the project scoring, all mentioned databases were verified as either Project-Specific (created for the project), or as a third-party (database provided by an independent third-party or project partner).

The following project characteristics were removed due to low inter-rater agreement and no sufficient method to improve repeatability:

- Meetings/Workshops
- Sample Collection Equipment
- Community data access

Appendix B
Supplemental Materials for Chapter 3

Appendix B External Resources

The following supplementary materials are available in the GitHub repository:

<https://github.com/J2Kidd/ThesisSupplMaterials>

External Resource B.1: Code Book (Excel File)

Appendix B Tables

Table B.1. Saturation assessment with a base size of 4 interviews and run length of 2 interviews.

Interview Number	1	2	3	4	5	6	7	8	9	10	11	12
New Themes/ Interview	18	7	5	4	4	0	2	0	1	2	0	0
New Themes in Run				34	4	2	2	1	3	2	0	
% change over base					12%	6%	6%	3%	9%	6%	0%	

Table 3.2. Summary of 33 specific recommendations from technology experts for the freshwater science sector.

Theme/Recommendation	Participants
Open Data Culture	
<i>Individuals and organisations that use, manage, and share freshwater data should:</i>	
Promote a culture of open data as a way to accelerate progress toward achieving freshwater resource protection and restoration goals.	1, 2, 3, 4, 8, 10, 12
Take on thought leadership roles that actively promote and demonstrate the value of open data practices.	1, 3, 5
Reward and recognize individuals and organisations who share their data to incentivise open data sharing.	1, 2, 3, 4, 7, 11, 12
Implement open data mandates with data review processes to ensure data verification occurs throughout the research process.	1, 4, 5, 9, 12
Data Access Permissions	
<i>Individuals and organisations that share freshwater data should:</i>	
Use data licences to support data reusability.	1, 2, 3, 8
Be able to restrict access to sensitive and private data.	2, 5, 8, 9, 12
Skills & Training	
Embed data literacy training into all academic courses that discuss data.	3, 10, 12
Seek mentorship and peer-to-peer learning opportunities to upgrade data skills.	2, 3, 4, 6, 7
Offer internal data training opportunities.	2, 3, 10, 12
Develop data normalisation and data joining skills.	2, 3
Freshwater Data Standard Development	
<i>Organisations that aim to develop a freshwater data standard should:</i>	
Explore existing standards before creating a new one.	5
First identify the questions that freshwater data users will likely want to answer.	7, 12
Publicly release a draft to allow people to use the standard and provide feedback to inform its development.	1, 4, 6, 8, 12
Include data collection and entry methods that simplify data management and reuse.	4, 6, 8, 9, 10, 12
Offer examples and support to help people follow the standard.	1, 2, 5, 6, 7, 8
Building Centralised Data Solutions	
<i>Spectrum of Centralised Freshwater Data Solutions</i>	
<i>Organisations that aim to build a centralised freshwater data solution should consider the following options:</i>	
Prioritise building a tool that finds data in its original form to support data discoverability.	1, 2, 5, 9, 11, 12
Focus on creating a place that is easy for people to share their data.	5, 7, 8, 12
Ensure all data are shared in a standard format to support data reusability.	4, 6, 7, 11, 12
<i>Centralised Data Solution Considerations & Features</i>	

<i>Organisations that aim to build a centralised freshwater data solution should:</i>	
Plan for its long-term maintenance.	1, 2, 5, 6, 7, 11
First explore pre-existing tools.	1, 3, 4, 5, 6, 7, 8, 10
Use data tags to support data discoverability.	1, 2, 5, 8, 9
Version control datasets to support data reusability and study reproducibility.	1, 2, 6, 7, 8, 9
Support peer-to-peer learning and reciprocity amongst data contributors and users to create community support for the repository.	3, 5, 7, 8, 9, 10, 12
Host contests to attract data contributors and users	8
Restrict access to those who upload data to the repository.	5, 10
Be able to contact data contributors to resolve questions related to data reusability.	2, 8, 9
Avoid seeking out Blockchain technology.	1, 3, 4, 6, 7, 8, 9, 10, 11
Focus on making the solution simple and easy to use.	4, 5, 10
Roles for the Canada Water Agency (CWA)	
<i>To improve freshwater data management and sharing, the CWA could:</i>	
Make the Government of Canada's online data courses publicly available	2, 3
Prioritise the development of a centralised data solution.	1, 4, 5, 6, 7, 9, 12
Prioritise developing a freshwater data standard.	4, 5, 6, 9, 10, 12
Prioritise creating incentives for data sharing to promote a culture of open data.	3, 4, 7, 8
Continue cross-sector learning to improve data management and sharing practices in the freshwater science sector.	3, 10

Document B.1

Recruitment Email

Good day,

My name is Jess Kidd, and I am currently pursuing a PhD at the University of Waterloo. I am reaching out to invite you to participate in a study entitled "A Fresh Perspective on Freshwater Data Management and Sharing: Exploring Insights from the Technology Sector." The goal of this study is to gather expert opinions on improving data management within the Freshwater Science Sector.

Given your role at [insert name of organization] and your experience in [insert area of expertise], your insights would be incredibly valuable to my research.

I am scheduling one-hour interviews that will be conducted online via Microsoft Teams. To best accommodate your schedule, I am flexible with dates and times between August 7, 2024, and September 26, 2024.

During the interview, you will be given a chance to tell your stories, perspectives, and opinions about data management and sharing policies and procedures, and any recommendations you have for the Freshwater Science Sector to achieve its data management goals. Interviews will be audio recorded and transcribed. This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Board.

If you are interested in learning more, I have attached a Study Background document that summarizes the current state of data management and sharing in the Freshwater Science Sector, including current efforts to better manage and share freshwater data and proposed solutions for further improvement recommended by people who work within the Freshwater Science Sector. Also attached, is an Information Letter with more study details.

If you are interested in participating, please respond to this email with you preferred date(s) and time(s) for your interview. Also, please feel free to contact me if you have any questions about the study. If this study does not align with your interests or availability, I completely understand and appreciate your consideration of this invitation.

Thank you for considering this opportunity to contribute to advancements in freshwater data management and sharing in Canada. I look forward to potentially working with you and benefiting from your expertise.

Warm regards,

Jess Kidd

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School of Environment, Resources and Sustainability

University of Waterloo

Faculty Supervisor: Simon Courtenay, PhD, MSc, BSc, Professor in the School of Environment, Resources and Sustainability, University of Waterloo. Phone: 519-888-4567 (x45796), Email: simon.courtenay@uwaterloo.ca

Document B.2

Study Background Document

Thank you for your interest in the study *A Fresh Perspective on Freshwater Data Management and Sharing: Exploring Insights from the Technology Sector*. With this study, we aim to gain insights from the Technology Sector on how the Freshwater Science Sector in Canada can improve how it manages and shares freshwater data. Below is a summary of the current state of data management and sharing in the Freshwater Science Sector, including current efforts to better manage and share freshwater data and proposed solutions for further improvement recommended by people who work within the Freshwater Science Sector. We are sharing this Study Background Document with all potential interviewees to ensure all study participants have the same background knowledge on the issues to be discussed during the interview.

Introduction

Climate change poses numerous risks to the Canadian environment, society, and economy. We still do not fully understand how these risks will affect freshwater resources, such as lakes, rivers, and wetlands. To understand and solve the complex problems posed by climate change, decision-makers urgently need access to more freshwater data (Hartwig et al., 2024; Miller et al. 2022; Stanley & Gunn, 2018;). Freshwater data are “paramount to supporting evidence-based decision-making,” which makes the ability to discover and access freshwater data so critical (ECCC, 2021). Despite its importance, most Canadian watersheds are data deficient (Carver et al., 2020; Goucher et al., 2021; Ho et al., 2021; Miller et al. 2022; Mishra & Coulibaly, 2010; Water Rangers, 2025).

Even when enough data are collected to understand the condition of a watershed, data deficiencies can persist when the data are not accessible and well-managed. For example, over 30 years of data have been collected from the Athabasca River Watershed to understand the impacts of Oil Sands operations (Wrona & Munkittrick, 2024). After hundreds of millions of dollars spent, significant challenges remain in accessing data from these data collection efforts.¹⁰ Consequently, it remains unknown how the watershed has been impacted and how resource management could be improved (Wrona & Munkittrick, 2024).

In response to the growing concerns for freshwater resources, the federal Canada Water Agency has been created to “work together with the provinces, territories, Indigenous communities, local authorities, scientists and others to find the best ways to keep our water safe, clean and well-managed” (Government of Canada, 2024a, p. 7). This new agency is creating a National Freshwater Data Strategy to address data accessibility concerns and fill data gaps to ensure resource management decisions are informed by robust studies (Environment and Climate Change Canada [ECCC], 2021). To date, many of the recommendations for the strategy have come from individuals and organizations that work in the freshwater science sector and thus, have environmental science education and experience (ECCC, 2021; Goucher et al., 2021).

While this expertise is essential, the Canada Water Agency may be missing insights from sectors with more mature data management practices. Learning from different sectors may help the agency avoid duplicating efforts and create a strategy that will effectively and efficiently achieve its goals. Below, we discuss the barriers to effective data management and sharing in the freshwater science sector and the solutions that are currently being considered.

Data Inaccessibility

Large amounts of freshwater data collected across the country are predominantly inaccessible (DataStream, 2024; Ho et al., 2021; Stanley & Gunn, 2018). These data remain behind closed doors, stored in filing cabinets, floppy disks, bookshelves, and personal hard drives, and some are never even analyzed (Goucher et al., 2021; Gunn & Stanley, 2018; Ho et al., 2021). One reason freshwater data are intentionally withheld is the reluctance of scientists to share their data (Gunn & Stanley, 2018). This reluctance stems from concerns about competition from other researchers, the time required to manage data for sharing, lack of recognition for data sharing, and fears of others misinterpreting data or exposing errors (Goucher et al., 2021; Hahnel et al., 2023; Roche et al., 2015). Datasets are also sometimes intentionally withheld due to perceived liability concerns and data readiness (Goucher et al., 2021). Individuals and organizations who do want to share their data may be unable to do so for a variety of reasons including a lack of data literacy, lack of detailed guides and toolkits on data sharing, confusion over who is the “data owner,” inadequate digital infrastructure, staff turnover, or weak data management policies and procedures (Ho et al., 2021; Roche et al., 2020).

Culture Change

Researchers need to be rewarded differently to promote a culture change that encourages open data practices (Goucher et al., 2021; Gunn & Stanley, 2018; Roche et al., 2015; Zipper et al., 2019). Data should be treated and cited as formal publications, with researchers receiving credit for open data sharing from hiring and promotion committees and funding agencies (Goucher et al., 2021; Gunn & Stanley, 2018; Roche et al., 2015). That said, reasonable embargoes should be facilitated when there are planned uses of the data (Roche et al., 2015).

Blockchain

Blockchain technology may promote people to share their data by offering a chain of custody that ensures data remain secure (Gunn & Stanley, 2018). Blockchain can allow people to know when and how their data are used, ensure they receive credit when the data are used, and guarantee metadata (information describing how, when, where, and why the data were collected) stay with the dataset and remain unchanged (Gunn & Stanley, 2018). However, the use of Blockchain technology may be cost-prohibitive.

Open Data Mandates

Open data mandates have become a popular approach to improve data access and sharing (Blodgett et al., 2016; Great Lakes Observing System [GLOS], 2021). Most leading research

journals and funding agencies now require public data access, which has increased the number of researchers who openly share their data (Goucher et al., 2021; Hahnel et al., 2023; Roche et al., 2020). The Canadian federal government's 2014 Directive on Open Government mandates government data be as open as possible (Roche et al., 2020). However, these mandates predominantly apply to data collected with public funds and do not yet extend to private companies who also collect large amounts of freshwater data (Ball et al., 2013; Sheelanere et al., 2013). Further, these mandates are ineffective if they lack enforcement mechanisms.

Data Discoverability

Even when data are “open”, it can be difficult to find them (ECCC, 2021; Gunn & Stanley, 2018; Wrona & Munkittrick, 2024). In Canada, freshwater data are collected and managed by various government agencies, private companies, researchers, and non-profit organizations, resulting in a large, disparate, and fragmented network of freshwater data (Canadian Water Quality Association [CWQA], n.d.; DataStream, 2024; Miller et al., 2022; Roche et al., 2020; Wrona & Munkittrick, 2024). As a result, considerable time and effort are required to discover and organize data, creating inefficiencies that reduce the time available for data analysis and interpretation (Goucher et al., 2021; Johnson et al., 2011; Miller et al., 2022; Stanley & Gunn, 2018; Wilkinson et al., 2016). Further, the limited budgets and resources allocated for freshwater studies do not allow for extensive data searches and collation efforts, thus limiting the quality of the studies and, consequently, limiting their application for decision-makers (Stanley & Gunn, 2018).

International Standards for Data Discoverability

The Canada Water Agency aims to incorporate international standards for data discoverability in the National Freshwater Data Strategy (ECCC, 2021).

Centralized Databases/Repositories

The freshwater data collected for various purposes could be united in a centralized database—accessible to all levels of government, rights holders, stakeholders, and researchers (CWQA, n.d.; Ducks Unlimited, 2023; Wrona & Munkittrick, 2024). Open-access, centralized databases for freshwater data are recommended to reduce the time and resources spent searching for and accessing data (Johnson et al., 2011; Miller et al., 2022; Wrona & Munkittrick, 2024). These repositories can also help researchers make their data open by offering them somewhere to store it (Hahnel et al., 2023). There are several non-profit open data initiatives that collate and share various datasets, including those collected by community-based monitoring programs (GLOS et al., 2021; Hartwig et al., 2024). Even though many agree that a centralized database would be useful, efforts to make this a reality remain fragmented with open data records stored in different data portals and repositories (Miller et al., 2022; Roche et al., 2020). Alternatively, data can be more discoverable by using pre-existing repositories such as figshare, Dryad, Knowledge Network for Biocomplexity (KNB), and Zenodo (Roch et al., 2015).

Data Management

Even when data are open and discoverable, the use of the data is inhibited when the data are poorly or inconsistently managed (Gunn & Stanley, 2018; Miller et al., 2022). Although freshwater scientists understand the need to share their data, they continue to struggle to know how to share it effectively because they typically receive minimal formal data management training (Roche et al., 2015; Roche et al., 2020). Many freshwater scientists are self-taught and develop personal protocols for data wrangling, managing, and sharing (Lowndes et al., 2017). Data are typically manually prepared (without coding) in Microsoft Excel with data processing decisions documented in Excel, Word, or emails (Lowndes et al., 2017). A 2015 survey of datasets from ecology research studies published in open-access journals found that 56% of the datasets were incomplete (e.g., missing data or insufficient metadata) and 64% were only partially available (e.g., processed rather than raw data, non-machine-readable file formats) (Roche et al., 2015). Journals and data repositories lack the resources required for data quality control (Roche et al., 2015). The data must be analysis-ready to inform the sustainable management of freshwater resources (GLOS, 2021).

Tools

Environmental researchers should use software development tools to make their research more efficient and reproducible (Lowndes et al., 2017). For example, R Studio, Git, and GitHub can be used to code data preparation and analysis (Lowndes et al., 2017). Large language models can be used to draft metadata and data availability statements (Hahnel et al., 2023).

Training and Skill Development

Open data practices need to be supported by education-based strategies and resources that improve data literacy and management skills (Goucher et al., 2021). The Government of Canada is currently investing in digital skill building, exemplified by the Data Science Network for the Federal Public Service that aims to build data science capacity across federal government agencies by providing a space of members to discuss training, best practices, and cutting-edge projects (Statistics Canada, 2024). The federal government has also created the GC (Government of Canada) Data Community, which was initiated to support data practitioners across federal government agencies by offering them a space to connect, receive training and professional development opportunities, learn about standard data ethics and governance practices, and attend an annual Government of Canada Data Conference (Government of Canada, 2024b). The federal government is also offering courses through the Canada School of Public Service, including Data Literacy, Big Data Fundamentals, Data Visualization, Data Modelling, and Data Security (Canada School of Public Service, 2024).

Data Standards

The National Freshwater Data Strategy will define a data standard to guide consistent data management and include collection standards, analysis standards, reporting standards, metadata

standards, and management and chain of custody standards (ECCC, 2021; Miller et al., 2022). The standard will need to include the essentials of good data management (Wilkinson et al., 2016). Standardized data documentation will allow data discovery and processing to be automated (Blodgett et al., 2016). The Canada Water Agency could consider adopting the United States Environmental Protection Agency Water Quality Exchange data standard, which has been developed and refined over a decade based on input from freshwater scientists (DataStream, 2024).

Metadata Standards

Metadata that provide sufficient information for data to be reusable should be a minimum requirement for data inclusion in any repository (GLOS, 2021). Metadata standards could be created for freshwater data by adapting existing metadata standards, such as those for hydrometric data from the World Meteorological Organization and geospatial data from the North American Profile of ISO 19115 - Geographic information – Metadata (GLOS, 2021; Government of Canada, 2024c).

Data Management Plans

Funding agencies, government agencies, and scientific publications are starting to require data management plans to improve data management standards (Kroetsch et al., 2021; Roche et al., 2015; Wilkinson et al., 2016; Zipper et al., 2019). Data management plans are documents that describe the purpose of data collection; data collection protocols; Quality Assurance/Quality Control protocols; methods for data transfer, storage, and sharing; data analysis methods, how the data will be used for decision-making, and any privacy and security concerns (Statistics Canada, 2024; Zipper et al., 2019). Data management plans need to become widely known and researchers require guidance and training on how to make effective data management plans (Hahnel et al., 2023; Statistics Canada, 2024). The Digital Research Alliance of Canada (DRAC) developed a Data Management Plan Assistant as a free tool to help researchers prepare data management plans (DRAC, 2024).

FAIR Data Principles

Data standards should ensure that data meet FAIR Data principles so that data are findable, accessible, interoperable, and reusable (DataStream, 2024; Hartwig et al., 2024; Roche et al., 2020). To be findable and accessible, data should be archived from an indexed and searchable public data repository (Roche et al., 2020). Data are interoperable and reusable when metadata allow data to be easily understood by computers and humans, and data can be explored and reused with nonproprietary software (Roche et al., 2020). These principles were created through a collaboration of academia, industry, funding agencies, and scholarly publishers to improve the reusability of scientific data and support data discovery through good data management (Wilkinson et al., 2016). The FAIR Data principles were recognized as critical for scientific data in the 2023-2026 *Data Strategy for the Federal Public Service*, which is why a FAIR principles assessment tool is currently being developed (Government of Canada, 2024d).

Data Sovereignty and Privacy

Not all data should be publicly accessible—data sovereignty and privacy must be considered before data are considered for open access (Zipper et al., 2019). With the rise in open access, the research community is focusing more on how to protect sensitive data and respect Indigenous data sovereignty. Sensitive freshwater data include high-resolution spatial data (e.g., satellite data), consumer data (e.g., household water consumption), and digital trace data (e.g., social media posts of water levels) (Zipper et al., 2019). Even though sensitive data are typically exempt from open access mandates, scientists tend to lack training in ethical, privacy, and data security issues (Zipper et al., 2019). Indigenous data sovereignty stipulates that Indigenous governments and communities have jurisdiction over the collection and sharing of data collected by or about their peoples and land (Zipper et al., 2019). As such, the Canada Water Agency aims to work with Indigenous peoples to respect access to Indigenous Knowledge, data, and information (ECCC, 2021). The federal government has created the *Transformational Approach to Indigenous Data Sovereignty*, which is a multi-year initiative that will support Indigenous peoples in developing capacity to collect, manage, and use their own data (Government of Canada, 2024d).

Indigenous Data Governance Principles

One way the National Freshwater Data Strategy could address the issue of data sovereignty and privacy would be the adoption of OCAP (ownership, control, access, and possession) and CARE (collective benefit, authority to control, responsibility, and ethics) principles for Indigenous Data Governance (DataStream, 2024; ECCC, 2021; GLOS, 2021; Goucher et al., 2021). There is a need to find data sharing technologies, platforms, and policies that can help develop a technological requirements framework that can incorporate the CARE and OCAP principles (GLOS, 2021). However, it is important to avoid the assumption that all Indigenous communities will choose to adopt the OCAP or CARE principles.

Data Residency and Control

Data repositories should create data privacy guidelines and require researchers to submit data privacy statements (Zipper et al., 2019). In accordance with the FAIR data principles, sensitive data can be withheld while its metadata can be published to allow for discoverability and include rules regarding how people can access the data (Wilkinson et al., 2016).

Document B.3

Interview Guide and Questions

Student Investigator: Jessica Kidd

Study Title: A Fresh Perspective on Freshwater Data Management and Sharing: Exploring Insights from the Technology Sector

Study Duration: August to September 2024

Interview Duration: 1 hour

Interview Type: Semi-structured individual

Interview Location: Microsoft Teams (online)

Interview Participants: People who have a minimum of 5 years' experience as a software developer, software engineer, or data scientist and currently work for a company/organization where revenue is directly linked to effective data management. Or people who previously held senior roles for a minimum of 10 years in companies/organizations where revenue was directly linked to effective data management.

Script

Thank you for agreeing to be interviewed for the study *A Fresh Perspective on Freshwater Data Management and Sharing: Exploring Insights from the Technology Sector*. With these interviews, we aim to gain insights from the Technology Sector on how the Freshwater Science Sector in Canada can improve how it manages and shares freshwater science data. For this study, freshwater science data refers to any information related to freshwater environments (e.g., lakes and rivers). As such, freshwater science data can include information about the physical environment and the plants and animals that live in or depend on freshwater habitats. This information is not limited to information collected by professional scientists and may include information collected by members of the public and students. This information is also not limited to data collected using Western Science methods. This information does not include water-related data for drinking water monitoring and treatment or wastewater monitoring and treatment.

Background questions

1. Please describe any formal education and training you have completed that has supported your work in the Technology Sector.
2. Please describe your work history in the Technology Sector. Include the roles you have held, the approximate length of time you held them, and the types of industries you worked for when you held those roles.

Main questions

Feedback on summary document information

1. Among the data management and sharing solutions listed in the Study Background document, which ones do you believe should be prioritized for investment and implementation in the Freshwater Science Sector?
2. From the data management and sharing solutions proposed in the summary document, are there any that you would recommend the Freshwater Science Sector avoid?
3. Are there additional data management and sharing policies, procedures, tools, or methods that you believe should be considered by the Freshwater Science Sector?

Advice for the Canada Water Agency

4. If you were to offer strategic advice to the federal Canada Water Agency on advancing data management and sharing in the Freshwater Science Sector, what specific actions or initiatives would you recommend?

Appendix C
Supplemental Materials for Chapter 4

Appendix C External Resources

The following supplementary materials are available in the GitHub repository:

<https://github.com/J2Kidd/natural-range-of-variation-source>

External Resource C.1: NRV R Package Guidance Document (R files, including guidance document in README file)

Appendix C Tables

Table C.1. Detailed results of NRV calculations for under-ice total metals concentrations.

Site	Parameter	Sample Size	Censored (%)	Number of Years	Start Year	End Year	Minimum	Maximum	Shapiro-Wilk	Shapiro-Wilk Log	NRV Method	Lower Threshold	Upper Threshold
Pooled	Arsenic	58	0.0	19	2003	2023	0.06275	0.284	0.0018	0.2484	TIFLog	0.051071947	0.392613779
Daring	Barium	20	0.0	19	2003	2023	1.6	14	0.0000	0.0000	TIF	0.65	3.65
Counts	Nickel	19	0.0	19	2003	2023	0.4025	0.84175	0.3638	0.6958	TIF	0.2695	0.9335
Daring	Strontium	20	0.0	19	2003	2023	6.9	38.9	0.0000	0.0000	TIF	5.2	11.6

Site: pooled if all reference data used or the name of the reference site with the highest concentrations used to calculate NRV thresholds.

Table C.2. Detailed results of NRV calculations for open-water total metals concentrations.

Site	Parameter	Sample Size	Censored (%)	Number of Years	Start Year	End Year	Minimum	Maximum	Shapiro-Wilk (p-value)	Shapiro-Wilk Log (p-value)	NRV Method	Lower Threshold	Upper Threshold
Pooled	Arsenic	124	0.0	23	1998	2023	0.0517	0.63	0.0000	0.0000	TIF	0	0.3169375
Pooled	Barium	177	0.0	23	1998	2023	0.974	3.5	0.0000	0.0001	TIF	0.023	3.41
Pooled	Nickel	175	2.9	23	1998	2023	<0.06	5.215	0.0000	0.0000	TIF	0	0.542708333
Daring	Strontium	50	0.0	20	2004	2023	3.8	6.1	0.0028	0.0002	TIF	4.05	6.85

Site: pooled if all reference data used or the name of the reference site with the highest concentrations used to calculate NRV thresholds.

Table C.3. Detailed Mann-Kendall Temporal Trend Analysis results for under-ice total metals concentrations.

Site	Parameter	tau	sl	S	p.value	KendallScore	n	Sen's Slope
Slipper	arsenic_total	0.403509	0.017359	69	0.0174	69	19	0.00575
Counts	arsenic_total	0.375368	0.027423	64	0.0274	64	19	0.003031
Moose	arsenic_total	-0.36765	0.043546	-50	0.0435	-50	17	-0.01127
LDG	barium_total	0.688656	1.03E-05	157	0.0000	157	22	0.075
Destaffany	barium_total	0.522478	0.001389	106	0.0014	106	21	0.041667
Grizzly	barium_total	-0.56667	0.002557	-68	0.0026	-68	16	-0.09716
Kodiak	barium_total	0.43402	0.010603	74	0.0106	74	19	0.275
Nanuq	barium_total	0.380117	0.025151	65	0.0252	65	19	0.028438
S3	barium_total	0.368421	0.030075	63	0.0301	63	19	0.038636
Slipper	barium_total	0.356725	0.035805	61	0.0358	61	19	1.019643
Grizzly	nickel_total	-0.56667	0.002557	-68	0.0026	-68	16	-0.01526
Slipper	nickel_total	0.480941	0.004574	82	0.0046	82	19	0.036111
Vulture	nickel_total	0.426901	0.01177	73	0.0118	73	19	0.003521
Nanuq	nickel_total	0.363638	0.032726	62	0.0327	62	19	0.00875
Destaffany	strontium_total	0.935276	0	195	0.0000	195	21	0.624667
LDG	strontium_total	0.887446	0	205	0.0000	205	22	0.784375
Leslie	strontium_total	0.719298	1.97E-05	123	0.0000	123	19	58.65
Kodiak	strontium_total	0.684211	4.95E-05	117	0.0000	117	19	1.058333
S3	strontium_total	0.637427	0.000158	109	0.0002	109	19	1.025
S2	strontium_total	0.647059	0.000206	99	0.0002	99	18	0.917857
Slipper	strontium_total	0.555556	0.001007	95	0.0010	95	19	14.20625
Nanuq	strontium_total	0.539592	0.001444	92	0.0014	92	19	0.084583
Nema	strontium_total	0.461988	0.006355	79	0.0064	79	19	29.75
Counts	strontium_total	0.45748	0.007028	78	0.0070	78	19	0.06625

Table C.4. Detailed Mann-Kendall Temporal Trend Analysis results for open-water total metals concentrations.

Site	Parameter	tau	sl	S	p.value	KendallScore	n	Sen's Slope
Cujo	arsenic_total	0.65368	2.34E-05	151	0.0000	151	22	0.026917
Slipper	arsenic_total	0.451486	0.002832	114	0.0028	114	23	0.010058
Kodiak	arsenic_total	0.472555	0.00307	99	0.0031	99	21	0.002512
S3	arsenic_total	0.364426	0.019214	84	0.0192	84	22	0.001767
Destaffany	arsenic_total	0.422385	0.022438	62	0.0224	62	19	0.004545
Counts	arsenic_total	0.316832	0.036874	80	0.0369	80	23	0.001926
Nema	arsenic_total	0.304348	0.044729	77	0.0447	77	23	0.004217
Slipper	barium_total	0.660079	1.17E-05	167	0.0000	167	23	0.533922
LDG	barium_total	0.524038	0.000579	131	0.0006	131	23	0.0375
Grizzly	barium_total	-0.35789	0.029723	-68	0.0297	-68	20	-0.03645
Counts	copper_total	-0.42105	0.010374	-80	0.0104	-80	20	-0.00634
Slipper	nickel_total	0.549407	0.000268	139	0.0003	139	23	0.020232
Moose	nickel_total	0.541502	0.000328	137	0.0003	137	23	0.129889
Leslie	nickel_total	0.548928	0.000573	115	0.0006	115	21	0.141852
Vulture	nickel_total	0.427724	0.0047	108	0.0047	108	23	0.004885
Nema	nickel_total	0.41502	0.00602	105	0.0060	105	23	0.044286
Kodiak	nickel_total	0.409524	0.010266	86	0.0103	86	21	0.031024
Counts	nickel_total	0.320158	0.034615	81	0.0346	81	23	0.005603
Destaffany	strontium_total	0.886497	0	203	0.0000	203	22	0.366667
LDG	strontium_total	0.920949	0	233	0.0000	233	23	0.5875
Leslie	strontium_total	0.8	4.77E-07	168	0.0000	168	21	33.17247
Nanuq	strontium_total	0.763559	8.34E-07	176	0.0000	176	22	0.059091
Kodiak	strontium_total	0.761905	1.55E-06	160	0.0000	160	21	0.452083
Vulture	strontium_total	0.731602	2.15E-06	169	0.0000	169	22	0.033958
Slipper	strontium_total	0.705628	4.89E-06	163	0.0000	163	22	6.41
Counts	strontium_total	0.69697	6.44E-06	161	0.0000	161	22	0.05162
S3	strontium_total	0.69697	6.44E-06	161	0.0000	161	22	0.820833
Daring	strontium_total	0.695623	2.93E-05	129	0.0000	129	20	0.070526
Nema	strontium_total	0.584416	0.000158	135	0.0002	135	22	12.56818
Cujo	strontium_total	0.549784	0.000381	127	0.0004	127	22	4.947024
Moose	strontium_total	0.515152	0.000877	119	0.0009	119	22	22.08333
S2	strontium_total	0.515152	0.000877	119	0.0009	119	22	1.61875
Grizzly	strontium_total	0.347065	0.042189	59	0.0422	59	19	0.017667

Document C.1

Data Requirements, Treatments, and Transformations

Natural Range of Variation Data Requirements and Method Selection

We only calculated the NRV on datasets that contained less than 50% censored data (i.e., values below the detection limit [BDL]). The method for selecting which NRV method—Tukey Inner Fence (TIF) or median ± 2 median absolute deviation (M2MAD)—was developed based on the results of our test of how each method performed with varying proportions of impacted data (Section 4.4.1 of Chapter 4) and is illustrated in Figure C1.1. Ideally, the NRV method will be performed using only data from reference sites (i.e., unimpacted sites). If data are available from known reference sites, then the NRV thresholds should be calculated using the TIF method, whereas if practitioners are unsure of which sites may be impacted, then the M2MAD method should be selected.

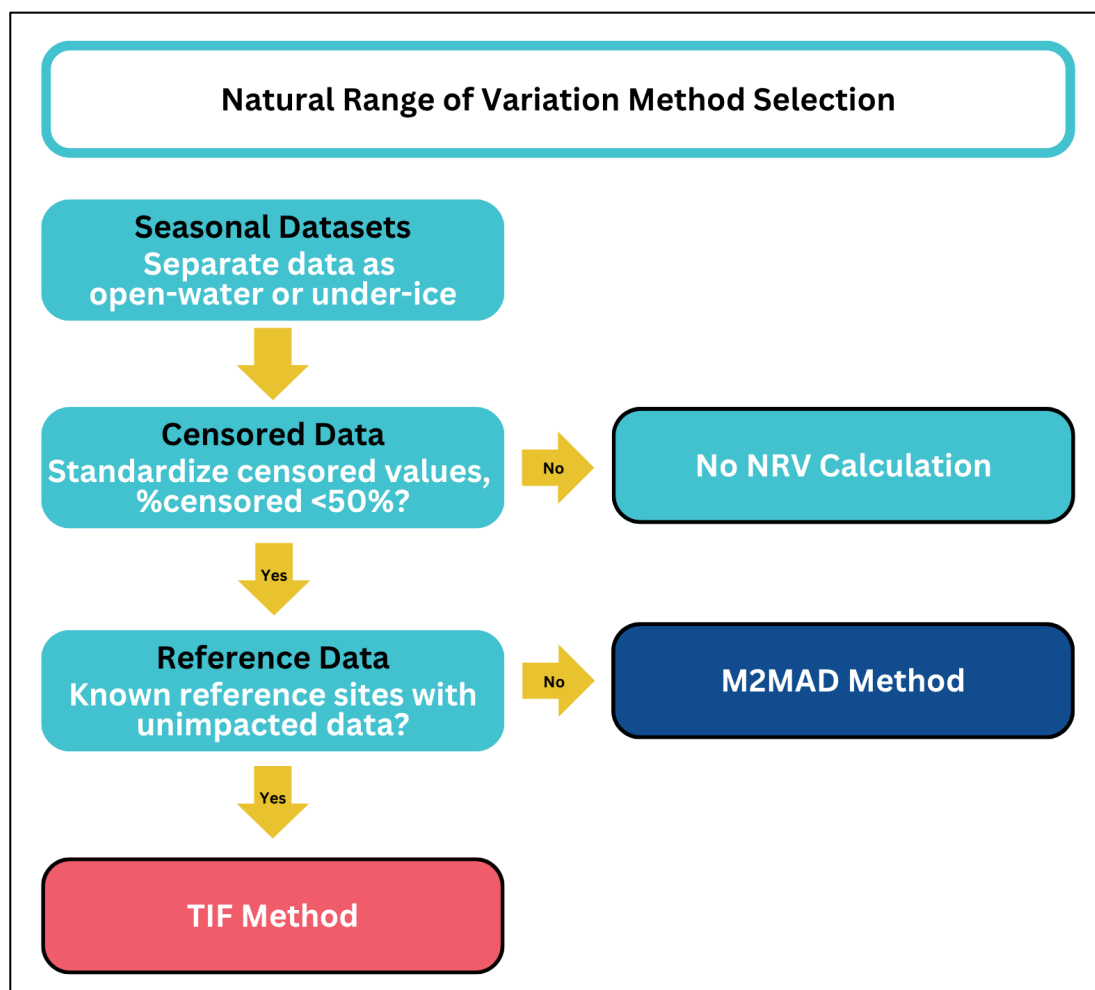


Figure C1.1. Natural range of variation (NRV) method flow diagram developed based on results of our test of how the Tukey Inner Fence (TIF) and median ± 2 median absolute deviation (M2MAD) methods performed with unimpacted and varying proportions of impacted data.

Data Selection

Testing varying proportions of impacted data

We tested how the TIF and M2MAD methods perform with varying percentages of data from sites known to be impacted by point-source pollution. We accessed an open source mine's surface water quality dataset from British Columbia's Environmental Monitoring System (EMS; BC EMS, 2023). The mine site is 25 km north of Stewart, British Columbia, within the Nisga'a Nation Treaty Lands (Ascot Resources Ltd [Ascot], 2024a, p. 1). Gold was mined from the site under various owners from 1918 until 1968 and 1988 to 1996 (Ascot, 2024a, p. 3). The mine site was under care and maintenance until late 2021 (Ascot, 2024a, p. 3), and construction of new mine operations began in 2023 (Ascot, 2024a, p.17). The dataset contained results for samples collected from 1994 to 2023 to monitor the impacts of historical mine operations on surface water quality.

We selected data from two sites on Cascade Creek: one upstream and one downstream of the mine operations. Cascade Creek and several of its tributaries drain the mine site, including waste rock dumps, the mill area, and a tailings storage facility (Ascot, 2024a, p. 1). The upstream site was labelled "CASCADE CRK ABOVE MINE INFLUENCE" (EMS ID E220201) in the EMS and "S-7" in the mine's water quality monitoring program (Ascot, 2024b, p. 6). This site is upstream of the mine's tailings pond and represents surface water conditions that are unimpacted by mine activities (Boliden, 2016, p. 16). The downstream site was labelled "CASCADE CRK AT LOGAN CRK" (EMS ID E214059) in the EMS and "S-27" in the monitoring program (Ascot, 2024b, p. 6). This site is downstream of the mine and tributaries that drain the mine and represents surface water conditions that are influenced by mine discharges into the receiving environment (Boliden, 2016, p. 16). Detailed site maps are in the mine's annual water quality report (Ascot, 2024b, Figure 1.1-1). Based on the mine's reports and the fact that the sites were on the same watercourse, we were confident that the reference site is appropriate for the monitoring site, and thus a strong demonstration of how the TIF and M2MAD methods perform with impacted and unimpacted surface water quality data.

We separated the data into seasonal datasets and selected the spring data because it had the most frequent sampling events. We removed the pre-2011 data because censored data dominated the pre-2011 data due to high detection limits. We then selected total metals parameters with less than 50% samples with censored values (aluminum, arsenic, barium, cadmium, lead, manganese, molybdenum, selenium, silicon, strontium, uranium, and zinc) to compare the *baseline* NRV thresholds calculated using the TIF and M2MAD methods without impacted data. To test how the TIF and M2MAD methods perform with impacted data, we selected cadmium and total zinc because they were known to be impacted by historical mine activities (Palmer, 2024, p. 27).

Comparison to contemporary assessment approach

To assess and refine the NRV method for surface water quality data, we assessed how the NRV method applied to a regional dataset that contains multiple reference sites and temporal trends, compared to a contemporary surface water quality assessment approach. To accomplish this, we combined datasets collected from two surface water quality monitoring programs in the Upper Coppermine Basin (UCB), Northwest Territories, Canada: A diamond mine's Aquatic Effects Monitoring Program (AEMP) and the GNWT Water Management and Monitoring Division monitoring program (WMMD program). We selected data from the UCB because statistically significant temporal trends in several water chemistry parameters from both impacted and unimpacted sites provided an opportunity for us to evaluate how NRV methods can be adapted to handle trends and assess cumulative effects from both point-source pollution and (likely) climate change. In addition, both unimpacted reference sites and sites impacted by mining activities are represented in publicly available datasets and are assessed annually in the publicly available diamond mine AEMP reports.

Data were collected as part of the AEMP and WMMD monitoring programs from 1998-2023 and 2000-2023, respectively. The publicly available AEMP dataset did not include the historical baseline data collected from 1993 to 1997 (i.e., data collected prior to mine operations). The publicly available AEMP dataset was also missing some data within the operational time period between 1998 and 2023 for specific sites and parameters, which are presented in Table C1.1.

Table C1.1. The years of monitoring data collected by the Aquatic Effects Monitoring Program (AEMP) to monitor the impacts of mine-related activities on the aquatic environment, and those years of data that were in the publicly available dataset used to apply the Natural Range of Variation (NRV) Method in this study.

Site	Season/Method					
	Under-Ice			Open-Water		
	AEMP	NRV	%Missing	AEMP	NRV	%Missing
Counts	2002–2023	2003–2009, 2012–2023	3 yrs (14%)	1998–2023	1998–1999, 2003–2023	3 yrs (12%)
Nanuq	2002–2023	2003–2009, 2012–2023	3 yrs (14%)	1998–2023	1998–1999, 2003–2023	3 yrs (12%)
Vulture	2002–2023	2003–2009, 2012–2023	3 yrs (14%)	1998–2023	1998–1999, 2003–2023	3 yrs (12%)
Grizzly	2003–2020, 2023	2004–2009, 2012–2020, 2023	3 yrs (16%)	1998–2020, 2023	1998–1999, 2004–2020, 2023	4 yrs (17%)
Kodiak	1999–2023	2003–2009, 2012–2023	6 yrs (24%)	1998–2023	2003–2023	5 yrs (19%)
Leslie	2003–2023	2003–2009, 2012–2023	2 yrs (10%)	2003–2023	2003–2023	0 yrs (0%)
Moose	2002–2023	2003–2009, 2012–2023	3 yrs (14%)	1998–2023	1998–1999, 2003–2023	3 yrs (12%)
Nema	2002–2023	2003–2009, 2012–2023	3 yrs (14%)	1998–2023	1998–1999, 2003–2023	3 yrs (12%)
Slipper	2002–2023	2003–2009, 2012–2023	3 yrs (14%)	1998–2023	1998–1999, 2003–2023	3 yrs (12%)
S2	2002–2023	2003–2007, 2009, 2012–2023	4 yrs (18%)	1998–2023	1999, 2003–2023	4 yrs (15%)
S3	2002–2023	2003–2009, 2012–2023	3 yrs (14%)	1998–2023	1999, 2003–2023	4 yrs (15%)

Data Treatment & Transformation

Testing varying proportions of impacted data

Data Preparation & Treatment

We divided the data into four seasonal data sets: winter [December to February] spring [March to May], summer [June to August], fall [September to November]. We chose the spring sample dataset because sampling was most frequent in spring.

For duplicate samples, if one sample was below the detection limit (BDL) and the other was above the detection limit, we removed the BDL sample. When duplicate samples had different detection limits, we inspected the dataset and removed any sample that appeared to be an error. We averaged all duplicate samples that were above the detection limit.

We substituted censored data—i.e., BDL values—with a value of one-half the detection limit. The substitution technique of one-half the detection limit has been reported to be a suitable method for determining summary statistics (Mikkonen et al., 2017). We removed censored data with detection limits greater than recorded values.

Data Transformations

We used the Shapiro-Wilk normality test to test the normality of data for each parameter and for each site. The Shapiro-Wilk test was performed in R using the `shapiro.test` function of the “stats” package version 4.3.1 (R Core Team, 2024). All data transformations were completed using the natural logarithm. If untransformed data failed the Shapiro-Wilk test (i.e., $p < 0.05$) then the data were log-transformed. If the log-transformed passed the Shapiro-Wilk test (i.e., $p \geq 0.05$) then the NRV calculations were performed on the transformed data. If the untransformed and log-transformed data failed the Shapiro-Wilk test then the data remained untransformed.

Comparison to contemporary assessment approach

Data Preparation & Treatment

We followed the data treatment methods according to the 2023 Aquatic Effects Monitoring Program to ensure comparability of our results. We divided the data into two seasonal data sets: under-ice and open-water. The under-ice and open-water samples were identified based on the month in which they were collected (under-ice [November to May], open-water [June to October]). Samples collected as part of the AEMP were taken at two depths during the under-ice season (mid and deep) and three depths during the open-water season (top, middle, and deep). We averaged the samples collected for each sampling event. In accordance with the 2023 AEMP, we averaged all samples collected at each site for

each sampling event collected at different depths (ERM Consultants Canada Ltd. [ERM], 2024a, p. 2-38). All censored data (i.e., values that were below the laboratory's minimum detection limit) were substituted with values of one-half the detection limit (ERM, 2024b, p. 1-4). Duplicate samples were averaged; if duplicates contained censored values, then the censored value was substituted and averaged value was denoted as TRUE for censored if it was below the minimum detection limit. We also removed censored data with detection limits greater than recorded values.

Data Transformation

We used the Shapiro-Wilk normality test to test the normality of data for each parameter and for each site. The Shapiro-Wilk test was performed in R using the `shapiro.test` function of the “stats” package version 4.3.1 (R Core Team, 2024). All data transformations were completed using the natural logarithm. If untransformed data failed the Shapiro-Wilk test (i.e., $p < 0.05$) then the data were log-transformed. If the log-transformed passed the Shapiro-Wilk test (i.e., $p \geq 0.05$) then the NRV calculations were performed on the transformed data. If the untransformed and log-transformed data failed the Shapiro-Wilk test then the data remained untransformed.

NRV Calculations with Reference Site Data

For each parameter, we initially calculated NRV thresholds separately for each reference site and a dataset containing all reference site data (i.e., pooled dataset). If reference sites individually did not pass the censored data criteria (i.e., had $\geq 50\%$ censored data) then they were not included in the pooled dataset. We then compared the individual and pooled NRV thresholds and selected the highest one to offer the most conservative comparison of the NRV method to the Aquatic Effect Monitoring Program.

Appendix D
Supplemental Materials for Chapter 5

Appendix D External Resources

The following supplementary materials are available in the GitHub repository:

<https://github.com/J2Kidd/ThesisSupplMaterials>

External Resource D.1: Literature list (Excel File)