Water Secure and Climate Resilient Ontario: Developing a Transdisciplinary Water Risk Management Framework and Decision Support Tool to Guide Multi-Sector Sustainable Water Management Policies and Strategies

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

I, Guneet Sandhu, am the sole author of Chapters 1 and 6, which were written under the supervision of Dr. Olaf Weber and were not written for publication.

This dissertation consists of four co-authored manuscripts, Chapters 2, 3, 4, and 5, which were written for publication. I am the lead author of those manuscripts and chapters.

Chapter 2 is based on a book chapter published in *Water Risk and Its Impact on the Financial Markets and Society: New Developments in Risk Assessment and Management*, where I was the lead author with Dr. Olaf Weber and Dr. Michael O. Wood as co-authors.

Chapter 3 on interdisciplinary water risk assessment is based on a research article published in *Water Resources Research.* Chapter 4 on water risk perception and evaluation is based on a research article published in *Environmental Research Communications.* Chapter 5 on water risk management and decision support is based on a research article under review in *Environmental Research Communications.* I was the lead author for all three research articles with Dr. Olaf Weber, Dr. Michael O. Wood, Dr. Horatiu A. Rus, and Dr. Jason Thistlethwaite as co-authors.

For all the co-authored works, I hereby state, that as the lead author, I was responsible for the conceptualization of research and the theoretical framework, methodology design, data collection, formal analysis, manuscript writing, and visualization. I was also the corresponding author for all the articles and I was responsible for the submission, revisions, and peer-review responses. Co-authors took a supervisory and support role throughout all the research stages, providing critical feedback, data validation, methodological guidance, and review of all original and revised drafts.

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Abstract

Sustainable management of water resources, which provide critical social, economic, cultural, and ecological functions, is essential for sustainable development, yet risks to water security are growing. The province of Ontario is an interesting case for investigating water risks, risk perception, and water risk management. Nestled between the Great Lakes, a "myth of water abundance" exists amidst a myriad of local water challenges, including the lack of safe drinking water in Indigenous communities, dwindling flows, groundwater overextraction, deteriorating water quality, regulatory complexity, and water-user conflicts. While academic interest in water risk assessment and sustainable water management is growing, the literature reveals limited interdisciplinary investigation of local water risks and how these risks are perceived, evaluated, and managed by influential non-state actors like the corporate and financial sector. Addressing these gaps, this dissertation focused on its phenomenon of interest of water security risks in Ontario. It executed a three-stage interconnected objective and examined water risk assessment, perception, evaluation, and management using a novel normative-analytical theoretical framework.

The first stage assessed interdisciplinary biophysical and social water risks at the sub-watershed scale in Ontario using secondary data analysis. It found high and moderate risk in at least 50% of studied sub-watersheds for all water risks, challenging the myth of water abundance. The second stage examined water risk perception and evaluation in the corporate and financial sector, using explanatory mixed methods (survey followed by interviews). It confirmed that risk-centric, individual-centric (cognitive, affective, socio-cultural demographic, trust-based), and spatial factors generate risk perception and impact water risk evaluation. Thus, revealing the nuanced model of expert risk perception. The third stage investigated water risk management strategies using a survey and interviews of corporate and financial practitioners. Moreover, using transdisciplinary approaches, it developed a contextually-attuned water risk decision support tool to guide multi-sector sustainable water management policies and strategies in Ontario. The results emphasize a combination of regulatory, voluntary, and multi-stakeholder participatory approaches, tailored based on the sector, location, and context, and risk severity, is necessary. Moreover, the criteria of flexibility, efficiency, strategic incentives, economic, and regulatory signals are essential.

This dissertation contributes to the knowledge in the fields of sustainability management, socio-hydrology, risk analysis, and water resources management. It is the first-of-a-kind comprehensive scholarship to address the wicked sustainability issue of water security using social-ecological perspectives and Risk Theory, a new theoretical arena, intersecting multiple disciplinary paradigms to empirically validate the normative-analytical theoretical framework for water. The interdisciplinary water risk assessment revealed a higher total water risk, highlighting the importance of including contextual variables. Revealing the impact of risk perception on water risk evaluation and management in the corporate and financial sector, the dissertation challenges the rational risk perception model of experts and practitioners, hence making a novel empirical contribution to risk analysis. Finally, the dissertation demonstrates the use of interdisciplinary data, transdisciplinary methods, and normative-analytical theoretical frameworks to investigate nuanced systems-based constructs like water risks, water risk perception, and develop decision support tools. Thus, advocating for widespread inclusion of interdisciplinary and transdisciplinary approaches in sustainability management research.

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Dedication

This dissertation is dedicated to my beloved parents, husband, and grandmother Maya Kaur.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AOC: Areas of Concern

CAD: Canadian Dollar

CDP: Carbon Disclosure Project

CFS: Corporate and the Financial Sector (also termed as the private sector)

CIB: Canada Infrastructure Bank

DST: Decision Support Tool

ERO: Environmental Registry of Ontario

ESG: Environmental, Social, and Governance

GRI: Global Reporting Initiative

IFRS: International Financial Reporting Standards

ISC: Indigenous Services Canada

MECP: Ontario Ministry of Environment Conservation and Parks

MNRF: Ontario Ministry of Natural Resources and Forestry

NGO: Non-Governmental Organizations

OECD: The Organization for Economic Cooperation and Development

PTTW: Permit to Take Water

SASB: Sustainability Accounting Standards Board

SDG: Sustainable Development Goal

SPA: Source Protection Area

TCFD: Task Force on Climate-related Financial Disclosure

UN: United Nations

UNDRIP: United Nations Declaration on the Rights of Indigenous Peoples

USAID: United States Agency for International Development

USD: United States Dollar

WATR-DST: Water Risk Decision Support Tool

WBCSD: World Business Council for Sustainable Development

WRI: World Resources Institute

WWF: World Wildlife Fund

Pavan Guroo Paanee Pithaa Maathaa Dhharath Mehath ||

"Air is the Guru, Water is the Father, and Earth is the Great Mother of all."

- Guru Nanak Dev

Chapter 1

1. Introduction

1.1 Research background and rationale

The province of Ontario in Canada is an interesting and unique case for contemporary water security issues, water risk assessment, and management (Johns, 2017; Mitchell, 2015; Sandhu et al., 2020a). Surrounded by the Great Lakes, there is a perception or a "*myth of water abundance*" in Ontario (Mitchell, 2017; Sandhu et al., 2020b; Sprauge, 2006). However, a myriad of critical water security challenges is revealed locally at the local sub-watershed scale. Challenges include the lack of safe drinking water in Indigenous communities, diminishing seasonal flows due to rapidly changing climate, regulatory uncertainty around water allocation and use, degrading water quality, and conflicts amidst different water-use sectors due to competing water demand (Bonsal et al., 2019; Climate Risk Institute et al., 2023; Dudley et al., 2022; Galway, 2016; Heinmiller, 2017; Horbulyk, 2017). Sustainable use and effective management of a shared resource like water, which provides critical social, economic, cultural, and ecological functions for human wellbeing, economic development, and environmental sustainability is fundamental to Sustainable Development (Di Baldassarre et al., 2019; Koehler, 2023; United Nations, 2018). Thus, sustainable water management is a key facet of the Sustainable Development Goal (SDG) 6, where the objective is to ensure adequate quantity, quality, and ecological integrity of water resources, or **water security**, is perpetually maintained while meeting all present and future social, economic, and environmental water demands (Bilalova et al., 2023; Dudley et al., 2022; Garrick et al., 2020; Garrick et al., 2017; Savelli et al., 2022; UN-Water, 2021).

Rockstrom's Planetary Boundary framework has quantified the limits of anthropogenic impact on nine key processes, which are crucial for the stable functioning and resilience of the Earth system to sustain human society (Rockström et al., 2023; Steffen et al., 2015). The recent update to the framework includes a revision of the boundary for "freshwater use" to "freshwater change" to comprehensively capture the extent of anthropogenic impact and changes across the entire water cycle ("blue" water includes surface water and groundwater resources and "green" water includes soil moisture available for plants) (Richardson et al., 2023). Interestingly, initial analyses reveal that the revised freshwater change boundary has been transgressed beyond the safe operating space for humanity (Richardson et al., 2023). Thus, highlighting the complexity, uncertainty, and spatial and temporal variability of water availability at local scales, which is exacerbated manifold due to climate change, economic activity, and population growth (Cosgrove & Loucks, 2015; Ortigara et al., 2018; Richardson et al., 2023; Zipper et al., 2020). Given the severe implications of water insecurity on food security, energy security, business revenues, public health, and cultural values, it becomes necessary to assess and manage water security risks by all extractive and in-stream water users for a water secure, sustainable, and climate resilient society, economy, and environment (Garrick et al., 2020; Rangecroft et al., 2021; Rusca & Di Baldassarre, 2019; Savelli et al., 2022; United Nations, 2023).

Given this background, the research problem or phenomenon of interest investigated in this dissertation, i.e., water security risks in Ontario, stems from three main areas of scholarly inquiry. First, water risks are a multifaceted construct, where biophysical dimensions of quantity and quality, along with groundwater and surface water interconnections need to be tethered with social dimensions of regulatory uncertainty, stakeholder perception, and legacy allocation and access issues to holistically assess and manage water risks (Dobbie et al., 2016; Koehler, 2023; Mitchell, 2015; Rockström et al., 2023; Rusca & Di Baldassarre, 2019; Savelli et al., 2022; Wyrwoll et al., 2018). Social water risk dimensions also include water user conflicts (i.e., controversies, disagreements, or competition) that arise locally with increasing drought potential, perception of inequitable water allocation, or high density of water user groups like corporate water users (Hoekstra, 2015; Jaffee & Case, 2018; Schulte et al., 2012; Shifflett, 2014). These interdisciplinary biophysical and social dimensions can shape local water security but are seldom assessed in extant literature using social-ecological systems perspectives at disaggregated spatial scales like the sub-watershed (Heinmiller, 2017; Savelli et al., 2022; Signori & Bodino, 2013).

A common strategy in the water risk assessment and sustainability accounting literature entails the use of siloed theories from the field of hydrology, focused on biophysical aspects of water, without integrating the contextual nuances of water risks (Cosgrove & Loucks, 2015; Savelli et al., 2022; Xu et al., 2018). Therefore, to manage multifaceted and interdisciplinary water risks, calls have grown for the use of social-ecological perspectives and in-depth case studies, to assess water risks in a comprehensive manner and develop transdisciplinary water risk management frameworks (Busch et al., 2023; Christ & Burritt, 2018; Cosgrove & Loucks, 2015; Di Baldassarre et al., 2019, 2021; Dudley et al., 2022; Healy & Morgan, 2012; Mitchell, 2015; Steffen et al., 2015; Xu et al., 2018; Zipper et al., 2020).

Second, water risk management and sustainable water management is a shared responsibility across all institutional actors nested within the wider hydrological, social, political, economic and cultural contexts on a sub-watershed basis (Cosgrove & Loucks, 2015; Dobbie et al., 2016; Dobbie & Brown, 2014; Koehler, 2023; Mitchell, 2015; Rangecroft et al., 2022; Renn & Klinke, 2015; Renn & Schweizer, 2009; Wyrwoll et al., 2018). The water risk management and governance landscape consists of multiple actors including the public sector, private sector, and civil society, representing their own knowledge, perceptions, values, and interests (Klinke & Renn, 2012, 2021; Koehler, 2023; Renn & Schweizer, 2009; Wyrwoll et al., 2018). As major users of this socially, economically, and environmentally relevant yet increasingly scarce resource, businesses and the financial sector that lends, insures, or invests in these businesses, are relevant and influential non-state actors that have a crucial role in water risk assessment and management, based on how they perceive, prioritize, evaluate, and manage different water risks (Busch et al., 2023; Christ & Burritt, 2017a, 2018, 2019; Hogeboom et al., 2018; Klinke & Renn, 2021; Signori & Bodino, 2013; Stafford-Smith et al., 2017; Weber & Saunders-Hogberg, 2020).

Interestingly, extant risk perception, evaluation and management research has primarily focused on the public sector, policy-makers, academia, and lay public, omitting the corporate and financial sector (also termed the private sector), which relies on water, impacts water security, and is affected by different water risks (Dobbie et al., 2016; Dobbie & Brown, 2014; Klinke & Renn, 2021; Mooney et al., 2020; Mumbi & Watanabe, 2020; Quinn et al., 2019; Sjöberg, 2002; Wyrwoll et al., 2018). Moreover, risk assessment and management are core functions in the financial sector (Weber & Feltmate, 2016). Thus, making the private sector, an underexplored yet influential actor to study, and water risk assessment, perception, and management in the private sector using a transdisciplinary, social-ecological, and risk lens, a major topic to be investigated.

Third, the contemporary normative-analytical risk governance approaches in the field of risk analysis are yet to be tested for the risk problem of water security and in the context of corporate and financial decision-making (Kasperson et al., 2022; Klinke & Renn, 2021; Koehler, 2023; Siegrist & Árvai, 2020). While academic, policy, and practitioner interest in sustainable water management is growing, the literature reveals major gaps in comprehensively assessing and managing interdisciplinary water risks at the sub-watershed scale in the private sector (Busch et al., 2023; Christ & Burritt, 2018; Di Baldassarre et al., 2021; Savelli et al. 2022; Xu et al. 2018; Zipper et al., 2020). Thus, the intersection of normative-analytical risk analysis, socio-hydrology, sustainability management, and environmental management (specifically sustainable water management) is an interesting research gap that provides an opportunity to apply interdisciplinary and transdisciplinary approaches to investigate water risks and risk perception, integrate practitioner perspectives, and design contextually-attuned tools for water risk management and decision-making (Di Baldassarre et al., 2021; Klinke & Renn, 2021; Mooney et al., 2020; Quandt, 2022; Quinn et al., 2019; Rangecroft et al., 2021, 2022; Renn et al., 2022; Savelli et al., 2022; Siegrist & Árvai, 2020). Thus, outlining the dissertation's rationale to investigate the assessment, perception, and management of the critical systemic sustainability and risk problem of water security in an underexplored yet influential actor i.e., corporate and financial sector, in Ontario, using a normative-analytical theoretical framework and transdisciplinary methodological approaches.

1.2 Key areas of literature in water risk assessment, management, and decision-making

Water insecurity is not only a key sustainability challenge but also a "wicked" or systemic risk problem with high ambiguity, complexity, and uncertainty (Klinke & Renn, 2012; Loucks, 2017; Reed & Kasprzyk, 2009; Renn et al., 2022; Rittel & Webber, 1973). Water challenges are **ambiguous** with multiple interpretations, competing explanations, values, beliefs, and response strategies in diverse water using sectors (Di Baldassarre et al., 2019; Dobbie & Brown, 2014; Klinke & Renn, 2012, 2021). Water is not only a key production input (also providing waste assimilation services) for industrial, agricultural, power, and water utility sectors but also has economic, recreational, spiritual, cultural, and ecological value (Loucks, 2000; OECD, 2013; Sadoff et al., 2020; Sandhu et al., 2020b). Thus, water challenges are **complex**, being a shared multi-value, and multi-user resource with interconnected and interdependent social, economic, hydrological and ecological systems with multiple non-linear causal linkages, levels, and scales for analysis (Cosgrove & Loucks, 2015; Di Baldassarre et al., 2021). Lastly, water challenges are **scientifically uncertain,** with evolving and conflicting knowledge, problem boundaries (political, hydrological or watershed, and problem-shed), and non-linear feedbacks and tradeoffs between the interconnected complex social-hydrological systems (Alvarado-Revilla & de Loë, 2022; Di Baldassarre et al., 2019, 2021; Rangecroft et al., 2021; Savelli et al., 2022; Wheater & Gober, 2015; Xu et al., 2018).

Given the complexity, uncertainty and ambiguity being a multi-dimensional, multi-actor, multi-value, shared resource with competing knowledge and interests of stakeholders, water is an important interdisciplinary and collective risk problem (Koehler, 2023; Renn et al., 2022; Wheater & Gober, 2015; Wyrwoll et al., 2018). Therefore, as an interconnected common resource, sustainable water management should not be primarily limited to the public (state) authorities, who are responsible for allocation and setting extraction and emission limits, but rather conceptualized as a shared responsibility of all actors that impact or are impacted by water related decisions in the institutional landscape, especially, large water users and influential actors like the corporate and financial sector (Christ & Burritt, 2019; Cosgrove & Loucks, 2015; de Loë & Patterson, 2017; Di Baldassarre et al., 2019; Dobbie et al., 2016; Klinke & Renn, 2021; Savelli et al., 2022; Wheater & Gober, 2015; Wyrwoll et al., 2018). To investigate the literature on wicked water risk challenges, extant approaches, and their gaps, this dissertation intersects the fields of sustainability management, social-ecological systems perspectives, and risk analysis with water.

1.2.1. Extant corporate water accounting and management approaches

The corporate sustainability management literature conceptualizes water risk as **a physical risk** to operations arising from local water stress and degraded water quality; a **regulatory risk** due to changing water allocation laws and policies, and a **reputational risk** due to conflicts amid competing water users, public concerns arising from actual or perceived adverse impact of corporate water use on local water resources (Christ & Burritt, 2017a; Gilsbach et al., 2019; Josset & Concha Larrauri, 2021; Morgan et al., 2020; Schulte et al., 2012; Signori & Bodino, 2013). These water-related risks can cause significant operational costs, regulatory uncertainty, and reputational concerns for the corporate and financial sector (Christ & Burritt, 2017a, 2017b; Hogeboom et al., 2018). Thus, the literature highlights clear incentives for the corporate and financial sector to spearhead sustainable water management strategies by proactively assessing and integrating sub-watershed wide water risks in operational, investment and lending decisions to ensure legal compliance, legitimacy, brand image, and alignment of stakeholder interests to retain competitive advantage and enhance financial performance (Bansal & Song, 2017; Christ & Burritt, 2017a, 2017b; Hogeboom et al., 2018; Weber & Saunders-Hogberg, 2020).

A core mantra for sustainable water management is the measurement of water risks and sector-specific impact, using consistent, reliable, and credible data and methods (Christ & Burritt, 2018; Gilsbach et al., 2019; Josset & Concha Larrauri, 2021; Morgan et al., 2020;

Signori & Bodino, 2013). While case studies on water intensive sectors like food and beverage or mining, highlight increasing water efficiency and stewardship initiatives with uptake of water accounting and disclosure practices, the literature also criticizes current practices for being reactive and insufficient (Busch et al., 2023; Christ & Burritt, 2018; Gilsbach et al., 2019; Lambooy, 2011; Money, 2014a, 2014b; Schulte et al., 2012; Talbot & Barbat, 2020; Wang et al., 2022). While water risk accounting tools like WRI Aqueduct, WWF Water Risk Filter, Global Drought Observatory, etc., have been employed by businesses and investors, to assess and disclose operational water risks, extant literature has criticized the use of highly aggregated data (Christ & Burritt, 2017b; Dudley et al., 2022; Gilsbach et al., 2019; Josset & Concha Larrauri, 2021; Money, 2014a; Morgan et al., 2020; Signori & Bodino, 2013). Moreover, the lack of quality and contextuality of the data used in underlying hydrological models, and insufficient reputational, regulatory, and water quality indicators have exposed the inadequacy of these tools, as they may underestimate total water risk at local scales, and opened avenues for research (Dudley et al., 2022; Gilsbach et al., 2019; van Vliet, 2023).

1.2.2. Application of social-ecological systems perspectives to corporate water management

As discussed, current corporate water accounting and management research focus on quantifying internal facility level data of physical operational risks (outside-in) and their impacts on the financial bottom line (Gilsbach et al., 2019; Hogeboom et al., 2018; Money, 2014a; Weber & Saunders-Hogberg, 2020). Thus, excluding the highly variable, interconnected, external (social-ecological) biophysical and contextual social, political, cultural, and institutional environments across the shared sub-watersheds that generate these multi-dimensional, and, spatially and temporally variable water risk hotspots (Di Baldassarre et al., 2021; Rusca & Di Baldassarre, 2019; Savelli et al., 2022; Schulte et al., 2012; Signori & Bodino, 2013). Overlooking the sub-watershed wide *outside-in* risks and the *inside-out* organizational impacts that affect all water users, results in fragmented decisions, policies, and actions, which can create undesired social, economic, and environmental trade-offs, detrimental to long term water security (Christ & Burritt, 2017a; Di Baldassarre et al., 2019; Signori & Bodino, 2013).

Instead of focusing only on financially relevant (material), environmental, social and governance issues for companies, i.e., single materiality, a locally-attuned, systems-based social-ecological approach can address sustainable water management holistically by assessing the impact of water-using sectors on water resources, i.e., a systems-based double materiality approach (Christ & Burritt, 2017a; Driver et al., 2023; Folke, 2006; Romano & Akhmouch, 2019; Weber & Feltmate, 2016; Weber & Saunders-Hogberg, 2020). Adopting an integrated social-ecological perspective can guide comprehensive (double materiality) assessment of the inside-out perspective of corporate social responsibility and outside-in water risks (Alvarado-Revilla & de Loë, 2022; Porter & Kramer, 2006; Weber & Saunders-Hogberg, 2020). Therefore, for a comprehensive and reliable water risk assessment and management, analysts and managers need transition from the extant narrowly focused corporate water accounting and management beyond facility boundaries, towards *general purpose* water risk assessment and management at the sub-watershed scale (Signori & Bodino, 2013). This allows a more accurate comparison of corporate water performance with actual biophysical (water quantity and quality risks), regulatory, social, economic, cultural, and ecological realities of the sub-watershed (Folke, 2006; Klinke & Renn, 2021; Koehler, 2023; Rangecroft et al., 2022; Savelli et al., 2022; Wyrwoll et al., 2018).

Moreover, the empirical examination of risk perception of the corporate and financial sector practitioners and decision-makers in water risk assessment, management and decision-making is an under-explored yet important research area in the literature (Christ & Burritt, 2018; Dobbie et al., 2016; Dobbie & Brown, 2014; Koehler, 2023; Renn et al., 2022; Siegrist & Árvai, 2020). Finally, decision support tools are user-friendly information system platforms that logically organize, integrate, and visualize information to assist water risk management strategies and decision-making in different water use sectors or policy-making (Giupponi & Sgobbi, 2013; Miles et al., 2023; Morales-Torres et al., 2016; Yang, 2017). A review of current literature reveals that a tangible decision support tool contextually-attuned for water risk management, corporate sustainability and environmental management is also a gap informing this dissertation's research objective (Busch et al., 2023; Christ & Burritt, 2019; Krueger et al., 2016; Loucks, 2023; Renn et al., 2022; Savelli et al., 2022).

1.2.3. Transdisciplinary normative-analytical risk approaches for water risk assessment and management

While multi-dimensional water security issues are captured in siloed datasets and analytical models across multiple disciplines, a disciplinary divide, responsible for information siloes, tends to exacerbate water challenges (Christ & Burritt, 2018; Evers et al., 2017; Krueger et al., 2016; Lélé & Norgaard, 2005). A need for interdisciplinary data integration and transdisciplinary approaches to knowledge co-development exists (Cosgrove & Loucks, 2015; Loucks, 2017; Renn, 2021; Renn et al., 2022). At the outset, it is important to make a conceptual distinction between the terms multidisciplinary, interdisciplinary, and transdisciplinary, used throughout the dissertation.

Multidisciplinary approaches, aligned with the reductionist paradigm, consist of concepts, knowledge, or theories from different disciplines, i.e., fields or sub-fields of knowledge used in siloes, but not integrated, to address the overarching research problem (Lélé & Norgaard, 2005; Schaltegger et al., 2013; Shrivastava et al., 2013). The disciplinary boundaries are kept intact and knowledge is the sum of individual parts (Christ & Burritt, 2018; Shrivastava et al., 2013). Interdisciplinary approaches, aligned with systems-thinking, entail an intersection and integration (synthesis) of knowledge, concepts, theories, or methods based on the collaboration between different disciplines to address the problem as a complex whole (Krueger et al., 2016; Schaltegger et al., 2013). Finally, transdisciplinary approaches, go beyond academic confines, where stakeholders, non-academic experts, and practitioners are engaged as hands-on participants in interdisciplinary research using participatory mixed research methods to co-develop and apply knowledge and tools (Krueger et al., 2016; Loucks, 2017; Renn, 2021). Transdisciplinary approaches operationalize systems-thinking in research and practice, and are apt for addressing wicked sustainability and risk challenges like water (Christ & Burritt, 2018; Krueger et al., 2016; Lélé & Norgaard, 2005; Renn, 2021; Renn et al., 2022).

Even though multi-sector decision-making for management of complex and wicked water risk problems necessitate, locally-attuned, interdisciplinary water risk assessment frameworks as well as transdisciplinary decision support tools, there is a gap in the literature regarding the development and operationalization of such frameworks and tools (Christ & Burritt, 2018; Cosgrove & Loucks, 2015; Di Baldassarre et al., 2019, 2021; Krueger et al., 2016; Rangecroft et al., 2021; Vörösmarty et al., 2018). Given these gaps, the field of risk analysis, can offer a sound interdisciplinary and transdisciplinary theoretical foundation to understand, develop, and operationalize a water risk assessment, evaluation, and management framework (CohenMiller & Pate, 2019; Dobbie & Brown, 2014; Klinke & Renn, 2021; Roeser et al., 2012). As discussed before, the focus of this dissertation is on the multi-dimensional water security risks. Applying the generic definitions of Risk from the field of risk analysis, sustainability, and environmental management to the core phenomenon of interest, the dissertation developed a comprehensive definition for water security risk. **Water risk (water security risk),** is defined as, the likelihood of occurrence and severity of impacts related to multi-dimensional water security issues (Aven, 2016; Aven & Renn, 2020; Mitchell, 2015). The issues include insufficient water quantity, quality, inequitable access, regulatory uncertainty, public concern, and conflicts among water use sectors that can negatively influence human productivity, health, wellness, profits, reputation, and environment (Christ & Burritt, 2018; Di Baldassarre et al., 2019; Dudley et al., 2022; Koehler, 2023; Rangecroft et al., 2021; Savelli et al., 2022; Wyrwoll et al., 2018; Xu et al., 2018).

Delving into the field of Risk, risk analysis is the overarching process entailing interdisciplinary risk assessment with technical and contextual components, risk evaluation by assigning priorities, based on risk acceptability, risk management and decision-making (Klinke & Renn, 2012, 2021; Renn & Klinke, 2015). Risk analysis, as an interdisciplinary field, is prevalent in the fields of finance, safety engineering, public health, transportation, supply chain management, environmental management including flood risk management, groundwater management, drinking water, etc. (Aven, 2016; Gough, 1997; Klinke & Renn, 2012; Renn & Schweizer, 2009; Vasvári, 2015). However, the application of concepts of risk analysis to the domain of water security, specifically, in the corporate and financial sector is an underexplored yet timely research arena. Traditionally, risk is rooted in objective scientific paradigms, where risk analysis entailed quantification of objective properties of risk including hazard identification, characterization, and likelihood, using verifiable data, probabilistic and linear cause-effect analysis, and complex statistical models (Aven, 2016; Aven & Renn, 2020; Renn et al., 2022). However, relatively recent constructivist approaches, conceptualize risk as a subjective value-based construct, generated by how stakeholders, analysts, and decision-makers, understand, interpret, and respond to risk (Dobbie & Brown, 2014; Klinke & Renn, 2021; Renn et al., 2022; Siegrist, 2021; Siegrist & Árvai, 2020; Slovic, 1999; Weber et al., 2001).

Psychometric studies conventionally considered lay public to be subjective, who use affect and emotions to assess risks but experts, analysts, and decision-makers are considered a value-free objective group that partakes in rational risk assessment based on reason (McDaniels et al., 1995; Renn, 1998; Roeser, 2012; Sjöberg, 2002; Slovic, 1987; Weber, 2001). However, the contemporary theoretical take on risk perception and analysis challenged this notion of value-free experts. It argues that, as risk problems get more complex and ambiguous, and the amount of objective data reduces, an expert's judgment can be influenced by cognitive (rational) and affective factors i.e., related to experiences, emotions, and socio-cultural demographic factors, (Aven, 2016; Dobbie & Brown, 2014; Siegrist, 2021; Siegrist & Árvai, 2020; Sjöberg, 2002; Slovic et al., 2004; Vasvári, 2015). Thus, expert risk perception can potentially influence how risks are prioritized in evaluation and decision-making (Dobbie et al., 2016; Dobbie & Brown, 2014). Thus, the concept of risk perception reflecting subjective judgment of practitioners and its impact on risk evaluation have become crucial to risk analysis, but remains under-investigated in the literature (Aven & Flage, 2020; Dobbie & Brown, 2014; Kasperson et al., 2022; Klinke & Renn, 2021; Siegrist, 2021; Siegrist & Árvai, 2020)

Risk analysis, hence, is intertwined with normative value-based perception or concerns, preferences, and judgments acting as filters that render results from purely analytical or techno-scientific quantitative estimation methods as insufficient (Aven, 2016; Klinke & Renn, 2021; Renn et al., 2022; Siegrist & Árvai, 2020). This led to the conceptualization of Risk Governance, a contemporary addition from social sciences to the field of risk analysis, which focuses on multi-level and multi-systems management of wicked risks by all relevant actors in that risk's institutional landscape (Kasperson et al., 2022; Klinke & Renn, 2021; Renn et al., 2022; Renn & Klinke, 2015; Renn & Schweizer, 2009; Van Asselt & Renn, 2011). The normative-analytical risk governance model integrates objective technical assessment and social concern assessment, followed by risk evaluation and management with normative and analytical components to capture the value-based preferences or judgement of practitioners (Aven, 2016; Gough, 1997; Klinke & Renn, 2012; Renn et al., 2022). The management and decision-making stage entails identifying options to address the evaluated risk, reflecting the decision-makers' priorities.

The dissertation adapted this contemporary framework of risk analysis, i.e., the **normative-analytical risk governance model** to investigate interdisciplinary water risk assessment, risk perception and its relationship with risk evaluation, water risk management strategies as well as develop a transdisciplinary decision support tool for water risks, which has not been addressed in extant literature (Kasperson et al., 2022; Klinke & Renn, 2021; Koehler, 2023; Renn, 2021).

1.2.4. Ontario as a case study for transdisciplinary normative-analytical water risk governance

Ontario is a relatively populous province in Canada, home to 40% of the national population with strong manufacturing and financial services sectors, adding 40% to the national GDP (Ontario Ministry of Finance, 2019). Amidst growing global water scarcity, Ontario, bordered by the Great Lakes (Figure 1.1), is considered to be a prime location for water-reliant industries, agriculture, investment, and trade (Horbulyk, 2017; Johns, 2017; Sandhu et al., 2020a, 2020b). However, the province of Ontario is an interesting case study, which may be perceived as a water secure region, but upon finer resolution of analysis, multi-dimensional water security issues and risks are revealed (Mitchell, 2017; Sandhu et al., 2020a; Sprauge, 2006).

For instance, the lack of access to clean drinking water in Indigenous communities in Ontario and Canada exemplify an inequity-based legacy issue stemming from Canada's rather dark colonial history (Bradford et al., 2017; Galway, 2016; White et al., 2012). Moreover, climate change-driven seasonal low flows, groundwater depletion, water quality issues, exacerbate existing conflicts amidst different water groups (industrial, recreational, agricultural, urban, and rural) and public concern. The changing regulatory landscape has further exposed the vulnerability of water reliant sectors to changing legal access to the resource (Heinmiller, 2017; Jaffee & Case, 2018; Mitchell, 2017; Morris et al., 2008; Sandhu et al., 2020b). Thus, as influential actors in the water management landscape and major water users, the corporate and financial sector are expected to play a critical role in assessing and managing the biophysical and social water risks and their financial, environmental, regulatory, and reputational implications at the disaggregated sub-watershed scale (Christ and Burritt, 2017a; Hogeboom et al., 2018; Martinez, 2015). Nonetheless, a comprehensive investigation of water security risks, risk perception, evaluation, and management in the private sector in Ontario is a pertinent research gap (Alvarado-Revilla & de Loë, 2022; Sandhu et al., 2020a).

Given the scholarly arguments, gaps, and transdisciplinary approaches yet to be operationalized, the dissertation focuses on the province of Ontario as a case study to develop a locally-attuned interdisciplinary water risk assessment, a novel transdisciplinary risk management framework, and decision support tool. While an interdisciplinary approach is apt for water risk estimation, a transdisciplinary approach is apt for water risk evaluation and management by engaging an influential actor, like the corporate and financial sector, as research participants, to elicit their preferences, priorities, and practical insights and co-develop and apply knowledge and understanding on water risk management (Christ and Burritt, 2018; Renn, 2021). Thus, the dissertation employs interdisciplinary concepts, theories, and transdisciplinary approaches by actively engaging corporate and financial practitioners as knowledge co-producers and users, to evaluate water risks, examine risk perception, and inform decisions for sustainable water management. Moreover, the decision support tool is an application-based and tangible outcome of the dissertation, such that findings on interdisciplinary water risks and perception-based priorities can be effectively communicated to assist multi-sector water risk management and decision-making (Busch et al., 2023; Christ & Burritt, 2018, 2019; Giupponi & Sgobbi, 2013; Loucks, 2023; Miles et al., 2023).

1.3 Research objective, questions, and spatial scope

The academic literature reveals major gaps in systematically assessing interdisciplinary water risks at disaggregated spatial scales and a lack of empirical examination of water risk perception and its relationship with water risk evaluation in the corporate and financial sector (CFS). Moreover, there is a paucity of decision support tools for water risk management based on transdisciplinary approaches to inform sustainable water management policies, strategies and practices in Ontario (Aven & Renn, 2020; Bilalova et al., 2023; Busch et al., 2023; Christ & Burritt, 2018; Di Baldassarre et al., 2021; Hogeboom et al., 2018; Klinke & Renn, 2012, 2021; Krueger et al., 2016; Quandt, 2022; Renn, 2021). Addressing these gaps and burgeoning academic interest in water risk assessment, management, and decision-making at the sub-watershed scale using normative-analytical theoretical frameworks, the dissertation has a three-fold objective, executed through studies covered in the four chapters. Firstly, it aims to develop a general purpose water risk assessment framework by investigating and estimating interdisciplinary water risks at the sub-watershed scale in Ontario. Secondly, it aims to examine the underlying factors of water risk perception of practitioners (analysts, managers, and decision-makers) in the CFS to unearth the relationship between risk perception and water risk evaluation. Finally, the dissertation concludes by investigating water risk management strategies in the CFS and develops a tangible decision support tool for sustainable water management in Ontario.

1.3.1. Dissertation's research questions

Aligned with the dissertation's objectives, the following questions are addressed through a 3-stage research project that has been covered in the four manuscripts. The three research questions and stages are logically interconnected and directly aligned with the water risk estimation, evaluation, and management stages of the dissertation's theoretical framework i.e., the normative-analytical water risk governance model.

RQ 1 [Stage 1, Interdisciplinary water risk estimation]: What are the interdisciplinary water-related biophysical risks, regulatory trends, as well as legacy and ongoing water user conflicts at the sub-watershed scale in Ontario, Canada?

RQ 2 [Stage 2, Water risk perception and risk evaluation]: What are the factors underpinning water risk perception of practitioners and decision-makers in the CFS in Ontario? How does water risk perception relate with water risk evaluation?

RQ 3 [Integration Stage 3, Water risk management and decision-making]: What are the strategies and preferences for water risk management in the CFS in Ontario? How can a transdisciplinary decision support tool be designed for water risk management and decision-making in Ontario?

1.3.2. Spatial scope of research

The case presented in this dissertation, is the province of Ontario, in Canada. However, given the necessity of using a granular sub-watershed spatial scale, especially for Stage 1 of the dissertation i.e., the interdisciplinary water risk assessment, 38 sub-watersheds in Ontario were included in the risk assessment. There is a lack of biophysical water risk data for sub-watersheds outside the Great Lakes watershed in Northern Ontario. Nonetheless, the 38 sub-watersheds included in the assessment consist of 95% of the provincial population and have high secondary data availability under the Source Water Protection Program and other federal and provincial initiatives (Auditor General of Ontario, 2014; Land Information Ontario, 2019).

The geospatial boundaries of the sub-watersheds correspond to the 38 Source Protection Areas (SPAs), as depicted in Figure 1.1, defined under the Clean Water Act, 2006 (Province of Ontario, 2007). The 38 SPAs are further aligned with 36 sub-watershed based conservation authorities of Ontario and 2 additional SPAs i.e., Northern Bruce Peninsula and Severn Sound. Nonetheless, for Stage 2 and 3, entailing the survey and interviews for water risk perception, priorities, and management strategies, the granularity of spatial resolution was not a limitation and hence the participant recruitment included the entire province of Ontario.

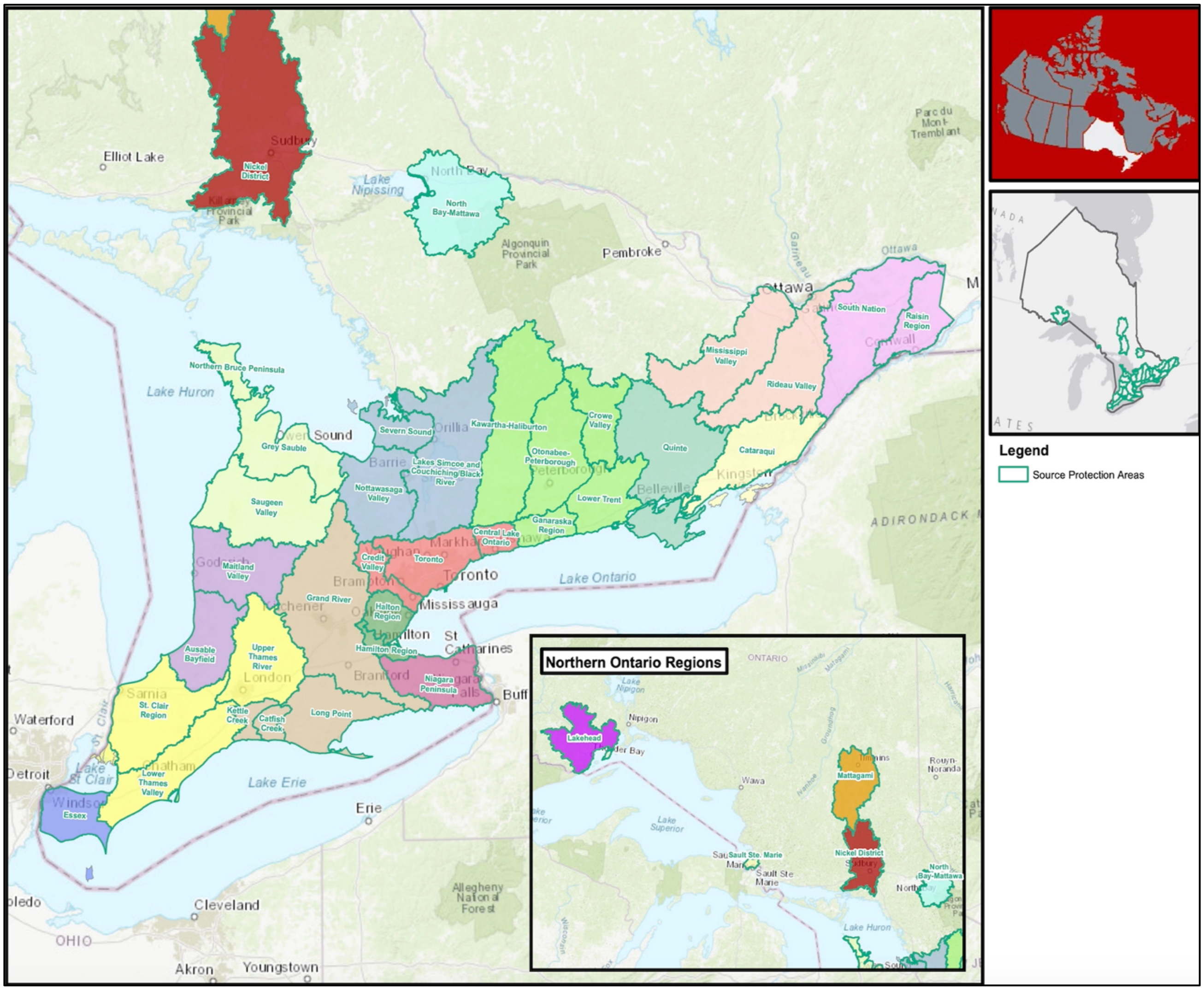

Figure 1.1: Spatial scope of Stage 1 water risk estimation in the Province of Ontario, Canada

Source: Ontario Ministry of Environment, Conservation & Parks, Source Protection Programs Branch (2018)

1.4 Theoretical framework

A critical review of the literature concludes that Risk is a highly intertwined construct spanning multiple disciplines and water risks are “wicked” risk and sustainability problems with dimensions of complexity, uncertainty, and ambiguity (Dobbie & Brown, 2014; Klinke & Renn, 2021; Siegrist & Árvai, 2020). Consequently, a single discipline, theory, or method is insufficient to investigate the analytical and normative aspects of water risk assessment, perception, and management in a comprehensive manner (Dobbie & Brown, 2014; Kasperson et al., 2022; Klinke & Renn, 2021; Krueger et al., 2016; Quandt, 2022). Therefore, water risk analysis requires interdisciplinary theories, uniquely combining different disciplinary paradigms and concepts, to develop a novel theoretical framework that is applied and validated for the risk problem of water security.

Since the dissertation employs interdisciplinary concepts, transdisciplinary approaches, and mixed methods, the distinction between a theoretical framework and theory is important. An interdisciplinary theoretical framework, aligned with the systems-based underpinnings of sustainability management, entails the integration of multiple paradigms, theories, and concepts from different disciplines guided by the overarching phenomenon of interest to identify interdisciplinary constructs, variables, and hypotheses to address the research questions of the dissertation (CohenMiller & Pate, 2019). Moreover, this framework is the theoretical analog and operationalization of "systems thinking", where the framework as a whole goes beyond the individual disciplinary components i.e., constructs, variables, theories, and methods, due multiple conceptual interactions (conceptual feedbacks or trade-offs) between components from different disciplines (CohenMiller & Pate, 2019; Von Bertalanffy, 1972; Williams et al., 2017). Transdisciplinary approaches are reflected in the dissertation's framework by the inclusion of practitioner priorities, preferences, and insights for risk evaluation, obtained using mixed methods, like surveys and interviews, where CFS practitioners are engaged as research participants to co-develop knowledge on water risk evaluation and management. Moreover, the development of a decision support tool as a tangible output based on the integration of interdisciplinary results and multi-sector practitioner insights to assist decision-making, is the bridge between interdisciplinary science and practice.

A theory helps analyze individual concepts, explain relationships between these concepts or causal mechanisms through hypotheses (e.g., explain risk perception factors and their underlying relationship with evaluation), to place the findings within the context of the broader field (CohenMiller & Pate, 2019; Creswell & Creswell, 2018). However, the theoretical framework provides an overarching logical model visually depicting these concepts, processes, and their interconnections, used to investigate the dissertation's research topic, integrate theories from multiple disciplines, hence connecting the concepts and hypotheses (relationships between concepts) of each research question to the overarching research problem (CohenMiller & Pate, 2019; Dobbie & Brown, 2014). Each stage of the research is aligned with a specific research question and these stages form the underlying foundation of the theoretical framework that are operationalized and tested. While a theory provides an analytical lens to investigate concepts and their relationships to answer a research question or help explain the findings in the literature, a theoretical framework is the common underlying foundation for the dissertation as a whole that logically connects the individual research questions or stages to achieve the overarching objective of the dissertation.

Given the theoretical need and novelty of an interdisciplinary theory for water risk assessment and management, the dissertation employed **Risk Theory**, a relatively new theoretical arena, which encompasses and integrates multidisciplinary theories, perspectives, and approaches for comprehensive risk analysis (Roeser et al., 2012). Risk Theory is a panoramic theory that conceptually tethers multiple disciplinary paradigms, theories (natural sciences, engineering, psychology, management sciences, sociology, economics, finance, political science, etc.), concepts, variables, and methods to develop frameworks to holistically understand, analyze, and explain assessment, perception, evaluation, and management of risk (Dobbie & Brown, 2014; Roeser et al., 2012). Thus, each research stage had a set of theories that were synthesized to analyze the underlying concepts of the complex whole. Thus, rather than relying on a monodisciplinary theory, the dissertation synthesized social-ecological perspectives and Risk Theory, conceptually drawing from Relational Theory, Psychometric Theory, Theory of Planned Behaviour, Value-Belief-Norm Theory, Cultural Theory, Risk Management and Governance Theory, and Sustainability and Environmental Management Theory, to explore the research problem holistically. The interdisciplinary breadth offered by Risk Theory was appropriate to address wicked risk problems like water (Cosgrove & Loucks, 2015; Kasperson et al., 2022; Klinke & Renn, 2021; Krueger et al., 2016; Van Asselt & Renn, 2011; Vasvári, 2015).

The overarching theoretical framework developed for this dissertation (Figure 1.2) is based on Klinke and Renn's (2012, 2021) **Normative-Analytical Risk Governance Model** that was applied to the risk problem of water security in Ontario. The normative-analytical risk governance model was proposed by Klinke and Renn (2012, 2021) as a generic model for all risk domains with analytical and normative aspects (see Section 1.2.3), for the stages of risk pre-estimation, interdisciplinary risk estimation, integrated risk analysis (perception and evaluation), management, and communication.

Based on the reviewed literature and research objective, the normative-analytical risk governance model was adapted for the stages of water risk assessment, management, and decision-making in the CFS. Risk Theory provided an interdisciplinary theoretical lens that was used to analyze different underlying stages of the normative-analytical risk governance model for the dissertation's core phenomenon of interest, i.e., water security risks in Ontario and how water (security) risks are evaluated and managed in the corporate and financial sector. Then, the framework was operationalized and validated through the dissertation's three stages. The communication and deliberation stages of the original model were combined with the management and decision-making stage (decision support tool and water risk management strategies), which was operationalized using deliberative and participatory methods to develop the decision support tool and revealing opportunities for transdisciplinary collaboration, research dissemination, communication, and trust-building.

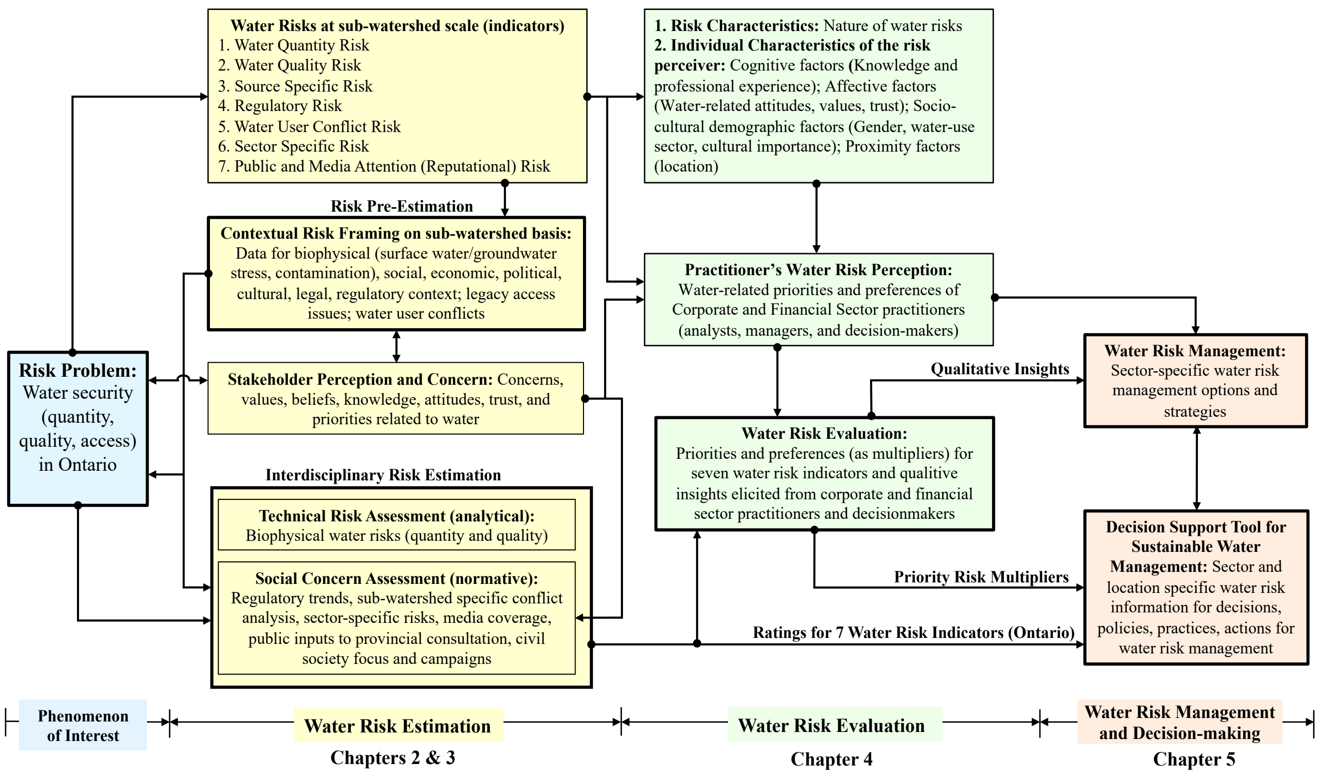

Figure 1.2: Overarching theoretical framework for water risk estimation, evaluation, and management

As discussed before, theories were drawn from multiple disciplinary paradigms and integrated within the interdisciplinary theoretical umbrella of Risk Theory (Roeser et al., 2012) for the analysis of the three individual stages of the dissertation's theoretical framework.

For Stage 1, entailing the exploratory risk pre-estimation and interdisciplinary water risk estimation (Chapters 2 and 3), Risk Theory encompassing interdisciplinary risk analysis (normative and hydrological risk components), systems based social-ecological perspectives (socio-hydrology), and Corporate Environmental Management theory, was used to investigate and estimate biophysical and social water risks at the sub-watershed scale for the case of Ontario (Busch et al., 2023; Christ & Burritt, 2018; Di Baldassarre et al., 2019; Linkov et al., 2014; Renn & Klinke, 2015; Savelli et al., 2022; Weber & Saunders-Hogberg, 2020; Xu et al., 2018). The risk pre-estimation sub-stage led to the identification of seven interdisciplinary water risk indicators, including the biophysical dimensions of water quantity, quality, and source-specific risk and social dimensions of regulatory risk, water-user conflict risk, sector-specific risk, and public and media scrutiny risk capturing the inequity-based legacy issues, regulatory trends, and water-user conflicts that shape stakeholder perception at the sub-watershed scale for Ontario. This framing of water risks captured relevant biophysical and social indicators as well as stakeholder perception not only to place the water risk problem in the local context but also to inform the comprehensive interdisciplinary water risk estimation sub-stage (Bilalova et al., 2023; Dobbie & Brown, 2014; Klinke & Renn, 2012; Quinn et al., 2019). The interdisciplinary water risk estimation is the integration of technical (objective) assessment of biophysical water risks (surface-water and groundwater quantity and quality) and social concern assessment to calculate differentiated ratings of the water risk indicators for 38 sub-watersheds in the study's scope.

For Stage 2, entailing water risk evaluation (Chapter 4), the dissertation examined water risk perception and its relationship with water risk evaluation in the corporate and financial sector using theoretical constructs and hypotheses from the psychometric and sociological paradigms (CohenMiller & Pate, 2019; Dobbie & Brown, 2014; Klinke & Renn, 2021). The physical, cognitive, affective, and socio-cultural factors risk perception factors and hypotheses were drawn from the Psychometric Theory and sociological theories like Cultural Theory, Value-Belief-Norm Theory, and Relational Theory, which are tethered under the panoramic Risk Theory and then adapted for the domain of water (Dobbie & Brown, 2014; Klinke & Renn, 2021; Roeser et al., 2012; Siegrist & Árvai, 2020; Slimak & Dietz, 2006). These theories enabled the comprehensive examination of water risk perception factors as well as unearth the complex relationship of these factors with water risk evaluation and management (Kasperson et al., 2022; Renn et al., 2022; Roeser et al., 2012). The water risk evaluation stage connects interdisciplinary risk estimation to risk management and decision-making, by eliciting the corporate and financial practitioners' and decision-makers' preferences, priorities, and insights for the seven water risk indicators identified in the risk estimation stage. Moreover, this stage theoretically delves into the model of practitioner's water risk perception, shaped by characteristics of water risks and individual characteristics i.e., the affective, cognitive, socio-cultural, and proximity factors, which is posited to influence evaluation of different water risks (Harris-Lovett et al., 2019; Kasperson et al., 2022; Klinke and Renn, 2012; McDaniels et al., 1997; Mumbi & Watanabe, 2022; Renn et al., 2022; Siegrist, 2021; Weber, 2001).

Finally for Stage 3, entailing water risk management and decision-making (Chapter 5), the conclusive and integrative stage of the dissertation, the Risk Management and Governance Theory (Renn & Klinke, 2015; Van Asselt & Renn, 2011), Environmental Management Theory (Busch et al., 2023; Weber & Saunders-Hogberg, 2020), and transdisciplinary approaches for decision support were used to investigate water risk management strategies and develop the decision support tool (Busch et al., 2023; Krueger et al., 2016; Renn, 2021). This stage integrates the results of Stage 1, i.e., ratings of seven water risk indicators from the water risk estimation stage, Stage 2, i.e., priorities elicited from practitioners in the risk evaluation stage as risk multipliers, with qualitative practitioner insights using transdisciplinary participatory approaches. These results and insights were integrated to develop a tangible decision support tool to inform and improve multi-sector sustainable water management decisions and outline strategies and opportunities for water risk management.

Each stage depicted in this theoretical framework was operationalized in the ensuing chapters of the dissertation. Thus, an expanded version of the individual stages of this framework and the interconnections with subsequent stages features in the corresponding chapters. Overall, the development, operationalization, and testing of this theoretical framework for the risk problem of water security in an influential actor like the corporate and financial sector are novel contributions to the theory of risk analysis, sustainability, and environmental management.

1.5 Philosophical foundations, research design, and methods

The dissertation's objective is multi-faceted, entailing assessment of interdisciplinary water issues, examination of risk perception, priorities, and preferences of practitioners, and developing comprehensive framework and decision support tools. Extant literature on risk and sustainability management highlights the strength and novelty of using mixed methods to address multi-faceted research problems by leveraging the strengths of quantitative and qualitative data and methods (Di Baldassarre et al., 2021; Quandt, 2022; Quinn et al., 2019; Siegrist, 2021; Siegrist & Árvai, 2020; Mooney et al., 2020). Much like siloed theories, a single method is insufficient in addressing complex systems-based research questions and there is a methodological gap, where mixed methods are applied to investigate water risks, risk perception, and develop tools investigating water risk perception and evaluation (Di Baldassarre et al., 2021; Quandt, 2022; Rangecroft et al., 2021, 2022). Thus, a transdisciplinary mixed methods research design is necessary for the systematic integration of interdisciplinary water risk evidence with the contextual social, cultural, and psychological aspects of risk perception and insights of practitioners (Christ & Burritt, 2018; Di Baldassarre et al., 2021; Harris-Lovett et al., 2019; Klinke & Renn, 2021; Quandt, 2022; Quinn et al., 2019; Renn, 2021, Renn et al., 2022).

Given the social-ecological nuances and plurality of the dissertation's phenomenon of interest and objective, the dissertation philosophically aligns with the problem-centric pluralistic worldview (research paradigm) of **pragmatism**. A pragmatic worldview focuses on the comprehensive understanding of multi-faceted interdisciplinary risk problem like water security and producing tangible outcomes influencing policies and practices (Creswell & Creswell, 2018; Quinn et al., 2019; Renn, 2021; Shan, 2022). For the overarching research design, a mixed methods design, consistent with the interdisciplinary and transdisciplinary approaches of the dissertation, which synthesizes quantitative robustness and qualitative explanatory and contextual depth, was used for the dissertation (Creswell & Creswell, 2018; Di Baldassarre et al., 2021; Greene et al., 1989; Renn et al., 2022; Renn, 2021; Vogt, 2008). The three-stage mixed methods research design aligned with the three stages and research questions of the theoretical framework is presented in Figure 1.3.

For **Stage 1**, addressing **RQ 1** on interdisciplinary water risk estimation, covered in Chapters 2 and 3, secondary mixed data analysis was used to investigate biophysical and social water risks (water quantity, quality risks, regulatory trends, social water user conflicts) and calculate sub-watershed and sector-specific ratings for 38 sub-watersheds in Ontario. For **Stage 2**, addressing **RQ 2** on water risk perception and evaluation, covered in Chapter 4, explanatory sequential mixed methods (survey→follow-up interviews) were used. The quantitative phase consists of an online cross-sectional survey to examine underlying factors of water risk perception of CFS analysts, practitioners, and decision makers and unearth the relationship between water risk perception and evaluation. The follow-up qualitative phase consists of in-depth semi-structured interviews of the same sample to help explain and complement the survey findings (Quinn et al., 2019; Siegrist, 2021; Siegrist & Árvai, 2020). For **Stage 3 (integration)**, addressing **RQ 3** on water risk management and the decision support tool, covered in Chapter 5, explanatory sequential mixed methods and secondary data analysis (survey → interviews + secondary data analysis) were used. Mixed methods like a survey and follow-up explanatory interviews were used to elicit practitioner preferences on the seven water risk indicators and insights on water risk management. Secondary data analysis was used to integrate the Stage 1 ratings for the seven risk indicators and Stage 2 practitioner priorities with Stage 3 water risk management insights to develop the transdisciplinary decision support tool. The decision support tool (WATR-DST) was designed and coded in MS Excel to calculate location and sector-specific ratings and a cumulative risk ratings based on user-defined inputs (Giupponi & Sgobbi, 2013; Loucks, 2023; Morales-Torres et al., 2016; Yang, 2017).

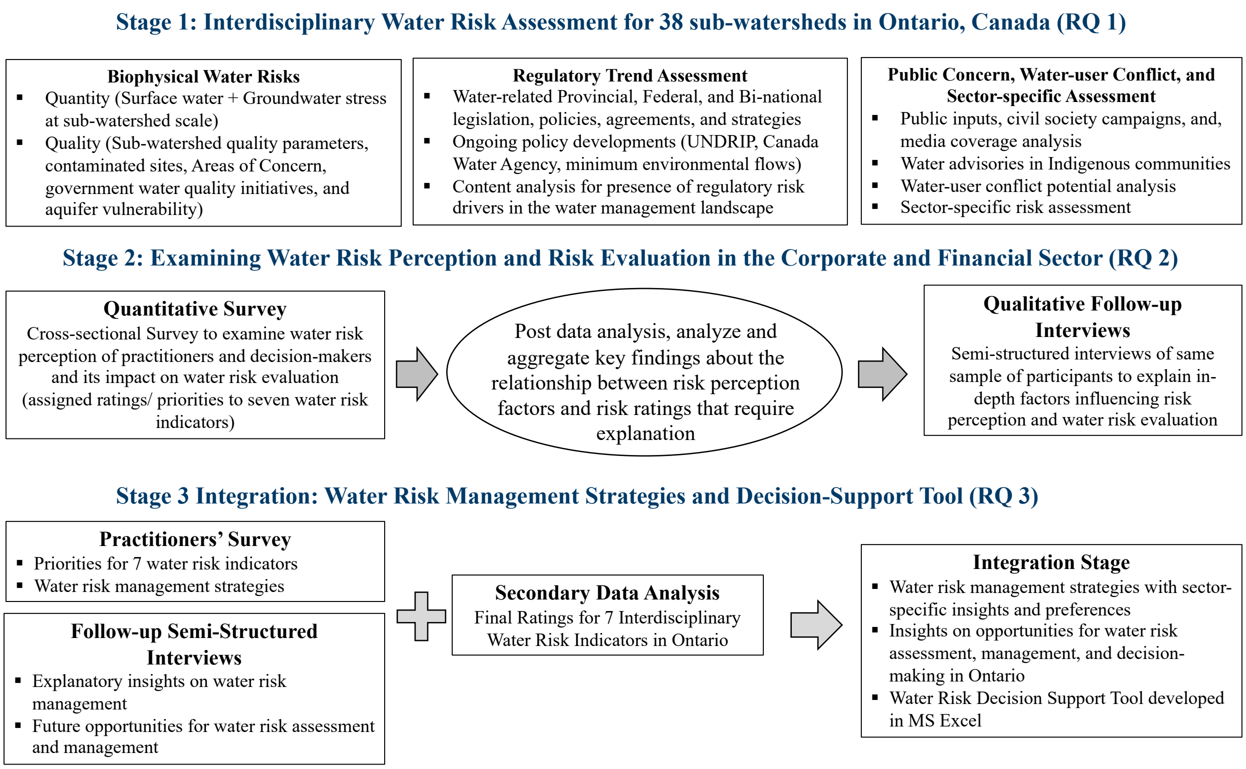

Figure 1.3: Dissertation's overall mixed methods research design

The mixed methods research design provided a comprehensive and robust framework to integrate interdisciplinary water risk data with perspectives and insights of the CFS practitioners at the local sub-watershed scale to examine water risk perception, evaluation, water risk management strategies, and develop a transdisciplinary decision support tool for water risk management (Christ & Burritt, 2018; Creswell & Creswell, 2018; Greene et al., 1989). For the research participants, as discussed before, private actors, i.e., the CFS or private sector, are influential actors in water risk management and governance landscape, but have been an underexplored population in the water risk assessment, perception, and management research (Christ & Burritt, 2018; Hogeboom et al., 2018; Money, 2014a, 2014b). Addressing the population gap, Stages 2 and 3 engage with the corporate and financial sector using a survey and interviews, to elicit their preferences and insights for water risk evaluation and management, and co-develop knowledge and inform design of practical tools, hence operationalizing transdisciplinarity from a methodological perspective (Christ & Burritt, 2019; Renn, 2021). The practitioners include sustainability analysts, managers, and decision-makers in businesses in water-use sectors like agriculture, environmental consulting, food and beverage, chemical manufacturing, automotive, power generation, and mining as well as financial institutions like banks, investment and insurance companies.

1.6 Organization and overview of the dissertation

The dissertation is organized on the manuscript-based format, composed of four manuscripts. Chapters 1 and 6 are the introduction and conclusion chapters respectively, providing the overarching summary and key conclusions of the dissertation. Chapters 2, 3, 4, and 5, present the four manuscripts that address the dissertation's overarching research objective and questions. All chapters are logically connected to each other and to the dissertation's objective. The interconnections are described in Section 1.4. and depicted by the three stages of the theoretical framework (Figure 1.2), i.e., interdisciplinary water risk estimation, water risk perception and evaluation, and water risk management and decision-making A summary of six chapters is provided in the ensuing paragraphs below.

Chapter 1 introduces the dissertation, providing a background on the core phenomenon of interest, water risk assessment, management, and decision-making in Ontario, and rationale for the research, brief overview of the literature and gaps pertaining to transdisciplinary normative-analytical risk governance approaches for water security risks. It then defines the dissertation's overall research objective, questions, and scope. The chapter also outlines the dissertation's theoretical framework, underlying theories, and stages, that have been operationalized in the ensuing chapters. The theoretical framework further establishes the logical interconnections between the chapters and alignment with the dissertation's research questions and research design. The chapter then delves into the philosophical foundations, mixed methods research design, organization of the dissertation, and finally the contributions to knowledge highlighting the key findings. Thus, the introduction chapter serves as a standalone overview and summary of the research presented in Chapters 2 to 5 of this dissertation.

Chapter 2 aligned with the dissertation's first research objective and question, provides an exploratory review on the different water-related risks, conflicts, and regulatory landscape in Ontario. It operationalizes the risk pre-estimation sub-stage of Stage 1 of the theoretical framework, focused on framing the water risk problem in the context of Ontario with a background on corporate water management. It then pivots into the case study of Ontario, highlighting past and emerging water issues, their multi-dimensional risks, and the state of water management and governance. It explores the biophysical, social, political, cultural, legacy, and institutional context related to water issues, their risks, and opportunities for water risk assessment and sustainable water investments in Ontario. Based on the reviewed literature, government and industry reports, it suggests a conceptual framework for assessing interdisciplinary water risks in Ontario, distills seven water risk indicators, and identifies key data sources. Thus, laying the groundwork for Chapter 3 on interdisciplinary water risk estimation. Furthermore, it establishes the foundation for the case study of Ontario, the common thread, connecting the remaining chapters of the dissertation.

Chapter 3 operationalizes the interdisciplinary water risk estimation sub-stage of Stage 1 of the dissertation's theoretical framework. It addresses the dissertation's first objective and question by quantifying interdisciplinary water risks for 38 sub-watersheds in Ontario, and then developing an assessment framework that provides spatially and sector differentiated ratings for these risks. It builds upon Chapter 2's risk pre-estimation by extracting and analyzing quantitative and qualitative data from the identified data sources to get a comprehensive picture of water security risks at the sub-watershed scale. Theoretically, the chapter uses a social-ecological perspective and applies the technical and social concern assessment approaches of Risk Theory to develop a comprehensive general purpose water risk assessment framework for Ontario. Methodologically, employing secondary mixed data analysis, the chapter integrated and analyzed, quantitative and qualitative data from 15 datasets for water quantity and quality risks, regulatory trends, public and media concern, and water user conflicts for 38 sub-watersheds along with sector-specific assessment for 70 water-use sectors in Ontario. The chapter finds high and moderate risk potential in at least 50% of the studied sub-watersheds for all water risk indicators that confirms presence of water security risks at the sub-watershed level and empirically challenges the myth of water abundance in the populous and economically productive Great Lakes watershed of Ontario. The chapter demonstrates the importance of disaggregated interdisciplinary risk assessment to avoid underestimation of total water risk. It provides the evidence on the seven water risk indicators and informs the design of the study on water risk perception and evaluation covered in Chapter 4.

Chapter 4 operationalizes Stage 2 of the dissertation's theoretical framework on water risk evaluation and delves into the water risk perception of the CFS practitioners. It addresses the dissertation's second objective and question by investigating the various underlying factors of water risk perception of corporate and financial practitioners, and then empirically examining the relationship between water risk perception and evaluation of water risks (identified in Chapter 3) in the corporate and financial sector in Ontario. By extending the definition of experts, to include CFS practitioners, i.e., practicing experts, who assess, analyze and manage water risks, the chapter focuses on the contemporary conceptualization of risk perception in experts and argues that experts have a nuanced perception of risk, which is impacted by values, beliefs, and experience. It integrates and uses Psychometric and sociological theories like Value-Belief-Norm Theory, Cultural Theory, and Relational Theory tethered under Risk Theory to identify the cognitive, value-based affective, trust-based, and socio-cultural factors that shape water risk perception and develops hypotheses to test the relationship between risk perception factors and risk evaluation. Methodologically, to collect data for testing the key hypotheses, the chapter uses explanatory sequential mixed methods, consisting of a cross-sectional survey (N=25) followed by semi-structured interviews (N=22), with a purposive sample of CFS practitioners in Ontario, Canada.

The survey data was first analyzed using exploratory factor analyses to validate the underlying theoretical constructs and variable reduction. Then multiple linear regression was used to analyze and explain the relationship between water risk perception factors and evaluation (ratings or priorities) of water risks. The interviews were used to explain interesting survey findings, further adding theoretical validity and reliability of findings. The chapter finds that cognitive, affective, and socio-personal factors, including knowledge, professional experience, perceived controllability, values, trust, location, and gender, shape the water risk perception of practitioners, influence water risk evaluation, and are contingent on the specific type of water risk. Further discussion also revealed factors, such as proximity bias, sector differences, trust in various institutions, as well as the influence of tacit knowledge, exposure, the role of regulations, media, and financial materiality that impact evaluation. The chapter concludes by confirming that water risk perception of corporate and financial practitioner is nuanced and influences the evaluation and hence management of water risks. Furthermore, the priorities and ratings for the water risk indicators elicited in Chapter 4, informed the design of the decision support tool developed in Chapter 5 for water risk management.

Chapter 5 operationalizes the final stage of the theoretical framework, i.e., Stage 3, on water risk management and decision-making. It addresses the third (and final) objective and question of the dissertation by investigating strategies and preferences of corporate and financial practitioners on water risk management in Ontario. It integrates findings from Stages 1 and 2, along with practitioner insights to develop a transdisciplinary water risk decision support tool, WATR-DST, as the tangible output of the dissertation. It utilized a transdisciplinary approach to engage the corporate and financial sector and employed mixed methods including a survey and interviews to examine sector-specific preferences and insights on water risk management. Then, the decision support tool was designed using secondary data analysis to integrate findings from the interdisciplinary water risk estimation (Stage 1, Chapter 3) and water risk evaluation (Stage 2, Chapter 4). The tool demonstrates the synthesis of data for seven water risk indicators with practitioner priorities, and calculates ratings based on the user's inputs for location and sector.

Theoretically, the chapter is anchored in the intersection of the Risk Management and Governance Theory, Decision (behavioral) Theory, and Environmental Management Theory. The chapter concludes that rather than a single approach for water risk management, a combination of regulatory, voluntary, and multi-stakeholder participatory approaches, contingent on the severity of water risks, sector, and context may be necessary in the corporate and financial sector. Moreover, the chapter emphasizes that flexibility, efficiency, strategic incentives, economic and regulatory signals are equally important considerations for bringing water risk assessment and management to the forefront of corporate and financial decision-making. The chapter concludes by highlighting the opportunities for transdisciplinary engagement, knowledge co-development, and trust-building in the water risk management and governance landscape. Finally, the salient features of the WATR-DST as a transdisciplinary research output are discussed, where it is envisioned to improve decisions and practices for sustainable water

management, corporate sustainability, and accountability. Thus, the chapter successfully tethers the first two stages of the theoretical framework i.e., water risk estimation and evaluation that address, “what are the water risks?”, “what is the severity or rating?”, and “how are water risk prioritized/ ranked in decision-making?” to the third stage of water risk management and decision-making, which addresses, “what to do about the assessed and evaluated water risks?”
Chapter 6 concludes the dissertation, providing the overarching conclusions and key outcomes of the doctoral research. It outlines how the dissertation addressed the scholarly arguments and gaps revealed in the literature. It then discusses the academic contributions made to knowledge in the fields of risk analysis, sustainability management, and environmental management (water resources management) as well as methodological developments. Given the necessity of contributing to theory in doctoral scholarship, the chapter further discusses the contributions to the interdisciplinary theories of risk, corporate sustainability, and environmental management. It then briefly delves into the practical implications of the research, specifically the transdisciplinary decision support tool, the WATR-DST, a key practical and transdisciplinary output of this dissertation. Finally, the chapter reflects on the limitations of the research and recommends areas for future work.

1.7 Contributions to knowledge

The academic emphasis on sustainable water management by systematically assessing and integrating water risks in decision-making, by influential institutions like businesses and the financial sector, is growing. However, one of the key topics yet to be empirically investigated in the fields of sustainability management, risk analysis, socio-hydrology, and environmental management (water resources management), is the interdisciplinary water risk assessment and management at disaggregated spatial and temporal scales, especially for the unique case of Ontario (Alaerts, 2019; Christ & Burritt, 2017a, b, 2018; Hogeboom et al., 2018; Hoekstra, 2014; Money 2014a). The research covered in Chapters 2 to 5 of the dissertation make five broad theoretical contributions that address gaps in the literature and advance knowledge in the fields of risk analysis, sustainability management, environmental management, and socio-hydrology, by applying Risk Theory and social-ecological perspectives to conceptually tease out water risk assessment, perception, and management in the corporate and financial sector.

First, overall, the dissertation applied Risk Theory, a relatively new theoretical area, which emerged in response to growing appeals for interdisciplinary approaches to risk analysis

(Aven & Renn, 2020; Dobbie & Brown, 2014; Klinke & Renn, 2021; Roeser et al., 2012). It intersected multiple disciplinary paradigms under the Risk Theory, including Psychometric, Cultural, Relational, Social-ecological, Sustainability, and Environmental Management theories, for the wicked risk and sustainability challenges of water. Thus, the dissertation contributed to the validation of the Risk Theory for water risk estimation, perception, evaluation, and management. Moreover, the dissertation expands and tests Klinke and Renn's normative-analytical risk governance model for the risk domain of water security in the corporate and financial sector, which had not been done in extant literature. The interdisciplinary water risk assessment and management framework was operationalized into a first-of-a-kind transdisciplinary decision support tool with quantitative and qualitative risk indicators along with risk priorities elicited from corporate and financial practitioners to inform water-related multi-sector decision-making (Dudley et al., 2022; Di Baldassarre et al., 2021; Klinke & Renn, 2012, 2021; Mumbi & Watanabe, 2020; Renn et al., 2022; Renn, 2021).

Second, Chapters 2 and 3 demonstrate the first-of-a-kind social-ecological systems-based application of Risk Theory using biophysical and social water risk data to assess interdisciplinary water risks at the local sub-watershed scale, broadening the siloed approaches of sustainability management theory (Di Baldassarre et al., 2019, 2021; Starik & Kanashiro, 2013; Xu et al., 2018). While extant aggregated water risk assessments do not indicate heterogeneity of contextual social water risks for Ontario, using mixed interdisciplinary data and novel methodological approaches for assessing and integrating public concern, media coverage, and conflict analysis, the research found heterogeneity in all investigated risk dimensions. It found higher total water risk, hence empirically challenging the myth of water abundance in Ontario and critiquing this serious omission by extant narrow disciplinary approaches (Cai et al., 2021; Dudley et al., 2022; Opperman et al., 2022). Thus, Chapter 2 and 3 advance knowledge in water risk assessment by applying social ecological perspectives, interdisciplinary approaches of Risk Theory, and mixed methods to provide a comprehensive assessment of water security and demonstrate integration of social science perspectives in the field of socio-hydrology.

Third, Chapter 4 makes a theoretical contribution by empirically examining and explaining the complex and underexplored construct of water risk perception and its relationship with water risk evaluation, in the sample of CFS practitioners in Ontario. It demonstrates the integration and application psychometric, cultural, and relational theories of risk to unearth the nuanced factors of risk perception and its influence on water risk assessment and decision-making (Di Baldassarre et al., 2021; Dudley et al., 2022; Klinke & Renn, 2021; Siegrist & Árvai, 2020). While extant research focused on risk perception of broader environmental issues using a siloed disciplinary theory and quantitative methods like surveys, this chapter explored risk perception of water security using mixed methods (Dobbie et al., 2016; Mumbi & Watanabe, 2020; Siegrist & Árvai, 2020; Slimak & Dietz, 2006). The constructs and hypotheses for water risk perception, drawn from interdisciplinary risk theories, were validated using exploratory factor analyses and regression models representing each water risk, hence making water-specific contributions to the broader Risk Perception Theory. Thus, it challenged the norm of a completely rational, objective, and value-free model of risk perception in experts and confirms a complex and nuanced model of risk perception (Dobbie & Brown, 2014; Roeser et al., 2012; Sjöberg, 2002)

Fourth, Chapter 5 makes a contribution by operationalizing and validating the normative-analytical risk governance model for water risk management and decision-making in the corporate and financial sector. The chapter also applied novel transdisciplinary mixed methods approaches, integrating practitioner perspectives with analytical risk data to co-develop knowledge and practical tools for water risk management. Theoretically, by uncovering the concerns of an influential stakeholder like the private sector, the study contributes to knowledge on risk analysis and sustainability management by revealing hybrid strategies for water risk management, communication, and trust-building to improve corporate sustainability and environmental performance (Busch et al., 2023; Gladwin et al., 1995; Klinke & Renn, 2021). Moreover, using the case study of Ontario, the chapter develops a first-of-a-kind transdisciplinary tool, “WATR-DST”, designed to identify and manage, sub-watershed, context, and sector specific water risks, hence informing water risk management strategies and sustainable water management decisions and practices for a climate-resilient and water secure Ontario.

Finally, the dissertation makes a novel methodological contribution by demonstrating the transdisciplinary application of mixed methods and interdisciplinary mixed data to address research questions on systems-based challenges like water security risk (Christ & Burritt, 2018; Di Baldassarre et al., 2021; Krueger et al., 2016; Renn, 2021). The use of mixed data and explanatory sequential mixed methods with the CFS practitioners to co-develop knowledge and tools are the key scientific strength and novelty of the dissertation. Quantitative and qualitative data and methods enabled the comprehensive assessment of different water risks (Siegrist & Árvai, 2020; Di Baldassarre et al., 2021). Moreover, engaging non-academic practicing experts, in the CFS, enabled a pragmatic examination of complex and nuanced constructs like water risk perception and risk evaluation, inclusion of practitioner priorities and preferences, and investigation of practical sector-specific water risk management strategies to co-develop and synthesize transdisciplinary knowledge and tools (Krueger et al., 2016; Renn, 2021). The interviews validated the survey's findings, provided reliability, theoretical depth and understanding, expanding statistical evidence further. Therefore, using mixed methods, the dissertation demonstrated the academic application of normative-analytical and transdisciplinary approaches, that helped enhance rigor, qualitative depth, and gain a nuanced understanding of all stages of the theoretical framework.

Chapter 2

2. Water Risks, Conflicts, and Sustainable Water Investments: A Case Study of Ontario, Canada

Contents of this chapter are published in:

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Ensuring sufficient quantity and quality of water resources is a necessary requisite for social well-being, economic prosperity, and environmental integrity. Water resources are continuously being threatened due to increasing population, economic activities as well as uncertainty posed by climate change. Moreover, risk to water security is a multi-dimensional construct of quantity, quality, access, and public perception that needs to be tethered together in policies and investments for a sustainable future. Given the wide social, economic, and ecological implications, it becomes necessary to conceptualize, assess, and manage interdisciplinary water risks as a means to ensure water security. As major users of this economically significant resource, businesses and financial investors fueling these businesses have a crucial role in designing sustainable water management practices by accounting for various water risks and response strategies. While existing literature on water disclosure and risk assessment highlights actions undertaken by businesses and investors in currently water-stressed regions, there is a gap in understanding current and future interdisciplinary water risks in regions perceived to be water-rich. Therefore, this chapter investigates different dimensions of water risk assessment, including an overview of current literature, gaps, and opportunities for sustainable water investment. Then using a case study approach, granular interdisciplinary water risk evidence is gathered for the Province of Ontario, Canada, and synthesized into a conceptual framework that can help design proactive decision support tools and guide the integration of sustainable water management principles in corporate and financial decision-making for a water-secure and sustainable future.

MANUSCRIPT BEGINS

2.1 Introduction

Water security is the ability to maintain sufficient quantity and quality of water resources, which is necessary for social well-being, economic development, ecological integrity, and climate resilience (UN-Water, 2013). Therefore, ensuring water security for current and future generations is the underlying foundation of Sustainable Development Goal (SDG) 6, but much progress needs to be made globally to attain this goal (United Nations, 2018). Water availability (quantity, quality, and access) is continuously being threatened due to increasing population, economic activities, and climatic uncertainty (Hoekstra, 2014). Given the wide social, economic, and ecological implications of water challenges, it becomes necessary to conceptualize, assess, and manage interdisciplinary water-related risks as a means to address various dimensions of water security, including the investment needs (OECD, 2013; United Nations, 2018).

Risks to water resources are multi-faceted due to the duality of water used as a material input for manufacturing, agriculture, power generation, as well as a common good essential for human health, sanitation, recreation, and ecosystem productivity (Hanemann, 2006). While certain uses of water are obvious (e.g., extractive uses for manufacturing, agriculture, municipal water supply, power generation), many in-stream uses (hydroelectricity generation, fisheries, recreation, tourism, and ecosystem services) connected with water resources are equally pertinent (Sandhu et al., 2020). Therefore, adverse water events can have a domino effect across entire watersheds or aquifers that multiplies the impact manifold (Vörösmarty et al., 2010). Moreover, degraded water quality due to chemical or biological contamination events also makes water sources completely unfit for use or highly cost-intensive to treat, thus contributing to water scarcity in the region (Sandhu et al., 2020).

Even though the access to safe drinking water was declared as a human right by the United Nations General Assembly in 2010, 2.2 billion people across the globe are still devoid of this basic human necessity (WHO, 2019). Economic scarcity of drinking water infrastructure is also a major water challenge not only in the global south, but also in Indigenous communities of high-income countries like Canada (White et al., 2012). As the globe grapples with the recent COVID-19 crisis, equitable access to safe water and wastewater treatment is seen at the forefront of preventing the spread of such viruses and bacteria. This intricate connection of water with public health, sanitation, and hygiene further prioritizes the allocation and provision of safe water for human well-being and re-establishes focus on water security (Sanitation and Water for All, 2020).

Water management is typically under public jurisdiction governed by different levels of national, provincial, and municipal governments and varies considerably across countries. However, sustainable water use and management to attain water security is not only the responsibility of governments, but also of different water-using sectors including the corporate sector. As major users of this economically significant resource, businesses and the financial sector fueling these businesses have a crucial role in designing proactive sustainable water management practices by accounting for various water risks and response strategies.

Even with the increasing academic and practitioner interest in integrating water risk data in operational and investment decisions, there is a gap in understanding and assessing granular interdisciplinary water risks to design holistic decision support tools and guide sustainable water investments (Christ & Burritt, 2018; Hogeboom et al., 2018). The chapter explores different dimensions of water risks, including an overview of the current literature, gaps, and future opportunities in the field. Then using the case study of Ontario, Canada, we gather interdisciplinary water risk evidence at the granular sub-watershed scale and synthesize it into a framework that can guide proactive decision-making in seemingly water-secure regions typically outside the investor or corporate scanner.

2.2 Background

To categorize water risks and tease out their interdisciplinary nuances, it is essential to understand the theoretical aspects of risk assessment, management, and current water risk management practices in the corporate and financial sectors. The field of risk assessment and management has been spurred by adverse industrial contamination events, natural hazards, or national security threats with severe human and ecological health implications as well as economic implications due to risky financial activities in the past. OECD (2003) and Aven & Renn (2010) define emerging systemic risks as an interdisciplinary and highly networked set of risks that threatens the underlying core systems (e.g., health, infrastructure, environment, energy, transport, etc.) responsible for the functioning of society. Since there is an interconnected nexus of water security with food security, public health, economic development, energy security, ecosystem health, and social well-being, water issues (quantity, quality, and access) are considered as "emerging systemic risks" requiring interdisciplinary assessment and management approaches rooted in risk theory (Aven & Renn, 2010).

2.2.1. Theoretical background on risk assessment and management

Aven and Renn (2009, p. 6) define risk as "uncertainty about and severity of the events and consequences (or outcomes) of an activity with respect to something that humans value." Uncertainty is a distinct concept that is discussed in tandem with risk; it is the possibility of different consequences after a hazardous event or the unpredictability of risks due to a lack of information or knowledge (Aven & Renn, 2009; Gough, 1997). Risk assessment involves verifiable data, theory, probabilistic analysis, and modelling using objective methods (Cienfuegos Spikin, 2013). Risk is rooted in society, and the perception of risk is contingent on values, norms, beliefs, personal experiences, attitudes, and cognitive knowledge. In conjunction with the objective or physical measurement of risk, there is an inherent subjectivity in how risk and severity of the outcome is observed and how tolerability of risk is judged, leading to public concern or outrage (Klinke & Renn, 2002; Renn, 1998).

Environmental, fiscal, and organizational policies are largely based on quantitative risk assessments, but the journey from data to an implementable decision-making framework is not devoid of judgement (Aven & Renn, 2009). From an implementation perspective, the field of risk management informs policies and formulation of regulations while operating within given social, economic, and political constraints. In practice, environmental protection policies are designed to prioritize foremost the concerns of the public constituents and contain contextual nuances. In certain cases, public perception and concerns about the potential impacts of a technology or industrial activity may catalyze policy actions triggering risk assessments pre-emptively (Renn, 1998; Russell & Gruber, 1987). Therefore, political, social, economic, and cultural aspects intersect for resources like water with multiple stakeholders, along with hydrological evidence for risk assessments (Gough, 1997; OECD, 2003).

Risk management in totality involves assessment, comparison, and design of strategies of avoiding, reducing, transferring, or adapting to identified risks. Since environmental risk includes ecological, social, cultural, and economic risks, existing risk management approaches can provide a comprehensive foundation where interdisciplinary data can be merged to make sustainable decisions for current and future generations (Gough, 1997; OECD, 2003). Three typical approaches used are *Technical Risk Assessment* (engineering, health, environment) that uses purely scientific assessments for decision-making, *Decision Analytic Approach* that includes subjective value judgment of decision makers about possible outcomes based on statistical estimates of an event, and *Comparative Risk Assessment* that includes ranking the issues and assigning priorities for response items. While the risks (social, ecological, human health) may be assessed from different data sources with varying reliability, the emphasis is on prioritizing issues to design action strategies (Gough, 1997).

Exposure to water risks is also closely related to society in general, hence the tolerability or acceptability of risks is defined by public perception shaped by technical, cultural, and economic contexts (Wyrwoll et al., 2018). In order to account for the contextuality and variability of water issues, the use of granular temporal and spatial scales also becomes warranted for holistic impact and risk assessment affecting a range of stakeholders (Loucks, 2000). A risk-based framework is often recommended in the literature for public water management where the source of risks, corresponding actions, and stakeholders are identified. This process often entails detailed hydrological studies, stakeholder engagement, and impact assessments leading to developing policy responses through the use of regulatory, economic, or stewardship instruments (OECD, 2013; Wyrwoll et al., 2018). Similarly, the field of corporate water accounting, disclosure, and reporting is a means of assessing and managing water-related risks. In modern risk management, risks are often not only a cost or regulatory liability, but also an avenue to identify opportunities for innovation, increased efficiency, and sustainability (Cienfuegos Spikin, 2013).

2.2.2. Corporate water risk assessment and management

Most industrial sectors not only require a certain quality and quantity of water for production operations and waste assimilation, but also rely on water-intensive supply chains (Christ & Burritt, 2017b). Given the complexity of water as a shared public, economic, and environmental resource, water risk has been articulated in corporate management literature as physical, regulatory, and reputational risks that can potentially culminate into adverse financial impacts for corporations and their investors (detailed extensively in Barton, 2010; Freyman et al., 2015; Christ & Burritt, 2017a; Morrison & Schulte, 2010; Schulte et al., 2012). Physical or operational risks arise from direct scarcity of intake water due to decreased hydrological flows or contamination of supply, or indirectly through water stress-related disruptions in supply chains or electricity inputs. Regulatory risks arise from changing public policies and legislation regarding the allocation and use of water resources resulting in reduced allowed extraction volume, increased water extraction fees, pollution fines, consultation, restrictions, monitoring, and reporting requirements (Signori & Bodino, 2013). Reputational risks arise from conflicts between competing water use sectors during, for example, drought conditions or existing conflicts with local communities over inequitable allocation or access to water resources that can negatively impact stakeholder perceptions and potential public lawsuits, and lead to regulatory actions like moratoriums or a loss of “social license to operate” (Schulte et al., 2012).

These three categories of water-related risks ultimately culminate in increased operational costs, loss of reputation, potential loss of investors, and increased scrutiny by internal and external stakeholders (e.g., governments, NGOs, suppliers, customers, investors, employees, local communities). Therefore, from a corporate perspective, sustainable water management by managing identified risks is essential to safeguard financial viability, maintain investor interests, and dissipate external stakeholder pressure (Freyman et al., 2015; Hogeboom et al., 2018). Nonetheless, the degree of water risk exposure of each organization is highly variable and contingent on operational factors, i.e., type of sector (water intensity, supply chain, quality of water needed, waste generation) and use of water-efficient technologies. Moreover, many external factors at the watershed or basin level like hydrological conditions, surrounding land use, socio-economic conditions, political and institutional conditions, legislations on water allocation, and use and discharge need to be accounted in such assessments (Signori & Bodino, 2013).

From the perspective of the private sector, water management is inherently complex due to the multidimensionality of water risks and the range of stakeholders involved (Christ & Burritt, 2017b). Nonetheless, the corporate water management framework employed to reduce, mitigate, and adapt to water risks involves firstly the acquisition of global, national, and local data on watershed trends; water accounting data at the facility level on the extraction; discharge and impact on local water resources; and regulatory and reputational water risk data (Christ & Burritt, 2017a; Signori & Bodino, 2013). A plethora of methods and tools have been used by businesses to collect data on watershed conditions, operational water use, the impact on watersheds (availability and quality) as well as regulatory and reputational risks (WBCSD-IUCN, 2012). While some tools like WWF Water Risk Filter and WRI Aqueduct provide hydrological risks based on different global hydrological simulation models, they do not capture the regulatory and reputational risks reflecting public concerns, regulatory context, or local watershed conditions at disaggregated sub-watershed scales (Jorisch et al., 2018; Morgan et al., 2020).

The practice of corporate disclosure of water risks and opportunities is seen as a means to develop accountability especially with rising demands by the public and institutional investors where third party rating agencies are involved in assessing companies (Freyman et al., 2015; Signori & Bodino, 2013; Vörösmarty et al., 2018). While water accounting is done internally to inform strategic decisions at the organizational level, disclosure is done for both internal and external stakeholders in a prescribed format using available best practices or guidance. Global Reporting Initiative (GRI) 303: Water and Effluents, CDP Water Questionnaire, Sustainability Accounting Standards Board (SASB), Alliance for Water Stewardship, UN CEO Water Mandate Corporate Water Disclosure Guidelines, and European Union Non-Financial Reporting Directive are some of the prominent disclosure mechanisms adopted voluntarily by firms to increase transparency and define reporting protocols (Freyman et al., 2015; WBCSD-IUCN, 2012).

While disclosure can facilitate stakeholder dialogue and better water management practices, there is widespread criticism of current corporate water reporting practices. These reports generally lack granular basin-level data, contextual information, stakeholder engagement, and supply chain risks that can help assess the financial and operational risks more accurately (Money, 2014a; Signori & Bodino, 2013). There is stagnancy in water reporting since firms react to issues that can improve operational efficiency within their boundaries rather than engaging with stakeholders on a watershed basis (Christ & Burritt, 2018; Signori & Bodino, 2013). The gaps found in water accounting and disclosure highlight the scarcity of appropriate sub-watershed water security risk data needed by stakeholders to make proactive assessments. The tools designed are fragmented, seldom encompassing, and the management frameworks lack the collaborative interdisciplinary approaches necessary for different types of risks (Christ & Burritt, 2017a, 2018).

2.2.3. Financial sector and water risks

The flow of financial capital sourced through debt (loans, bonds) or equity is necessary to drive and sustain economic activities in every region and sector. Financial sector comprising of commercial and investment banks, insurance companies, and asset management companies are the backbone of a healthy economy and have employed risk assessment and management techniques to assess borrowers, insurance policyholders, or investees (Alaerts, 2019). Risks to water security pose a significant threat to the financial sector through different asset classes of their portfolios if they culminate in rising operational costs, loss of production, decreased credit ratings, or rising insurance claims due to water-related disasters like floods, hurricanes, or droughts (Hoekstra, 2014; Hogeboom et al., 2018). Reduced cash flows due to a water scarcity event negatively affect the value of assets, repayment of loans, profitability, and share value. Thus, these water-related risks can adversely affect financial viability due to loss of valuation and credit default as well as reputational damage across assets in prime sectors like manufacturing, agriculture, energy, logistics, and real estate (Alaerts, 2019; Jorisch et al., 2018; Money, 2014b). While climate-driven water risks are highly variable across sectors, companies, and locations, investors with long-term investment horizons like pension funds or insurers are most exposed (Alaerts, 2019).

Given the adverse impact of climate change on the financial performance of corporate investments and financial markets, there is increasing emphasis on assessing and disclosing the exposure to climate risks by investors, regulators, and central banks (Alaerts, 2019; Hogeboom et al., 2018; Money, 2014b). Water-related risks are closely associated with climate change, and the management of these risks is foreseen as a leading strategy for climate adaptation leading to a resilient and sustainable economy (Alaerts, 2019). Therefore, the financial sector has a unique position to proactively integrate these risks in their investment policies, risk assessments proposal requirements, credit ratings, or underwriting, and incentivize water security initiatives (Alaerts, 2019; Hoekstra, 2014; Hogeboom et al., 2018). However, with the lack of granular context-based data, regulatory mandate, and complexity of interdisciplinary risk assessment, the integration of water risks in the financial sector has yet to peak (Vörösmarty et al., 2018; Jorisch et al., 2018).

The financial sector in large has been curious about water risks awareness, action, and stakeholder engagement, but the systematic evaluation of local risks using a standardized framework presents a research opportunity (Jorisch et al., 2018). While investor-specific risk assessment and guidance tools like WWF Water Risk Filter, WRI Aqueduct, Ecolab Water Risk Monetizer, Ceres Aquagauge, CEO Water Mandate, and Pacific Institute’s Conflict Tool exist, the need for local, reliable, publicly available, and peer-reviewed data persists. Freyman et al. (2015) report that investors have identified the need for collaboration with the scientific community to obtain reliable water security data as well as with regional experts to gain insights about the contextual nuances of water resources to evaluate risks. In the wake of limited information about a company's actual water performance from corporate disclosure, sustainable water investment and practices are expected to benefit from collaboration between investors, academics, and water management and governance experts at granular geographic scale (Vörösmarty et al., 2018).

Nonetheless, the need for water security also reveals investment opportunities and solutions catering to water efficiency, treatment, and reuse in line with SDG 6 (Alaerts, 2019; Hogeboom et al., 2018). The need for investment in sustainable drinking water, wastewater, and stormwater treatment infrastructure and technologies is on the rise in both the Global South and developed nations and estimated at around USD one trillion by 2025 worldwide (Alvarez & Rodriguez, 2015; RobecoSAM, 2015). Moreover, water-related mutual funds are not only socially responsible investments, but also financially perform at par with conventional funds with added diversification value (Alvarez & Rodriguez, 2015). Rising above the notion of socially responsible investments as philanthropic specialty products offered by a few financial institutions, sustainable investing is seen as a valuable proposition where financial, environmental, and social benefits are realized when sustainability metrics are used to guide investments (Weber & Feltmate, 2016). However, institutional investors and banks need realistic assessments, including social and environmental aspects to safeguard the financial viability of projects (Jorisch et al., 2018). Thus, granular water risk assessment in terms of physical, reputational, and regulatory risks is needed for investing in water security solutions and managing water risk exposure in financial portfolios (Alaerts, 2019).

2.2.4. Gaps and opportunities in water risk assessment

The extent to which a particular firm or asset is exposed to water risks is highly contingent on the local or granular spatial-temporal hydrological conditions, regulatory environment, type of sector (water extraction, consumption, or potential for water pollution) and competing water users (Hogeboom et al., 2018). Water scarcity is evident in emerging economies like China and India, or developing countries where population growth, economic growth, and weak regulations have already led to unsustainable resource extraction (Alaerts, 2019; Schulte et al., 2012). Even in developed countries like Australia, Israel, or the USA, the emphasis on sustainable water management is more pronounced in arid regions or in European countries that are densely populated (Morrison et al., 2009). Therefore, rather than using a proactive approach of mitigating emerging water risks, decisions regarding water management are made as a reaction to major water events or focus only on currently water-scarce areas (OECD, 2013). While most water risk assessment tools tend to focus on operational risks for water-intensive sectors based on facility-level data and global hydrological models, the contextual watershed risks including water availability, quality, regulatory risks, and reputational risks are aggregated nationally. Moreover, these tools, based on different models with certain assumptions, may not fully represent water security risks at the disaggregated basin level that can have adverse financial implications for future businesses and investors (Jorisch et al., 2018; Morgan et al., 2020).

With an evolving understanding of water scarcity in terms of quantity, quality, and access, there is a serious omission of seemingly water-abundant countries, where emerging water risks need to be proactively managed (Sandhu et al., 2020; Wolfe & Brooks, 2003). For instance, Canada is typically considered as a water-rich country with large freshwater resources per capita. However, there is a vast spatial variability of water resources across Canada where 60% of the freshwater resources are available in the sparsely populated North, and the densely populated southern watersheds have been facing temporal water scarcity and quality issues (Mitchell, 2017). In the Canadian context, the assessment and management of flood-related risks and their economic impact are gaining momentum (Thistlethwaite et al., 2020). However, the perception of water abundance masks the stressors contributing to water scarcity with increasing demand amidst diminishing seasonal flows, quality, and equitable access (Mitchell, 2017).

In the recent staff notice “Reporting of Climate Change-related Risks,” the Canadian Securities Administrators (CSA) emphasize water availability and quality as material physical risks arising from climate change that can have adverse economic implications for businesses and investors (Canadian Securities Administrators, 2019). Even though water risks are exacerbated manifold by climate change, many cumulative factors exist within Canada like temporal and spatial hydrological conditions, increasing demand, pollution as well as changing legislation pertaining to access, minimum environmental flows, lack of drinking water infrastructure, and social conflicts that contribute to water scarcity (Bakker & Cook, 2011; Curran, 2019). Given these gaps, ripe opportunities prevail to explore and design water risk indicators by harmonizing interdisciplinary quantitative and qualitative data available at the granular spatial and temporal scale (Christ & Burritt, 2018; Jorisch et al., 2018). Therefore, using Ontario as a case study, the ensuing sections aim to tease out multidimensional aspects of water risks intertwined with spatial and temporal resource variability, regulatory environment, and legacy issues that can help design decision support tools for businesses, investors, governments, regulators, and local communities.

2.3 Case study: The Province of Ontario, Canada

Canada is a compelling case of a developed resource-rich economy that is relatively water-rich with established water management regulatory mechanisms. From an investment and business perspective, it is a prime location for water-intensive sectors and trade (Sandhu et al., 2020). However, if we consider the regional and local scales, the picture of water security, regulatory stability, and equitable water access changes considerably (Mitchell, 2017). Recently, Environment and Climate Change Canada (2019) has released a report that reveals significant changes in the seasonal availability of freshwater under various carbon emission scenarios. Earlier snowmelts, warmer winters, permanent loss of glacier ice, and declining groundwater tables (reduced baseflow for connected surface water) will contribute to lower summer flows when the demand is at its highest. While the average annual precipitation is expected to increase, summers will be much drier, resulting in temporal water stress (Bush & Lemmen, 2019). These emerging water crises, further intensified by climate change across provinces in Canada, need to be accounted for in corporate and investment decisions (Heinmiller, 2017).

The province of Ontario, Canada, (Figure 2.1) is surrounded by the Great Lakes and many surface water and groundwater sources, supporting a growing population, natural ecosystems, as well as agricultural and manufacturing activities. It hosts approximately 40% of the Canadian society and contributes to about 40% of the Canadian GDP (Ontario Ministry of Finance, 2019). However, this seemingly water-rich province has not been immune to conflicts around water availability, degrading water quality, and lack of drinking water infrastructure in Indigenous communities (Galway, 2016; Mitchell, 2017). These conflicts and changing regulatory landscape have exposed the vulnerability of businesses to water risks and generated a keen interest in sustainable water management (Sandhu et al., 2020). Therefore, the assumption of water security in Ontario needs to be verified, especially from the perspective of corporations and investors looking to integrate water risks in long-term investment and operational decision-making.

Figure 2.1: The Province of Ontario, Canada (Source: Natural Resources Canada, 2002)

2.3.1. Water management and governance landscape for Ontario

According to the Constitution Act of 1867, the management of water resources is distributed between federal, provincial, municipal, and First Nations governments (Bakker & Cook, 2011). The constitution delegates ownership and management of water resources to provincial governments who can assign the right to use water through allocation frameworks that vary across different provinces. The federal government retains rights over certain divisions like fisheries, navigation, shipping, international, interprovincial and federal works, rivers, lakes, canal, harbor improvement, reserved aboriginal lands, and internationally shared waters (with the United States) (Brandes & Curran, 2017). Given the colonial history of Canada, treaty rights of Indigenous Peoples (First Nations, Inuit, and Métis) in the form of historic, modern, and claims over ownership of traditional lands, water, and natural resources are yet to be resolved.

Therefore, engagement with Indigenous communities is an essential component of water-related decision-making in Canada (Bakker & Cook, 2011; Bradford et al., 2017).

Delving into the water management in Ontario, the province uses a *regulated riparian model* to allocate water to different users under the Ontario Water Resources Act, 1990, where extraction[1] of more than 50,000 L/day of surface or groundwater requires a Permit to Take Water (PTTW) from the Ontario Ministry of Environment, Conservation and Parks (MECP) (Ontario Ministry of Environment, Conservation & Parks, 2020a). While the bulk transfer of water is prohibited from individual watersheds, the export of water-intensive products is possible (Jaffee & Case, 2018). MECP uses a risk-based approach in granting these permits and categorizes applicants into three groups based on increasing environmental risk of the proposed water use and location (Ontario Ministry of Environment, Conservation & Parks, 2020a). In addition to an administrative fee for PTTW applications contingent on the risk category, an additional 'water conservation charge' of CAD 3.71/million liters of water extracted is imposed on highly water consumptive industrial sectors[2] (Ontario Ministry of Environment, 2007). However, post the moratorium on new water bottling permits, the volumetric charge for existing permit holders in the sector was increased to 503.71/million liters (Sandhu et al., 2020). Moreover, the MECP-PTTW Director has considerable discretion over the fate of the applications that can be refused, cancelled later, or subjected to additional protocol. While this gives enough flexibility for the ministry to adapt water policies, it adds a high level of uncertainty for businesses, who may not have assessed the implications of local regulatory conditions (Kreutzwiser et al., 2004).

In addition to the provincial legislation on water allocation, there is a whole tier of legislation on source water quality, protection and sustainable water use, and management, e.g., Clean Water Act, 2006; Safe Drinking Water Act, 2002; Environmental Protection Act, 1990; Environmental Assessment Act, 1990; Ontario Water Opportunities and Water Conservation Act, 2010; Nutrient Management Act, 2002; Great Lakes Protection Act, 2015; Lakes and River Management Act, 1990; and Sustainable Water and Sewage Systems Act, 2002, among others (Ontario Ministry of Environment, Conservation & Parks, 2017). The concerns of algal blooms, industrial activity, nuclear energy and fracking development, groundwater over-extraction and climate change have also led to binational Governments (US-Canada) to update their existing transboundary Great Lakes agreements with an emphasis on ecological health and sustainable water use in the basin (Johns, 2017). Moreover, there is also considerable authority with individual municipalities in Ontario pertaining to water use, quality and wastewater under the Municipal Act, 2001; Planning Act, 1990; and Health Promotion and Protection Act, 1990, that can intersect with provincial authority (Kreutzwiser et al., 2004; Kreutzwiser & de Loë, 2002).

The province of Ontario has also instituted thirty-six sub-watershed specific agencies called "conservation authorities" under the Conservation Authorities Act, 1990, that are responsible for water and natural resource management interfacing with the provincial government, municipalities, and other stakeholders (Kreutzwiser et al., 2004). Conservation authorities have grassroots expertise in monitoring water levels, quality, and technical assessments of water-related risks, and they lead the Ontario Low Water Response program for watershed-based drought planning and management (Disch et al., 2012). These conservation authorities have undertaken many watershed assessments that are not only useful for policy making, but also for corporate water risk assessments (Sandhu et al., 2020).

There is a plethora of federal, provincial, and sub-watershed data sources and scientific reports capturing hydrological, regulatory, conflicts, public perception, and concerns that can lend insights to water-related risks from an investor and business perspective. In the ensuing sections, we present local water issues and risks within the physical, regulatory, and reputational risk framework at the sub-watershed scale for Ontario, Canada.

2.3.2. Sub-watershed based physical risks

Spatial water scarcity (quantity and quality): The risks stemming from spatial and temporal water scarcity in regions sensitive to declining water quantity and quality (contamination) need to be assessed at the sub-watershed scale. The Ontario Clean Water Act, 2006, instituted after the tragic bacterial contamination of drinking water wells from surrounding farmland in the town of Walkerton, lay the foundation for the "Source Water Protection Plans." Conservation authorities quantify water quality and quantity threats and subsequent risks at the quaternary watershed scale to surface water and groundwater sources used for drinking water (Conservation Ontario, 2018; Sandhu et al., 2020). While the aim is to protect the drinking water sources using regional data and scientific modeling, these water quantity (surface and groundwater) risks and quality threats have been assessed for high use sub-watersheds provincially and nationally. Therefore, this high quality, scientifically reviewed granular data used for provincial and municipal policymaking can be used to account for current and future water demand, environmental flows, seasonal availability, drought scenarios, and aquifer vulnerability (Sandhu et al., 2020).

Temporal Water Scarcity: The Ontario Ministry of Natural Resources and Forestry has also issued the "Ontario Low Water Response Level" maps that depict different severity of drought conditions developing in real-time across sub-watersheds (Disch et al., 2012). The provincial surface water monitoring center, in association with individual conservation authorities, issue these maps based on stream-flows and precipitation monitoring under the Ontario Low Water Response Program (Ontario Ministry of Natural Resources, 2009).

Sector Specific Risks: Certain industrial sectors tend to consume more water than others wherein the water extracted is permanently removed (incorporated in the product, evaporated, or diverted) from the watershed. The Province of Ontario uses specific metrics to distinguish high, moderate, and low water consumptive sectors (Ontario Ministry of the Environment, 2007). Therefore, this provincial categorization of water consumptive sectors can be used for more harmonized water risk assessments by the corporate and financial sector.

Legacy Contaminated Sites and Areas of Concern: The federal government has maintained a database of active, suspected, or remediated brownfield sites across each province that have been contaminated due to past industrial activity, e.g., underground petroleum, chemical storage tanks, and landfills, which can have an adverse environmental impact to neighboring water resources and soil (Government of Canada, 2020). Provincially, The Office of the Auditor General of Ontario has also compiled their findings on "Management of Contaminated Sites" in their 2015 report detailing active contaminated sites along with their location, contaminants, and financial liability. In 2004, the report on the "Groundwater Program" also listed contamination groundwater sites where people had to resort to an alternate source of drinking water (Auditor General of Ontario, 2004; 2015). Under the Canada-US Great Lakes Water Quality Agreement, forty-three "Areas of Concern" (twelve in Canada and five binationally shared) were identified in the Great Lakes basin with severely degraded water quality and ecosystem health (Environment and Climate Change Canada, 2020). These sites are currently under the policy scanner for remediation and have been a source of public concern resulting in subsequent stringent regulations (Johns, 2017). From a business or investment context, these sites must be accounted at relatively high risk for source water treatment requirements as well as regulatory and reputational implications.

2.3.3. Federal, provincial, and municipal regulatory risks

The fragmented, decentralized legislative and regulatory framework for water management in Canada and Ontario has been discussed in Section 2.3.1 (Bakker & Cook, 2011). Evidently, there is a whole suite of overlapping international, federal, provincial, and municipal laws and regulations pertaining to water resources, especially in the Great Lakes basin that cumulatively makes the regulatory landscape much more complicated especially for businesses and investors trying to assess regulatory risks. However, the current legislative and regulatory frameworks have also been criticized for being insufficient in catering to existing and emerging water issues and the assertion of Indigenous rights to water and land (Bakker & Cook, 2011; Brandes & Curran, 2017). The assessments used decades ago did not consider the dynamic ecological, social, and economic conditions of modern times. Therefore, there is a lot of potential reform and revisions being proposed in water-related legislation and regulation (Curran, 2019).

It is also important to acknowledge that the regulatory actions undertaken by the province are typically reactive to public concerns, especially around the water bottling sector. For instance, following drought conditions in the Grand River watershed in 2016, public interest regarding groundwater extraction for water bottling by Nestlé in Wellington County spurred the province to issue a moratorium on new water taking permits for water bottlers (Jaffee & Case, 2018; Ministry of Environment, Conservation & Parks, 2020b). As a consequence, a series of policy reviews, groundwater management initiatives, and monitoring and environmental assessments have been undertaken (Sandhu et al., 2020). In response to the policy review in June 2020, the MECP has proposed changes to the water quantity framework, including placing the highest priority of water use for environment and drinking water, followed by irrigation in high risk locations (Ontario Ministry of Environment, Conservation & Parks, 2020b). Even though the Ministry's review found no significant impact of water bottling operations on the sustainability of water sources, public concerns and perceptions were seen as drivers for proposed actions and regulatory changes for the sector, including the requirement to obtain support from the "host municipality" (Professional Geoscientists Ontario, 2020).

In another instance, in May 2018, the automotive glass manufacturer Xinyi Glass Holding Ltd., proposed to build a CAD 450 million glass manufacturing plant in Guelph Eramosa township in Wellington County, Ontario (Wellington Advisor, 2018). The proposed plant raised public concerns over traffic, emissions, and the company's 1.6 million liter/day groundwater withdrawal, resulting in a motion against the proposal by local citizens and water advocacy groups. Based on the municipal zoning bylaw that categorized the site for "dry-use" industries, the Township's council accepted the motion to reject the proposal on water usage even before the provincial review of water taking (Council of Canadians, 2018). Therefore, there has been an emphasis on integrating stakeholder concerns and perceptions about water security in management decisions and mitigation strategies for all water-using sectors (Wolfe & Brooks, 2017). Normative perception is also a key element in risk assessment theory and needs to be accounted for in water risk assessments (Gough, 1997).

The legislation on minimum environmental flows is also gaining traction across Canada. Given the importance of water-dependent ecosystems and biodiversity, the amount of surface water and groundwater that can be sustainably extracted primarily during low flows needs to be regulated (Curran, 2019). The conservation authorities across Ontario have given due consideration for maintaining minimum flows for the environment in their water quantity risk assessments, and the spatial variability of these ecological conditions have been acknowledged (Shifflett, 2014). The MECP does warrant technical and ecological impact assessments of specific water taking permit applicants and provides technical guidance on evaluating environmental flows (Ontario Ministry of Environment, Conservation & Parks, 2020a). However, there has been a call for legally mandating the environmental flows within provincial allocation regulations and policies that can potentially impact existing and future water users in the sub-watersheds (Brandes & Curran, 2017; Curran, 2019).

Unresolved and outstanding land and water treaties concerning Indigenous Peoples of Canada have also been cited as a driver for change in water law and governance across Canada (Bakker & Cook, 2011). The UN Declaration on the Rights of Indigenous Peoples (UNDRIP) endorsed by the Government of Canada in 2016 can also have a significant impact on how water resources are allocated and to whom (Black & McBean, 2017; Von der Porten & de Loë, 2013). However, taking a more active role in decision-making and co-management with Indigenous communities will alter the existing legal and social license to operate (Bradford et al., 2017; Brandes & Curran, 2017). The private and financial sector will have to foresee how to engage and collaborate with all crucial stakeholders and Indigenous communities in Ontario (Johns, 2017).

In terms of stakeholder consultation, everyone in Ontario has the right under the Environmental Bill of Rights, 1993, to provide inputs, comments, and recommendations for proposals, decisions, and legislative and regulatory changes pertaining to the environment using the online Environmental Registry of Ontario (Ontario Ministry of Attorney General, 2019). There has been active participation of state and non-state actors in water policy development and water management initiatives, including environmental NGOs, local irrigation advisory committees, and fisheries groups, but leadership and engagement of the private sector have been minimal (Johns, 2017). With the recent federal mandate to institute a new Canada Water Agency, in addition to the reprised federal involvement, a new and collaborative regulatory regime for water management and governance is expected (Brandes et al., 2020).

From the discussion above, it is evident that an understanding of the complex legal and regulatory frameworks for water use, management, discharge as well as governance structures including all levels of the governments, formally instituted local watershed agencies like conservation authorities, non-state actors, and other public groups (NGOs, social justice and action, watershed stewards) are essential for future business and investment decisions. Stakeholder inputs, concerns, and backlash have all contributed to the dynamic water regulations and decisions that can pose an operational and reputational risk to businesses. Thus, watershed specific water issues and fast-evolving regulatory landscape should capture investor and business interests for assessing risks more accurately rather than maintaining the status quo in Ontario.

2.3.4. Reputational risks, conflicts, and legacy issues

The province of Ontario and specifically the Great Lakes region has had a fair share of conflict amidst competing user groups since the mid-90s over water allocation and use (Kreutzwiser et al., 2004). Ontario has been prone to short-term droughts, low flow conditions, and declining well levels that have created tensions between rural well owners, golf courses, water bottling companies, farmers, aggregate mining and quarry dewatering companies, and suburban water users (Morris et al., 2008; Shifflett, 2014). These conflicts spike in the dry summer months when the municipal, industrial, and agricultural water demand is high. Factors like regional water availability, different types and number of water user groups, economic dependence on water, potential interference with municipal water sources and presence of provincially significant wetlands, areas of natural and scientific interest, and environmentally sensitive areas are considered determinants of conflicts in drought contingency reports (Shifflett, 2014).

In the Canadian context, there is a lack of reliable drinking water infrastructure in Indigenous communities exacerbating existing social inequity issues. More than 600 Indigenous communities with unique histories, cultures, traditions, and close spiritual connection with water are an integral part of Canada. Indigenous peoples (First Nations, Inuit, and Métis) represent <5% of the Canadian population, but they have experienced excessively higher number of drinking water quality issues within on-reserve communities as compared to off-reserve communities (Lam et al., 2017). The jurisdiction of on-reserve Indigenous communities rests with the federal government including the provision of safe drinking water and wastewater treatment. Even with the federal funding support for drinking water and wastewater infrastructure in collaboration with First Nations leadership (Chiefs and Band Council), many First Nations communities are under a long-term or short-term drinking water advisory (White et al., 2012).

Ontario hosts 133 First Nations communities and the largest population of Indigenous peoples in Canada. However, about 400 on-reserve drinking water advisories lasting an average of 294 days were reported between the years 2004-2013 in Ontario due to equipment failure or lack of operator training (Galway, 2016). The largest First Nations reserve “Six Nations of the Grand River” within the Grand River watershed is a mere 100 kilometers away from the megapolis Toronto but has witnessed short-term boil water advisories and contamination from upstream off-reserve activities (Collins et al., 2017). Even in the midst of the COVID-19 pandemic, 51 long-term and 12 short-term drinking water advisories were in effect in October 2020 across Ontario (Indigenous Services Canada, 2020). The underlying social, economic, political, and historical inequities are evident in the lower life expectancies, incomplete education, unemployment rates, lower access to health care, and higher vulnerability to water borne illness in on-reserve Indigenous communities, invoking sharp criticism regarding environmental discrimination and injustice (Galway, 2016; Lam et al., 2017). Water is central to Indigenous cultural, spiritual, and livelihood traditions; therefore, the lack of reliable drinking water and contamination of source waters resulting in dependence on bottled water is a grave paradox forced upon them (Galway, 2016; White et al., 2012). Lack of access in this context is not a technical or financial lapse but rather a social inequity legacy issue rooted deeply in colonial history (White et al., 2012).

With water quality issues, competing and inefficient water use, environmental degradation, and the growing influence of citizens and social action groups, economic sectors increasingly face significant reputational risks in the region. The public attitudes and perceptions about different aspects of water resource management continue to be captured nationally and regionally within Great Lakes watershed by surveys and polls (Johns, 2017). While Ontario does offer a competitive advantage to water-dependent businesses and waterways connectivity for trade, existing multi-jurisdictional water management and governance networks do not necessarily favor economic interests over environmental concerns (Heinmiller, 2017).

Environmental action and awareness campaigns, coupled with media coverage on water issues about access, quality, and inequity have shaped public perception and political interest at the grassroots level (Jaffee & Case, 2018). The country-level data on reputational risks is unable to capture these granular and heterogenous issues beyond biophysical metrics, especially when the perception of water security varies considerably in Indigenous communities (Baird et al., 2015). Given the social and contextual nuances involved, undermining these risks in business and investment decisions can have substantial reputational implications on responsible and equitable business and investment practices (Schulte et al., 2012).

2.4 Opportunities for sustainable water investments

To drive sustainable investment in water and manage portfolios exposed to water risk, a granular assessment of local geographies at the sub-watershed level is necessary. In the case of Ontario, Canada, the interrelated physical, regulatory, and reputational risks at the local level demand corporate and investor attention. Therefore, interdisciplinary investment decision support tools need to be developed using granular data to reflect local hydrological, regulatory, and social conditions. As demonstrated with a case study approach, the deep dive into hydrological risk assessments by local watershed agencies, regulatory developments, past water user conflicts, and legacy of social issues reveal the need for proactive water risk management even in regions like Ontario, perceived to be water secure.

Based on the reviewed literature, the synthesized conceptual water risk assessment framework capturing local sub-watershed risks for Ontario, Canada, is presented in Figure 2.2. The framework can be operationalized into decision support tools using publicly available, reliable, and peer-reviewed data from government databases that allows harmonization of data used for public policies, investments, and corporate water policies. Hence, the confluence of spatial and temporal biophysical and social data provides realistic insights into grassroots water conditions and risk perceptions envisioned to aid proactive decision-making for sustainable water investments and corporate water sustainability. A case study approach can be applied to any geography, and the framework can potentially be adapted for different regions, revealing different risks and available data sources for assessments.

Physical Risks

- Statistics Canada freshwater supply and demand assessment
- Environment and Climate Change Canada Water Indicators
- Sub-watershed Source Water Protection Assessment Reports
  - Quaternary watersheds identified for surface water and groundwater quantity risk
  - Regions near municipal water sources at risk for contamination
- Proximity to Great Lakes Areas of Concern and other federal water quality initiatives
- Previous contaminated sites
- Population density and land use
- Annual water extraction by sector and region (PTTW database and Statistics Canada)
- Temporal low flow maps by Ontario Ministry of Natural Resources
- Minimum environmental flow requirements by Province

Regulatory Risks

- Provincial water allocation and extraction charges legislation
- Priority water use groups
- Water consumptive sectors classification by OMECP
- Water quality legislation
- Decentralization of water governance and all state and non-state actors involved
- Transboundary water sharing agreements (conservation, sustainable use, ecological health)
- Existing or past sector-specific moratoriums on water permits
- Developing legislation, regulations around water (allocation, environmental flows, consultation)
- Regulatory actions proposed or undertaken through consultation via Environmental Registry of Ontario (ERO)

Reputational Risks

- Concentration of different water user groups
- Past regional conflicts between water user groups
- Public perception water surveys (RBC Canadian Water Attitudes Survey, Binational Great Lakes Basin Poll)
- EBR comments on water regulations
- Auditor General and Environmental Commissioner of Ontario's reports
- Social action or citizen group campaigns
- Legacy issues
  - Federal database on drinking water advisories (Environment and Climate Change Canada and Indigenous Services Canada)
  - Water contamination events
  - Past or ongoing treaty agreements

Figure 2.2: Conceptual water risk assessment framework for Ontario, Canada

In addition to integrating water risk metrics across investment portfolios, sustainable finance is gaining traction to address the financing gap in sustainable water management initiatives in line with targets of SDG 6 (WWF, 2019b). The funding needs in technical solutions and infrastructure for water security including drinking water treatment, wastewater treatment, water recycling, conservation and efficiency, low impact development, desalination plants, flood control, drought control, and stormwater management are projected as a ripe financial and socially responsible investment opportunity to foster the green economy (Alvarez & Rodriguez, 2015; WWF, 2019b). Even in developed economies like Canada, the federal and provincial governments are unrolling public-private partnerships to finance green technology and infrastructure projects, including sustainable water management that seems like profitable ventures for the private financial sector (Infrastructure Canada, 2020).

Canada Infrastructure Bank (CIB) is a crown corporation that has been instituted to invest CAD 5 Billion in revenue-generating green infrastructure projects (including water and wastewater treatment systems) to attract private and institutional investment (Infrastructure Canada, 2020). CIB has already invested CAD 20 million in a water and wastewater project in Mapleton, Ontario (Canada Infrastructure Bank, 2019). The province of Ontario, being a hub for the financial industry, aims to leverage the private sector for pooling sustainable finance (e.g., by issuing green bonds) into future green or clean tech projects (Ontario Ministry of Environment, Conservation & Parks, 2018). Typically, investments in water-related projects are considered to be low risk and high value in developed economies due to the perception of social and political will pertaining to private sector involvement (Alaerts, 2019). However, a closer assessment reveals many regulatory and reputational risks pertaining to privatization, even in a stable and developed country like Canada. Therefore, water-related risks can be accounted for and assigned appropriate weights using an interdisciplinary granular framework so as to design appropriate communication and engagement strategies within existing and future portfolios to achieve the stipulated financial, social, and environmental outcomes of the project (Vörösmarty et al., 2018).

2.5 Conclusion

Water risks pertaining to biophysical or hydrological metrics, regulatory trends, social equity, and public perceptions are material for companies and investors. The temporal, spatial, and contextual sensitivities of water make it a more dynamic risk that can have a cascading impact on both individual securities and portfolios (Jorisch et al., 2018). Financial actors like investors, lenders, and insurance companies need to actively account for water risk exposure and response strategies within their current and potential portfolios (Hogeboom et al., 2018). While Task Force on Climate-related Disclosures (TCFD) recommendations for climate risk disclosure are currently being implemented in the financial sector, assessments and scenarios for water-related risks are mostly lacking in investment strategies (WWF, 2019a). Climate change and water management are intricately linked, but unlike globally standardized carbon reduction targets, water-related metrics are more locally defined, as explored in this chapter. The private and financial sectors need a deeper understanding of interdisciplinary water risks on the local sub-watershed basis to mitigate long-term impacts on their operations and investments (Freyman et al., 2015).

The gaps in water risk accounting and disclosure, as well as the needs of the financial sector to acquire technical and contextual water information to make sustainable investment decisions have been highlighted in academic and practitioner literature. Responsible investment in water needs to account for social nuances, legal and regulatory environment, existing legacy issues, conflicts amid competing water users, and water intensity trends in local social-economic-environmental context (Jorisch et al., 2018). Moreover, the lack of appropriate risk assessment and management tools is leading to a path dependency where water risks are generalized to certain geographies and sectors without evaluating granular watershed conditions and impacts (Jorisch et al., 2018; Money, 2014a). Contrary to this generalization, this chapter reveals many existing and impending water risks in Ontario, Canada, which is considered a water-rich country. Assessing water risks and their impacts is crucial to ensuring social well-being, building a strong financial sector and hence a climate-resilient economy. Given the growing interest of regulators, investors, and businesses to develop robust guidelines to integrate water risks, it becomes crucial to design holistic indicators using granular information (Vörösmarty et al., 2018). The role of the financial sector, regulators, central banks, and credit rating companies in incentivizing sustainable water management and finance is also critical to realizing the objectives of water security (Alaerts, 2019). However, the interdisciplinary understanding of water risks is still developing, and detailed data on a sub-watershed basis is required. Therefore, using a case study approach, this chapter aims to contribute by proposing an interdisciplinary framework that harmonizes biophysical, regulatory, and contextual evidence at the granular watershed level and can be operationalized to assess and rate water risks. Accounting for these multifaceted water risks proactively reveals opportunities for sustainable water management and investments for transitioning into a climate-resilient as well as water-secure economy and society.

Notes:

1. Water used for domestic purposes, livestock watering, firefighting, wetland conservation and construction is exempt from requiring a PTTW.
2. Water bottling, beverage manufacturing, fruit/vegetable canning, certain chemical manufacturing where the majority of the water extracted is incorporated in the final product and not returned as wastewater to watershed.

MANUSCRIPT ENDS

Chapter 3

3. An Interdisciplinary Water Risk Assessment Framework for Sustainable Water Management in Ontario, Canada

Contents of this chapter are published in:

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The Province of Ontario in Canada illustrates contemporary water security issues, where despite perception of water abundance, water challenges arise locally. Water risks stem from biophysical dimensions of groundwater depletion, low surface water flows, and degraded quality, and, contextual dimensions of regulatory uncertainty, public concerns and perception. While academic, policy, and practitioner interest is growing, literature reveals major gaps in comprehensive assessment of multi-dimensional water risks at the sub-watershed scale. Addressing these gaps, the study developed a locally-attuned and interdisciplinary water risk assessment framework. Using secondary mixed data analysis, the study integrated quantitative and qualitative data for water quantity and quality risks, regulatory trends, water user conflicts for 38 sub-watersheds in Ontario. The framework identifies sub-watersheds and sectors at high, moderate, and low risk along with media and public concern themes. The study finds high and moderate risk potential in at least 50% of studied sub-watersheds for all water risk indicators and challenges the myth of water abundance in Great Lakes watershed of Ontario. The study advances knowledge in water risk assessment by applying social ecological perspectives, interdisciplinary approaches of Risk Theory, and mixed methods to provide a comprehensive evaluation of water security and demonstrates integration of social science perspectives in the field of socio-hydrology. Our framework assesses interdisciplinary water risks to inform multi-sector sustainable water management decisions. While spatially scoped to populous sub-watersheds of Ontario, this framework can be methodologically generalized to other geographical regions by using local data.

MANUSCRIPT BEGINS

3.1 Introduction

Water is a multifaceted and shared resource providing critical social, economic, cultural, and ecological functions for all aspects of human wellbeing, economic development, and environmental sustainability (Cosgrove & Loucks, 2015; United Nations, 2018). Therefore, sustainable water management is inherently at the core of Sustainable Development (United Nations, 2018). As reflected in Sustainable Development Goal 6, objective of sustainable water management is to ensure *water security,* i.e., adequate quantity, quality, and ecological integrity of water resources, is perpetually maintained while meeting all present and future water demands (Di Baldassarre et al., 2019; Sandhu et al., 2020b). Nonetheless, significant uncertainty, spatial and temporal variability of water availability, exacerbated manifold due to climate change, economic and population growth, threaten interconnected food and energy security and biodiversity of freshwater ecosystems (Cosgrove & Loucks, 2015; Sandhu et al., 2021).

To foster sustainable development and water security, a keen focus on resilience (stress absorbing capacity) and adaptive capacity of social-ecological systems including organizations reliant on water resources is equally necessary (Folke, 2006; Xu et al., 2018). Thus, going beyond state-centric water management approaches, developing proactive policies, strategies and actions for risk management focused on a multipronged approach by all private non-state (e.g., businesses, investors, insurance firms, lenders) and other water-using sectors is championed (Cosgrove & Loucks, 2015; Sandhu et al., 2021). As risk influences a system's ability to respond and adapt to adverse events, risk assessment and analysis is a central component of risk and resilience management (Linkov et al., 2014).

Given the multi-dimensionality of water security risk as a construct, *water security risk* (called "water risk" thereafter) is defined as the likelihood of occurrence of water issues manifested as seasonal low flows, groundwater depletion, degraded quality, regulatory uncertainty of access or use, water user conflicts or other legacy issues that can adversely impact human wellbeing, profitability, and environment (Di Baldassarre et al., 2019; Hall & Borgomeo, 2013; Sandhu et al., 2021). Moreover, from a social-ecological perspective, sub-watersheds are considered to be the appropriate spatial scale for assessing and managing water risks (Steffen et al., 2015; Veale & Cooke, 2017). Nonetheless, there is a paucity of multi-sector, locally attuned and interdisciplinary water risk assessment frameworks that can integrate both biophysical and social variables to inform sustainable water management policies, strategies, and production practices for a water secure and resilient future (Linkov et al., 2014; Xu et al., 2018).

While the field of socio-hydrology emerged to integrate social and hydrological aspects for water resource management, dominance of reductionist /technocratic modelling approaches focusing on simulating/quantifying feedbacks and interactions of human-water systems persists (Di Baldassarre et al., 2019; Xu et al., 2018). Extant socio-hydrology approaches are rooted in positivist paradigms of hydrology and are critiqued as narrowly framed, overlooking in-depth, interdisciplinary perspectives, mixed methods, human centric variables, and social science paradigms (Xu et al., 2018). Thus, an in-depth examination of society and water interactions is needed by intersecting interdisciplinary perspectives of social-ecological systems, sustainability management, and risk analysis using quantitative and qualitative data, mixed methods and case studies (Di Baldassarre et al., 2019; Xu et al., 2018).

3.1.1. Ontario as a case study for interdisciplinary water risk assessment framework

The province of Ontario in Canada (Figure 3.1) illustrates contemporary water security issues, where despite the perception or *"myth of water abundance"* driven by the presence of the Great Lakes, water challenges arise (Sandhu et al., 2021; Sprauge, 2006). Ontario may seem to be a water secure region with the Great Lakes containing 20% of global freshwater but upon finer analysis, water security risks emerge (Sandhu et al., 2020a, 2021; Shrubsole & Draper, 2007; Wheater & Gober, 2015). One of the most pressing water issues, in Ontario and more generally in Canada, is the lack of safe drinking water access in Indigenous communities (Baijius & Patrick, 2019; Galway, 2016). Drinking water advisories have been prevalent, highlighting inequity-based legacy water access issues and social vulnerability rooted deeply in Canada's colonial history (Bradford et al., 2017; Galway, 2016; White et al., 2012). Moreover, with less than 1% annual renewable recharge in the Great Lakes, issues like climate-related low flows, groundwater depletion, degrading water quality, and conflicts amidst competing water-using groups are also revealed (Bonsal et al., 2019; Heinmiller, 2017; Sandhu et al., 2020a).

Another issue pertains to the complex and siloed water allocation, management and governance landscape in Ontario with overlapping federal, provincial, and municipal responsibilities especially due to the binationally shared Canada-US Great Lakes (Sandhu et al., 2021). The Provincial government and sub-watershed based agencies called Conservation

Authorities undertake water risk assessments based on biophysical indicators to ensure sustainability of drinking water sources under the Source Water Protection Program. However, water user conflicts arise locally with increasing drought potential, high population growth areas, and high density of corporate water users (Hoekstra, 2015; Morris et al., 2008; Shifflett, 2014). These conflicts (i.e., disagreements, grievances, criticisms, controversies) in Ontario are less driven by actual biophysical scarcity but by perception of unfairness and possible benefits for certain water-using sectors (including profit-making companies) compared to ordinary citizens (Jaffee & Case, 2018; Schulte et al., 2012). Legacy issues such as drinking water advisories, actual contamination or overextraction incidents, or even the possibility of overextraction, can result in public concern/criticism, negative media coverage, and regulatory (re)action triggering province wide implications like restrictions, moratoriums, fines etc., affecting all current and future water-using sectors across the sub-watershed (Heinmiller, 2017; Signori & Bodino, 2013).

Figure 3.1: The Province of Ontario, Canada with all major water resources.

Source: Natural Resources Canada (2002)

On the other hand, the economically diverse province of Ontario with strong manufacturing and financial sectors, is perceived to be water abundant and positioned to be a major global location for water-intensive industries, investment, and trade (Sandhu et al., 2020a, 2021). As major water users, globally and in Ontario, the corporate sector and the financial sector funding these businesses are expected to spearhead sustainable water management by assessing local water risks and their implications (Weber & Feltmate, 2016; Weber & Saunders-Hogberg, 2018). Moreover, other sectors relying on shared water resources including agriculture, municipal water utilities, power production, recreational, etc., are also affected by biophysical and social water risks (Sandhu et al., 2021). Therefore, given the widespread impact of multi-dimensional water risks, Ontario is a relevant case study for developing a locally-attuned interdisciplinary water risk assessment framework.

3.1.2. Gaps in extant water risk assessment and management approaches

Empirical studies reveal a plethora of tools, used by businesses, investors, and other stakeholders, including WRI Aqueduct and WWF Water Risk Filter that utilize data from global integrated hydrological models to assess water risks (Christ & Burritt, 2017; Josset & Concha Larrauri, 2021). However, the lack of high resolution datasets and quality of data used in hydrological models, use of highly aggregated data for reputational, regulatory, and other context-based risk indicators have exposed the inadequacy of extant tools as they may underestimate the total water risk at regional scales especially for Canada (Gilsbach et al., 2019; Josset & Concha Larrauri, 2021; Sandhu et al., 2021). Moreover, current water accounting practices primarily focus on quantifying *internal* facility level volumetric data without considering the highly variable and interconnected, *external* biophysical and social, political, and institutional conditions across shared sub-watersheds (Alvarado-Revilla & de Loë, 2022; Rusca & Di Baldassarre, 2019; Signori & Bodino, 2013). Such omissions result in fragmented decisions, policies, and actions detrimental to long term water security that affect all water users (Di Baldassarre et al., 2019; Signori & Bodino, 2013).

Given the extant narrowly-focused socio-hydrology and water accounting approaches, the interdisciplinary field of risk analysis can offer a sound theoretical foundation to develop a comprehensive water risk assessment framework (Dobbie & Brown, 2014; Klinke & Renn, 2021). Constructivist approaches conceptualize risk as a subjective mental construct generated by how stakeholders understand, interpret, and respond to risk problems like water security

(Klinke & Renn, 2021; Renn et al., 2022). Moreover, contextually-attuned *general purpose* water risk assessment allows an accurate comparison of multi-sector water use with actual biophysical, regulatory, social, and ecological realities (Christ & Burritt, 2018; Signori & Bodino, 2013; Wheater & Gober, 2015). Therefore, literature emphasizes using social-ecological approaches and mixed methods to assess risks as well as guide social, institutional, and technological transitions for sustainable water management (Folke, 2006; Linkov & Trump, 2019; Xu et al., 2018).

3.2 Research objective, questions, and spatial scope

The academic, policy, and practitioner interest in biophysical and social water risk assessment is growing. Nonetheless, literature reveals a lack of: comprehensive assessment of contextually-attuned water risks, high resolution risk data, and systems-based social-ecological frameworks. Addressing these gaps, the objective of this study is to develop an interdisciplinary water risk assessment framework using quantitative and qualitative water risk data at the sub-watershed scale for Ontario.

Aligned with the research objective, the study addresses the following research questions:

RQ 1: What are the water-related biophysical risks, regulatory trends, as well as water user conflicts and issues at the sub-watershed scale in Ontario, Canada?

RQ 2: How can a locally-attuned and interdisciplinary water risk assessment framework be designed to guide multi-sector sustainable water management policies, strategies, and actions?

Spatially the study is scoped to include 38 sub-watersheds in Ontario (Figure 3.2, consistent with boundaries of Source Water Protection Areas), covering the Great Lakes watershed with over 95% of the provincial population (Land Information Ontario, 2019; Province of Ontario, 2007).

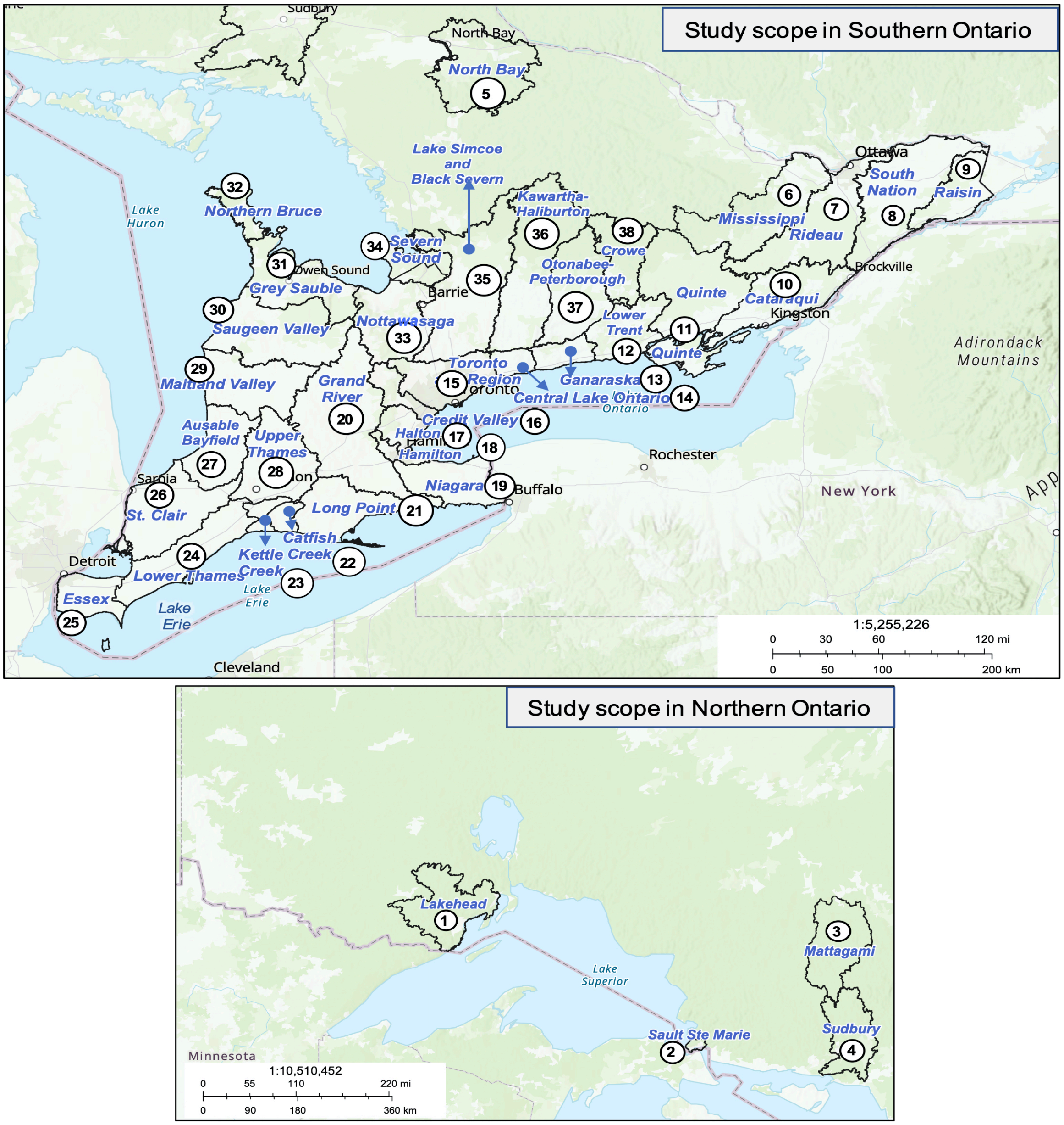

Figure 3.2: Spatial scope of the study in Ontario, Canada. Source: Authors' own using ArcGIS Online, Base boundary layer: Ontario Ministry of Environment, Conservation, and Parks, 2021f

3.3 Theoretical framework

Risk Theory provides a sound interdisciplinary theoretical foundation to develop a comprehensive water risk assessment framework (Renn et al., 2022; Roeser et al., 2012). This interdisciplinary approach is appropriate for a multifaceted resource like water, where the biophysical dimensions of quantity and quality can be integrated with social dimensions of equity, legacy issues, regulatory trends, and stakeholder perception (Aven, 2016; Gough, 1997;

Klinke & Renn, 2012; Renn, 1998). Thus, we combined and adapted the decision-making process by Kristensen et al. (2006) and the interdisciplinary *normative-analytical risk governance model* by Klinke and Renn (2012), to design our theoretical framework for water risk assessment and management (Figure 3.3).

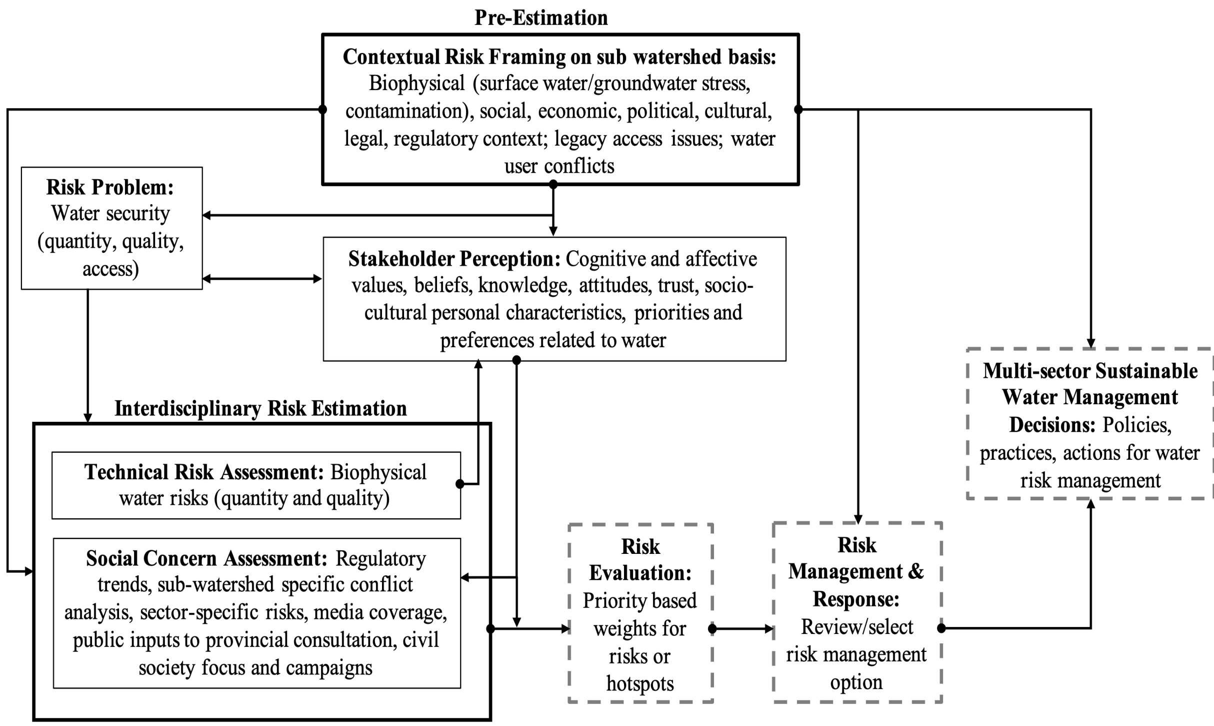

Figure 3.3: Theoretical framework for water risk assessment and management

The *exploratory pre-estimation* or *contextual framing* stage investigates water quantity and quality risks (ecological dimensions), social, institutional, regulatory landscape, conflicts and legacy access issues (social dimensions) at the sub-watershed level that further shape perception of different water user groups (Dobbie & Brown, 2014; Klinke & Renn, 2012). Contextual framing and stakeholder perception help identify relevant water security issues as the risk problem to be addressed by *interdisciplinary risk estimation* (Klinke & Renn, 2012; Ortigara et al., 2018). The estimation entails integration of technical assessment of biophysical water risks and social concern assessment informed by regulatory trends, sub-watershed conflict analysis including the legacy access and social vulnerability issues, sector-specific risks, media coverage, public inputs to consultations, and civil society campaigns (Sandhu et al., 2021).

Connecting risk estimation to management decisions, the *risk evaluation stage* requires decision analytical approaches. In this approach, decision-makers input their preferences, priorities, and judgements to evaluate risks and select *water risk management options* (Aven, 2016; Gough, 1997). In addition to integrating stakeholder concerns and perception for risk assessment, concepts of resilience, social vulnerability, social learning, collective action, and adaptive capacity are important for risk management and governance (Renn et al., 2022; Xu et al., 2018). Thus, an understanding of how societies can manage resilience, vulnerabilities, and adapt to the uncertainties of changing hydrological conditions is critical for multi-sector sustainable water management decisions (Linkov et al., 2014; Xu et al., 2018).

Since this study's objective is primarily scoped to design a water risk assessment framework that is the foundational core of management frameworks (risk, social vulnerability, and resilience), only pre-estimation and interdisciplinary risk estimation stages (solid borders) of the theoretical framework have been operationalized. Other risk evaluation and management stages (dashed borders) will be addressed in subsequent studies.

3.4 Methods and data

To design a water risk assessment framework based on our theoretical framework (Figure 3.3), we employed two stage secondary mixed data analysis.

3.4.1. Stage 1: Investigation and secondary data extraction for interdisciplinary water risks

In Stage 1, we investigated and extracted secondary data for developing six Databases for water risk indicators including biophysical water quantity risks, quality risks, regulatory trends, and legacy and potential water-user conflicts for 38 sub-watersheds in Ontario (Figure 3.2). Given the multi-source data needed, detailed overview with description of sub-indicators, data sources, method of data extraction, keywords, and time frames, is provided in Table 3.1. An alternative flowchart format for Table 3.1 is provided in Appendix A as Figure A.1 (1-3). The selection of sub-indicators to assess different water risks is conceptually informed by the literature (see Sandhu et al., 2021) and our theoretical framework.

Table 3.1: Detailed overview of secondary data extraction for Stage 1

Risk Indicator	Sub-Indicator Description	Method of data extraction and sources
Database 1: *Biophysical Water Quantity Risk*	▪ Identification of quaternary watersheds for sub-watersheds under "high" and "moderate" surface water and groundwater stress assessed and reported in the water budget analysis undertaken by Ontario's Source Water Protection Committees for Source Water Protection Plans under the Clean Water Act, 2006 (Sandhu et al., 2021, 2020b; Province of Ontario, 2007)	▪ Online retrieval of stress assessment tables from publicly available Approved Technical Assessment reports for **38** sub-watersheds/Source Protection Areas of Ontario (Conservation Ontario, 2021; Ontario Ministry of Environment, Conservation and Parks, 2017)
Database 2: *Biophysical Water Quality Risk*	▪ Identification of quaternary watersheds for sub-watersheds under "very poor", "marginal", and "fair" surface water quality assessed based on monitored biophysical parameters (e.g., phosphorus, E. Coli, benthic invertebrates etc.,) (Sandhu et al., 2021). "Good" and "very good" categories imply very low threats and are excluded ▪ Moderate-high aquifer (groundwater) vulnerability to contamination ▪ Active and suspected legacy contaminated sites (used for industrial/mineral extraction, commercial, fuel storage, waste management activities) under the management of Federal and/or Provincial government (Sandhu et al., 2021) ▪ Identification of chronic sub-watershed wide water quality issues proxied by Binational Great Lakes (Canada-US) Areas of Concern (AOCs) and Federal, and Provincial water quality management initiatives, agreements, strategies, action plans in the study area (Sandhu et al., 2021, 2020b)	▪ Online retrieval of latest publicly available **36** sub-watershed report cards prepared by conservation authorities to extract quaternary watersheds under all risk categories along with monitored parameters. (Conservation Ontario, 2018; Grand River Conservation Authority, 2020) ▪ For **2** sub-watersheds without a dedicated conservation authority, i.e., Northern Bruce Peninsula and Severn Sound, retrieval of source water protection technical assessment reports to extract quaternary watersheds with water quality threats for municipal water systems (Conservation Ontario, 2021) ▪ Retrieval of aquifer vulnerability assessment tables from Approved Technical Assessment reports for **38** sub-watersheds (Conservation Ontario, 2021) ▪ Retrieval of Federal and Provincial inventory of contaminated sites for Ontario and corresponding quaternary watershed (Auditor General of Ontario, 2015; Treasury Board of Canada Secretariat, 2021) ▪ Retrieval of binational, federal, and provincial reports to extract water quality initiatives and their sub-watersheds (Government of Canada, 2020a; Province of Ontario, 2021c) ***Search Keywords:*** "Great Lakes" OR "Great Lakes protection" OR "protecting" AND "agreement" OR "program" OR "action plan" OR "strategy". ***Results:*** **11** AOCs, **12** water quality initiatives in study area
Database 3: *Regulatory Trends*	▪ Identification of Federal and Provincial water management laws, regulations, policies, and agreements. Relevance criteria includes water allocation, abstraction/extraction permits, extraction charges, water quantity management, environmental considerations, water quality management, and fines/penalties; operational aspects like efficiency, conservation or use restrictions for drought management, moratoriums, and/or monitoring and reporting requirements (Barton, 2010; CDP, 2020, 2021; Sandhu et al., 2021) ▪ Amendments to extant water laws and regulations that indicate increasing stringency and evolving changes. Environmental Registry of Ontario (ERO) is an online platform used by the Provincial Government to post notices of changes to environment related laws, policies, and regulations (Province of Ontario, 2021b) ▪ Identification of authority level, municipalities and sub-watersheds, and sectors in water-related laws, regulations, and policies	▪ Retrieval of consolidated legislative Acts or statutes/laws and regulations from the Official Province of Ontario e-Laws website (Province of Ontario, 2021a) ***Search Keywords:*** "water"; ***Filter:*** current; statutes and regulations; ***Results:*** **495**; Post relevance and duplicates screening: **31** water-related Acts ▪ Retrieval of water-related amendments to 31 identified water-related regulations, Acts, or policies posted on ERO (Province of Ontario, 2021b). ***Search Keyword:*** "water", ***Filter:*** Regulation, Policy, Act; ***Notice Stage:*** Decision; ***Date Range:*** January 1, 2005 to June 30, 2021. ***Results:*** **636** amendments for 31 Acts Retrieval of water-related Federal laws, policies and mandates from the official Justice Laws and Government of Canada website (Government of Canada, 2020b, 2021). ***Search Keywords:*** "water", "Great Lakes". ***Results:*** **9** relevant water related Acts and regulations ▪ Retrieval of provincial, federal, and bi-national water related agreements, strategies, policies, guidelines, or programs (Government of Canada, 2020a; Province of Ontario, 2021c). ***Results*: 8** Provincial policies, programs, and strategies, **5** Binational Agreements, policies, mandates
Database 4a: *Public concern and perception of water issues*	▪ Identification of public concern and perception, proxied by the public "leave to appeals" posted on the ERO and Auditor General's reports. Under the Ontario Environment Bill of Rights, 1993, residents of Ontario can challenge provincial decisions, regulations, Permit to Take Water (PTTWs) or other approvals by filing "leave to appeal" or permission to appeal the decisions and indicate locations, issues, and sectors under scrutiny (Ontario Ministry of Environment, Conservation and Parks, 2021c; Sandhu et al., 2021) ▪ A 20 year period, i.e., 2000-2021, is chosen to capture chronic and acute water issues (Lam et al., 2017; Sandhu et al., 2020b). ▪ Prevalence of water related campaigns and initiatives by NGOs, citizen-led groups indicate increasing civil society concern (Sandhu et al., 2021)	▪ Retrieval of leaves to appeal posted on the ERO and historical archives (Province of Ontario, 2021b). ***Search Keywords:*** "leave to appeal", "water"; ***Date range:*** January 1, 2000 to June 1, 2021. ***Results:*** **140;** Post duplication screening, **42** appeals and **2** notices of court action. Details including date, location or sub-watershed, sector/sub-sector under focus, and contested issue was populated ▪ Retrieval of Auditor General of Ontario and Environmental Commissioner of Ontario reports (Auditor General of Ontario, 2021) ***Search Keywords:*** "Environment", ***Filter:*** Water, ***Year Range:*** 2000 to 2021. **7** water relevant reports reviewed for chronic and acute water issues, sector/subsectors, and sub-watersheds in focus ▪ Retrieval of civil society campaigns in Ontario from **42** relevant environmental NGOs and citizen-based groups based on a broad web engine search

Database 4b: ***News media coverage***	▪ Identification of water issues covered in news media over 15 year period to capture preceding water issues that shaped public concerns, perception, and triggered regulatory action and media coverage (Lam et al., 2017; Sandhu et al., 2021, 2020b) ▪ Content populated includes month, year, location, and details of the water-related issues, controversy, or criticism	▪ Retrieval of water-related international, national, regional, and local news coverage for Ontario using the online news database **FACTIVA** (Dow Jones and Company, 2021) ***Search Keywords:*** (water issues OR water scarcity OR water pollution OR drought) AND Ontario. ***Regional Filter:*** Ontario, ***Country:*** Canada. ***Date Range:*** January 1, 2005 to July 25, 2021. ***Results:*** **3200** articles (omitting duplicates) and post relevance screening of the headline and first paragraph (Lam et al., 2017), **360** articles were relevant ▪ Other popular water specific online outlets like OOSKA (***Filter:*** Ontario, Canada), Circle of Blue (***Filter:*** Ontario, Canada) and Water Canada (***Filter:*** Ontario and water issues) searched for convergent validity (Circle of Blue, 2021; OOSKA News, 2021; Water Canada, 2021)
Database 5: ***Water user conflict potential and legacy access issues***	▪ Potential for conflict based on density or spatial concentration/ clusters of 10 or more permit to take water holders, past low flow conditions, high population and economic growth regions, and public and media attention (Morris et al., 2008; Shifflett, 2014) ▪ Under Ontario's Low Water Response Program, three low flow levels (1, 2, 3) can be temporarily triggered based on increasing likelihood of drought for a sub-watershed (Sandhu et al., 2021, 2020b). ▪ Prevalence of in-effect or lifted long term and/or in-effect short term (<1 year) drinking water advisories (DWA) in First Nations indigenous communities in Ontario that signal legacy access and environmental justice issues (Indigenous Services Canada, 2021d; Sandhu et al., 2021). ▪ A 20 year period, i.e., 2000-2021, chosen to capture water user issues and media coverage from the year 2005 (Lam et al., 2017; Sandhu et al., 2020b).	▪ Retrieval of active PTTWs in 38 sub-watersheds from Ontario Source Protection Information Atlas as of June, 2021 (Ontario Ministry of Environment, Conservation and Parks, 2021a, 2021b). ***Geospatial Layer:*** Water Quantity: PTTW (active); ***Administrative Layer:*** 38 Source Protection Areas; ***Spatial Resolution:*** 20 km ▪ Retrieval of sub-watersheds, frequency and duration of low water levels (1, 2, and 3). ***Date Range:*** January 2001 to July 2021 (Ontario Ministry of Natural Resources and Forestry, 2021). ▪ Retrieval of high growth municipalities and corresponding sub-watersheds from Ontario Places to Grow Act, 2005, S.O. 2005, c. 13 (Province of Ontario, 2005) ▪ Retrieval of DWA in sub-watersheds from publicly available Indigenous Services database (Indigenous Services Canada, 2021a, 2021b, 2021c) ▪ ***Results:*** As of June, 2021, 47 in-effect long term, 3 recommended, 43 lifted, 14 in-effect short term ▪ Identification of sub-watersheds with public concern/civil society focus and media coverage from Database 4a and 4b
Database 6: ***Sector-specific risk assessment***	▪ Identification of sector-specific impacts based on nature of water use, i.e., extraction, consumption (water as part of the product, recirculation/recycling, or evaporation losses) and effluent discharge ▪ Identification of "High", Moderate", "Low" focus of specific sectors in the public concern Database 4a and media coverage in Database 4b ▪ Sector-specific impact assessment based on a literature review (Barton, 2010; CDP, 2018; Ceres, 2021; Freyman et al., 2015; Hoekstra, 2015; Morrison et al., 2009; Pegram et al., 2009)	▪ Populated list of 70 sectors based on Provincial classification and consumptive use categories (Ontario Ministry of Environment, Conservation and Parks, 2021d; Ontario Ministry of Natural Resources and Forestry, 2014) ▪ Coded PTTW requirement, imposition of water extraction charges, effluent reporting requirement, additional regulatory focus for each sector as Yes or No (Database 3) ▪ Coded sector based priority levels: 1 (High) - 4 (Very Low), as defined in the Provincial Water Quantity Management Program (Ontario Ministry of Environment, Conservation and Parks, 2021d, 2021e).

3.4.2. Stage 2: Secondary data analysis and risk ratings for water risk assessment framework

In Stage 2, we analyzed data extracted in Stage 1 for 38 sub-watersheds to calculate the aggregated risk scores of each water risk indicator as identified in Databases 1-6, i.e., water quantity risk; quality risk; regulatory trends; public concern and media coverage themes; sub-watershed-specific water user conflicts; sector-specific risks. Sub-indicators of the six risk indicators were measured in categorical values based on either a binary scale of Yes/No, ordinal scales (e.g., High/Moderate/Low) or counts. For the analysis, categorical values were converted into numerical values before aggregating the cumulative score of that risk indicator. Since the data values were dimensionless values or counts, normalization and transformation were not required before aggregation (USAID, 2005). Cumulative scores were then converted to differentiated risk ratings for each sub-watershed or sector. The details for each water risk indicator are provided in the ensuing sub-sections.

3.4.2.1. Sub-watershed specific biophysical water quantity risk assessment

Database 1 consists of technical water quantity stress data for the 38 sub-watersheds, quaternary watersheds under high and moderate surface water quantity stress and groundwater stress have been identified in the primary data source (Table 3.1). Therefore, differentiated risk ratings of high and moderate under surface water quantity stress and groundwater quantity stress are extracted and assigned as it is. Since no additional sub-indicators for water quantity risk were required, cumulative analysis or weighting or aggregation was not required.

3.4.2.2. Sub-watershed specific biophysical water quality risk assessment

Database 2 consists of 7 sub-indicators/proxy variables for water quality risk, selected based on the literature (Table 3.1). Aligned with best practices for developing qualitative and hybrid indicators, the water quality sub-indicators, data values/scales used to measure the sub-indicators, and corresponding scores are presented in Table 3.2 (USAID, 2005). Data values are categorical/qualitative representing whether quaternary watersheds were identified in the assessed sub-watershed to be under that threat. Categorical values were converted to numerical scores based on relative importance to baseline categories defined in the original dataset or literature. "Sparse" data category was included for the sub-indicators because in few sub-watersheds, less than two quaternary watersheds were identified, which is <10% of average number of quaternary watersheds in the sub-watersheds. To avoid overestimation in "sparse" cases due to multiple sub-indicators, the score was multiplied by 10%.

Using the scorecard presented in Table 3.2, the data for the sub-indicators under each sub-watershed in Database 2 was analyzed. Using the additive aggregation method, a total cumulative score "R" was calculated by adding the scores for all 7 sub-indicators for each sub-watershed. The maximum observed aggregated risk score in the dataset was 10. Using the benchmarking procedure based on the maximum risk score, we developed a 5-point cumulative water quality risk rating scale (Very high, High, Moderate, Low and Very low) with a score range of 2. This scale was used to convert cumulative water quality risk scores to risk ratings. In case of tied scores (straddling between categories), presence of Area of Concern was used as a tie breaking rule. For example, Essex sub-watershed had a cumulative risk score of 10, leading to a cumulative rating of "Very High".

Table 3.2: Cumulative water quality risk score card and rating scale

Water Quality Risk Sub-indicators	Sub-indicator Values	Numerical Score	Additional Explanatory Notes
Very Poor – Surface Water	Yes (>=3 quaternary watersheds identified) Sparse (<3 quaternary watersheds) No (no quaternary watershed)	3 0.3 0	Weighted score of 3 is based on the original dataset. Very Poor is the highest threat category out of three (see Table 3.1).
Marginal – Surface Water	Yes (>=3 quaternary watersheds) Sparse (<3 quaternary watersheds) No	2 0.2 0	Weighted score of 2 is used because it is the middle threat category
Fair – Surface Water	Yes (>=3 quaternary watersheds) Sparse (<3 quaternary watersheds) No	1 0.1 0	Unweighted score of 1 is used because it is the baseline threat category out of the three categories
Moderate-High Aquifer Vulnerability	Yes (>=3 quaternary watersheds) Sparse (<3 quaternary watersheds) No	2 0.2 0	Sub-indicators 1 to 3 are based surface water parameters but aquifer vulnerability is accounted in this indicator. A weighted score of 2 is used based on literature to signal higher risk of groundwater sources in a sub-watershed (Sandhu et al., 2021).
Contaminated Sites under Federal or Provincial Management	Yes (>3 quaternary watersheds) Sparse (<3 quaternary watersheds) No	2 0.2 0	Weighted score of 2 is used based on literature to signal higher importance of legacy contamination in a sub-watershed than baseline (Sandhu et al., 2021).
Bi-national Areas of Concern	Yes No	2 0	Binational areas of concern cover large contaminated area of the sub-watershed and there are no individual quaternary watersheds identified so the response is dichotomous Yes or No. A weighted score of 2 is used to signal higher risk (Sandhu et al., 2021).
Federal/ Provincial Water Quality Management Initiatives	Yes No	1 0	An unweighted score of 1 is used because it is baseline quality sub-indicator compared to other legacy contamination issues (Sandhu et al., 2021).

Cumulative Water Quality Rating	Risk Category	Aggregated Risk Score Range
5	Very High	R>8
4	High	6<R<8
3	Moderate	4<R<6
2	Low	2< R<4
1	Very Low	R<2

3.4.2.3. Regulatory trends assessment

Database 3 includes 53 water-related Provincial and Federal legislation, policies, agreements, and strategies for Ontario retrieved from the official e-Laws website. Additional data on the jurisdiction level, amendments, specific municipalities/sub-watersheds and sectors was also extracted. 12 regulatory risk drivers, i.e., characteristics of regulations, laws, or policies that pose different risks to water use sectors due to stringency or restrictions in access or use, are established from the literature (Barton, 2010; CDP, 2020, 2021; Signori & Bodino, 2013; WBCSD-IUCN, 2012). 12 regulatory risk drivers, corresponding water use stage and the type of risk are presented in Table 3.3.

These drivers are predetermined list of codes used to analyse the content of 53 laws/agreements/policies and subsequently a binary score of 1 or 0 is assigned if that driver/characteristic was present or not (Creswell & Creswell, 2018; USAID, 2005). For example, if a law states "area/region/watershed-based approach for water taking", "source water protection" then a score of 1 was assigned under the risk driver "sub-watershed based water management requirements". The vertical sum of the score under each driver (maximum score possible of 53) is calculated and a prevalence rating of **low** (<33% of maximum score), **moderate** (33-67% of maximum), or **high** (>67% of maximum) is assigned for each risk driver. Out of 53 entries, 29 stated this driver/requirement, leading to a score of 29 or moderate prevalence rating. Following the same procedure, scores and ratings for all 12 drivers was calculated. Coding was done by one research team member and was independently reviewed and cross checked for consistency by other four members (Creswell & Creswell, 2018).

Table 3.3: Regulatory risk drivers and type of risks

Regulatory Risk Driver	Water Use Stage	Type of Risk/Implication for Water-Using Sector
1. Statutory requirement for obtaining water extraction permits, extraction charges, monitoring and reporting 2. Increased difficulty in obtaining/renewing water extraction permits (e.g., via moratoriums) 3. Sub-watershed based water management requirements 4. Consideration for the environment 5. Possibility of short-term or long-term changes to water withdrawal limits/ monitoring during low flow seasons	Abstraction/ Withdrawal	Financial (costs), legal (compliance), operational (water allocation changes), impact on social license to operate, reputational (brand image)

6. Requirement for operational water efficiency, recycling and conservation	Operations	Financial, operational (process design and technological changes)
7. Regulations on effluent discharge quantity and quality 8. Additional effluent management	Effluent/ Discharge	Financial, operational (technological changes), legal, social license to operate
9. Regulatory fines/penalties for violations 10. Stringency and tighter regulations 11. Impact from evolving laws and rights like United Nations Declaration on the Rights of Indigenous Peoples (i.e., Bill C-15 of Canada), Human Right to Water 12. Uncertainty due to ongoing regulatory amendments	All Stages	Financial (costs), legal, social license to operate, reputational

3.4.2.4. Water related public concern, perception, and news media coverage assessment

Databases 4a and 4b consist of content related to legacy and current water issues, public concern and perception (from year 2001 to 2021) from public comments and "leave (permission) to appeals" filed by the general public/residents of Ontario on the Environmental Registry of Ontario, Auditor General of Ontario's reports, and civil society campaigns. A 20-year time period is chosen to capture the preceding water user conflicts/issues that trigger chronic regulatory (re)action and media coverage in the 15-year frame (Lam et al., 2017). For news media coverage, we used online data sources including FACTIVA, OOSKA, Circle of Blue, Water Canada, and extracted relevant articles (year 2005 to 2021) using broad search keywords (e.g., water issues OR water scarcity OR water pollution OR drought AND Ontario). Further screening details and filters are provided in Table 3.1. For thematic analysis, content was reviewed and assigned open codes, then categorized into water issue themes, also identifying sub-watersheds and sub-sectors (Creswell & Creswell, 2018). Initial coding and categorization were done by one research team member. To ensure consistency and reliability, samples of the codes, categories, and resulting themes were independently cross checked by other four members (Creswell & Creswell, 2018).

3.4.2.5. Sub-watershed specific conflict analysis

Database 5 includes conflict potential analysis based on 6 sub-indicators including Permit to Take Water (PTTW) density, drought potential, high growth region identification, prevalence of drinking water advisories, public and civil society focus, and media attention as informed by the literature (Sandhu et al., 2021). The score card is presented in Table 3.4 and lists the 6 sub-indicators, data values used to measure the sub-indicators, and corresponding numerical scores used to calculate the cumulative risk scores.

The comparative geospatial density or concentration of close clusters of water user PTTWs in the 38 sub-watersheds is analysed using the online Ontario Source Protection Information Atlas at a resolution of 20 Km. A close cluster is defined as 10 or more permits at the minimum resolution of 1 Km. Minimum observed PTTW density is less than 2 clusters in a sub-watershed and is assigned the baseline “low” category, 3 to 6 clusters is “moderate” and more than 7 is “high”. For example, Kettle Creek sub-watershed has only 1 close PTTW cluster and is assigned a “low” density category. Drought potential rating is assigned based total number of counts or triggers for low water conditions in the sub-watershed from year 2001 to 2021. To account for higher severity of level 2 and 3 triggers, a weighted sum is used, i.e., any counts for level 2 and 3 are multiplied by a factor of 2 and 3 respectively and then the total count is calculated. The total weighted sum is then compared to a 3-point scale differentiated based on the maximum weighted sum of counts registered for any sub-watershed in the 20 year period (i.e., 40). The rating scale and corresponding counts for analysis is, **Low**: <33% (<13 total weighted counts); **Moderate**: 34-67% (14-26); **High**: 67%+ (27+). For example, Grand River sub-watershed registered 21 Level 1 counts, 5 Level 2 counts, and 0 Level 3 counts. So, the total weighted sum of counts is 31 leading to a “High” drought potential rating. The prevalence municipalities identified as a “High growth region” are coded as “yes”. Identification of any long term/short-term in-effect, lifted drinking water advisories, public concern or media focus, from Database 4 is also coded as “yes” under the corresponding sub-watershed.

Using the scorecard presented in Table 3.4, data in Database 5 was analyzed. Using the additive aggregation method, a total cumulative score “RC” was calculated by adding the scores of all sub-indicators for each sub-watershed. The maximum aggregated risk score in the dataset was 11. Using benchmarking procedure, we developed the 5-point cumulative water quality risk rating scale (Very high, High, Moderate, Low and Very low) with a score range of 2.2 (Table 3.4). This scale was used to convert rounded cumulative risk scores to cumulative risk ratings. In case of tied scores, drought potential was used as a tie breaking rule. For example, Grand River sub-watershed has a cumulative risk score of 11 leading to a rating of “Very High”.

Table 3.4: Sub-watershed conflict potential risk score card and rating scale

Conflict Potential Sub-indicators	Sub-indicator Values	Numerical Scores	Additional Explanatory Notes
PTTW Density Analysis	High	3	Analysis of PTTW density is explained in the text and the
	Moderate	2	scores are based on 3 point ordinal scale (high/mod/low)
	Low	1	that measure the PTTW density
Drought Potential	High	3	Same as above

	Moderate Low	2 1	
High Growth Region	Yes No	1 0	Unweighted score of 1 is used due to baseline importance compared to other sub-indicators
Presence of Drinking Water Advisories	Yes No	2 0	Weighted score of 2 is used due to higher relative importance of this social vulnerability centric indicator in the literature
Public Concern	Yes No	2 0	Weighted score of 2 is used due to higher relative importance of public attention in literature for conflict potential
Media Coverage	Yes No	2 0	Weighted score of 2 is used due to higher relative importance of media attention in literature for conflict potential

Cumulative Conflict Potential Rating	**Risk Category**	**Aggregated Risk Score Range**
5	Very High	RC>9
4	High	7<RC<9
3	Moderate	5<RC<7
2	Low	2.5< RC<5
1	Very Low	RC<=2

3.4.2.6. Sector-specific water risk assessment

Sector specific risk assessment based on Database 6 for 7 sub-indicators including consumptive water use category, PTTW requirement or additional regulatory focus, imposition of water extraction charges, provincial sector priority, impact of water taking and discharge, public concern, and media attention (Table 3.1). Table 3.5 includes the score card and lists the sub-indicators, corresponding data values used to measure the sub-indicator, and numerical scores used to calculate the cumulative risk score for the 70 water-using sectors.

The consumptive water use category (high, moderate, low) and sector priority (1: high to 4: very low) is directly based on the provincial classification. PTTW requirement, imposition of water extraction charges, and additional regulatory focus is coded as "yes", if the sector was identified in the results of regulatory trend assessment presented in Database 3. The sector specific High/moderate/low impact assessment by water taking or extraction and effluent discharge is based on literature review results as cited in Table 3.1.

For public concern, connected to the results of Database 4a, number of counts for sector mentioned per total counts or mentions in the "leave to appeal" and civil society content analysis is calculated and compared to a 3 point scale based on the average count assigned a moderate rating. For "leave to appeals" rating where 47 total sector-specific counts are observed for 17 sectors, **High:** 4+ counts/mentions, **Moderate:** 1-3 counts, **Low:** Nil. For civil society focus, 27 total counts are observed for 11 sectors, **High:** 3+ counts, **Moderate:** 1-2 counts, **Low:** Nil.

Media focus is assigned a binary yes or no if the sector is mentioned in the media coverage analysis of Database 4b.

Using the scorecard presented in Table 3.5, data for the sectors in Database 6 was analyzed and sub-indicator scores were assigned. Using the additive aggregation method, a total cumulative score "RS" was calculated by adding the scores for all sub-indicators for the 70 sectors. The maximum observed aggregated risk score in the dataset was 15. Using benchmarking procedure, we developed the 5-point cumulative water quality risk rating scale (Very high, High, Moderate, Low and Very low) with a score range of 3 (Table 3.5). This scale was used to convert cumulative risk scores to cumulative risk ratings. Negative media attention was used as a tie-breaking rule for tied scores.

Table 3.5: Sector-specific water risk score card and rating scale

Sector-specific Water Risk Sub-indicators	Sub-indicator Values	Numerical Scores	Additional Explanatory Notes
Consumptive Water Use Category	**High** **Moderate** **Low**	3 2 1	Scores are based on 3 point ordinal values (high/mod/low) used in primary data source (See Table 3.1). Baseline is the low consumptive category with a score of 1.
PTTW Requirement/ Regulatory Focus	**Yes** (sector identified) **No**	1 0	Unweighted score of 1 is used because water extraction charges are considered as separate sub-indicator
Water Extraction Charges Imposed	**Yes** **No**	1 0	Same as above
Sector Priority	**4** **3** **2** **1**	3 2 1 0	Scores are based on 3 point ordinal values. Sectors with the first or highest priority, i.e., 1 is assigned zero risk score because the sector has no risk of water use restrictions. The baseline score of 1 is sector priority 2.
Negative Impact of Water Taking and Effluent Discharge	**High** **Moderate** **Low**	3 2 1	Scores based on original dataset and analysis using 3 point ordinal scale.
Public Concern or civil society focus	**High** **Moderate** **Low**	3 2 1	Same as above
Negative Media Attention	**Yes** **No**	2 0	Weighted score of 2 is used due to high importance in literature

Cumulative Sector Risk Rating	Risk Category	Aggregated Risk Score Range
5	Very High	RS>12
4	High	9<RS<12
3	Moderate	6<RS<9
2	Low	3< RS<6
1	Very Low	RS <3

3.5 Results

The ensuing sections report biophysical and social water risks for the 38 sub-watersheds. Moreover, addressing RQ 2, the tangible water risk assessment framework is the primary output of the study consisting of six water risk databases and risk ratings. The complete framework is published on Figshare (Sandhu et al., 2022).

3.5.1. Sub-watershed specific water quantity and quality risk hotspots

Our study finds, among investigated 38 sub-watersheds, 50% have at least one quaternary watershed at high *surface water quantity* stress and 66% have at least one quaternary watershed at moderate stress. For *groundwater quantity stress*, 55% have at least one quaternary watershed at high stress and 63% have at least one quaternary watershed at moderate stress.

The colour coded *water quality* risk ratings based on Table 3.2 have been geospatially mapped in Figure 3.4. The analysis finds 63% of the sub-watersheds have a very high and high water quality risk rating and 24% have a moderate rating.

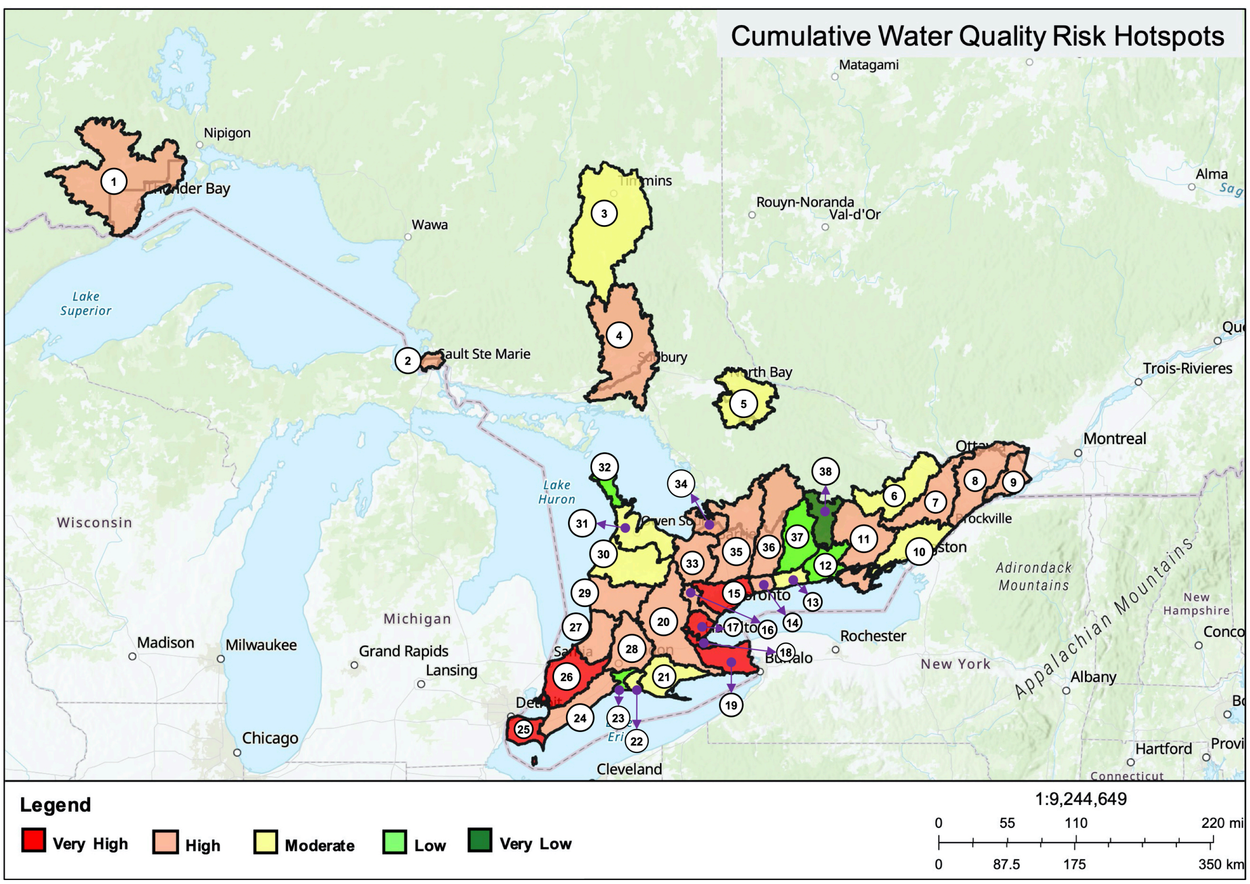

Figure 3.4: Cumulative water quality risk ratings. Source: Authors' own using ArcGIS Online, Base boundary layer: Ontario Ministry of Environment, Conservation, and Parks, 2021f

3.5.2. Regulatory risk ratings

The analysis finds 33% of the regulatory risk drivers at high and 67% at moderate prevalence in the Provincial and Federal water management laws, regulations, policies, and agreements (see Table 3.6). Therefore, all 12 regulatory risk drivers and their risks are present in the current water regulatory framework in Ontario.

Table 3.6: Regulatory trend assessment results

Prevalence Rating	Regulatory Risk Drivers
High Prevalence	Consideration for the environment (allocation, extraction impact); Implications for effluent treatment/ management costs; More stringent regulatory standards; Regulatory uncertainty due to ongoing amendments/changes
Moderate Prevalence	Increased difficulty in obtaining water withdrawal/operations permit; Sub-watershed based water management; Possibility of short-term or long-term changes to water withdrawal limits/monitoring; Potential Impact from evolving laws and rights like UNDRIP (Bill C-15), Human Right to Water; Regulation of discharge quality/volumes; Requirements for permits, extraction charges, monitoring and reporting; Violations resulting in fines, enforcement orders, and/or penalties; Water efficiency, conservation, recycling or process requirement.
Low Prevalence	Nil

3.5.3. Sub-watershed specific conflict hotspots

The colour coded results of the sub-watershed specific conflict based on rating scale of Table 3.4 have been geospatially mapped in in Figure 3.5. 82% of the sub-watersheds are found to be at very high and high conflict potential and 11% at moderate conflict potential.

3.5.4. Sector specific risk assessment

Key results of sector-specific risk assessment are reported in Table 3.7. Out of 70 water-using sectors, 50% are found to be at very high and high water risk, 31% at moderate risk, and 19% at low and very low risk. The differentiated risk ratings can be used by analysts and decision-makers to compare water risks and impacts across different water-using sectors further informing sector-specific strategies and policies for sustainable water management.

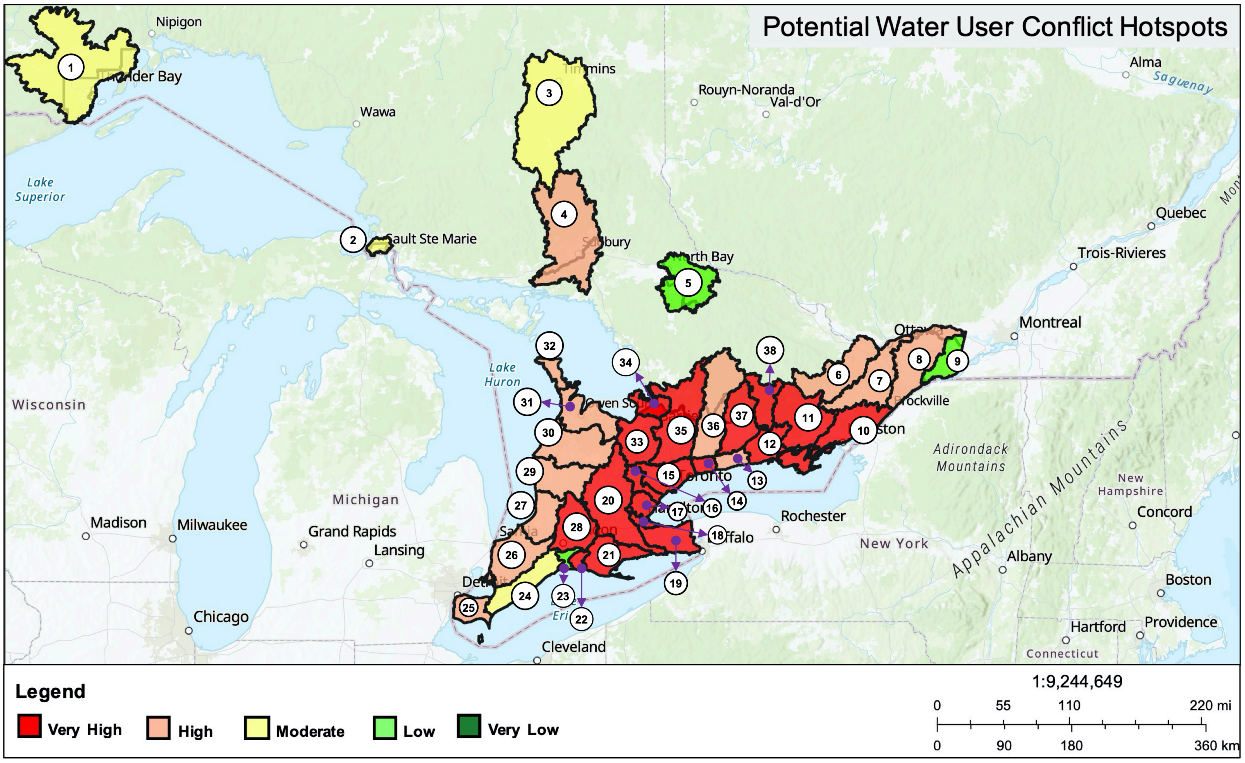

Figure 3.5: Water-related conflict potential ratings. Source: Authors' own using ArcGIS Online, Base boundary layer: Ontario Ministry of Environment, Conservation, and Parks, 2021f

Table 3.7: Key results of sector-specific water risk assessment

Risk and Impact Rating	Water-using Sectors
Very High	Aggregate sector; Commercial golf courses; Manufacturing sector: Water bottling; Ready-mix concrete and other non-metallic mineral, Inorganic and agricultural chemicals; Mining; Oil and gas extraction.
High	Agricultural sector; Commercial snow making; Dams and reservoirs (other than power production) Manufacturing: Food and beverage, Primary metal, Pulp and paper, Wood products, Petroleum and coal product, Plastics and rubber, Fabricated metal product, Computer and electronic product, Transportation equipment, Furniture and related products; Pipeline testing; Power production: Thermoelectric (including nuclear), Hydroelectric.
Moderate	Commercial: Aquaculture, Mall/Business; Construction dewatering; Livestock sector; Manufacturing: Textile and textile product, Leather and allied product, Machinery; Recreation; Remediation; Wind Power Production; Heat pumps and other testing; Water supply: Communal, Municipal water utilities, Self-Supplied Domestic Use.

3.5.5. Key Themes from Media Coverage Analysis

Based on thematic analysis of the news media coverage in Ontario, key themes of water issues and controversies are reported in Table 3.8.

Table 3.8: Key themes from media analysis

Risk Category	Results from media analysis
Themes of water issues, controversies, and criticism	▪ Unsafe drinking water in First Nations communities; ▪ Great Lakes water quality issues and protection initiatives; ▪ Legislative and regulatory changes in Ontario for water management; ▪ Water governance issues (need for more coordinated action, need for stakeholder and First Nations inputs, calls for Federal involvement in water management); ▪ Concerns for negative impact of industrial extraction and discharge, oil pipelines; ▪ Nuclear waste burial (deep glacial repository), impact of Uranium conversion, potential radionuclide contamination; ▪ Droughts and low flow conditions as triggers of public action; ▪ Groundwater management issues (quantity and contamination); ▪ Opposition to intra-basin and inter-basin bulk water transfer pipelines; ▪ Concerns, protests, and action against privatization and commoditization of water (bulk water exports, water bottling); ▪ Divest from investments (e.g., pension funds) in private water utilities in Chile; ▪ Changing water pollution limits; ▪ Overarching threats to water security (climate change, population growth, and urban development); ▪ Treatment and supply infrastructure issues (lead, leaky pipes, insufficient wastewater treatment, sewage and stormwater combined outflows)

3.6 Discussion

From the study's analysis, four key dimensions of water security, i.e., biophysical water quantity, quality, regulatory changes, and public perception as suggested by the literature are confirmed for the Great Lakes watershed in Ontario. These interconnected dimensions interact with each other spatially and temporally to generate overall water risk, conflict potential, and sector specific impact. Furthermore, the study finds high and moderate risk potential in at least 50% of the investigated sub-watersheds under all biophysical and social water risk categories hence providing empirical evidence challenging the myth of water abundance in the Great Lakes watershed of Ontario.

While tools like WWF Water Risk Filter 6.0 and other nationally aggregated global risk assessments do not indicate spatial heterogeneity of risks of regulatory changes, potential water user conflicts, public concern and media scrutiny for Ontario, our study evidently finds heterogeneity in all investigated risk dimensions and hence higher risk (Cai et al., 2021; Opperman et al., 2022; WWF, 2021). Moreover, corroborating with the literature on water risk assessment, integrated biophysical and social risk analysis is found to provide contextually attuned water risk hotspots that reflect sub-watershed conditions, areas of public concern and media attention more accurately (Gilsbach et al., 2019; Josset & Concha Larrauri, 2021; Ortigara et al., 2018; Signori & Bodino, 2013).

Aligned with the theoretical model of Klinke and Renn (2012), our study verifies that overall water security risk in Ontario is equally driven by contextual aspects indicated by evolving regulatory landscapes, stakeholder concerns, as well as perceived risks of water use sectors (Alvarado-Revilla & de Loë, 2022; Rusca & Di Baldassarre, 2019; Wheater & Gober, 2015). The regulatory analysis reveals changes and increasing stringency related to water management laws resulting in moderate to high risk indicating uncertainty and complexity in the regulatory landscape. Regulatory risks are proactively accounted for in this study's water risk assessment that suggest changes in quantity of water *legally available* for multi-sector extraction, use, and discharge (Cai et al., 2021; Sandhu et al., 2021).

The public concern and media coverage analysis reveal themes of legacy water issues (Table 3.8) that shape perceived local water security and trigger regulatory change but may not coincide with biophysical parameters measured by hydrological models. Therefore, sub-indicators of public concern, media focus, regulatory focus used in the integrated conflict analysis (Figure 3.5) and sector-specific risk assessment (Table 3.7) are important contributions of this study for comprehensive water risk assessment.

3.6.1. Theoretical and practical contributions of study

The study addresses a gap in the literature by applying the normative-analytical risk governance model and interdisciplinary assessment approaches of Risk Theory to design a novel theoretically sound water risk assessment framework with quantitative and qualitative indicators (Klinke & Renn, 2012, 2021). The comprehensive assessment framework, integrates social-ecological dimensions of water risks, and overcomes the weaknesses of existing provincial water risk assessments that continue to myopically focus on biophysical water risks (Sandhu et al., 2021). Using the case of Ontario, our study reveals more accurate multi-dimensional water security risk hotspots at the sub-watershed scale. Moreover, our study successfully demonstrates the application of interdisciplinary social science perspectives, risk theory, and mixed methods to broaden the extant siloed approaches of socio-hydrology and water accounting tools (Di Baldassarre et al., 2019; Xu et al., 2018). Hence, our interdisciplinary framework is a novel methodological contribution that advances knowledge in the fields of water resource management, socio-hydrology, and risk analysis.

Going beyond academic contributions, the interdisciplinary water risk assessment framework is a tangible research output. Multiple stakeholders like current and future businesses, investors, regulators, policy makers, and civil society can employ our framework to identify high or moderate risk sub-watersheds, sectors, regulatory trends, and conflict themes, for locally-attuned water risk accounting, decision-making and strategic engagement (Christ & Burritt, 2018; Di Baldassarre et al., 2019). For instance, the study reveals legal and societal impediments to large scale bulk water transfers across the Great Lakes. Hence making proactive sustainable water use and management approaches a more viable option for alleviating water security risks than reactive resource transfer approach. While the study is spatially scoped to Ontario, the assessment framework can be methodologically generalized to other geographical regions. Procedures presented in Table 3.1 and Section 3.4.2, can be followed for comparative case analysis beyond Ontario (Creswell & Creswell, 2018).

3.6.2. Limitations of study and future work

As a limitation, the framework is based on secondary baseline data that is current as of year 2021 and needs to be updated every 5 years or as latest data becomes available. Moreover, the study includes 38 sub-watersheds with 95% of the provincial population and high data availability but the analysis can be extended to remaining sub-watersheds, when provincial data becomes available. Secondly, this study focuses on baseline water risk assessment, which is exploratory, descriptive, and static instead of being dynamic or predictive. Nonetheless, this framework provides granular water risk data useful for comparing or calibrating future predictive models. The underlying causal mechanisms that explain the interconnections and temporal trends between risks, vulnerabilities, and perception *is not* under the scope of this study but are pertinent future research questions.

This study reveals multiple avenues to systematically integrate decision-makers' judgement for water risk and resilience management. Future research can operationalize the evaluation and management stages of our theoretical framework (Figure 3.3) and undertake social vulnerability assessments in sub-watersheds identified at risk. Thus, risk, social vulnerability, and resilience management can be integrated to inform transitions for water secure development pathways (Linkov et al., 2018). Moreover, socio-hydrological models can be adapted to include interdisciplinary indicators for multi-sector decision support tools (Di Baldassarre et al., 2019).

3.7 Conclusion

While proactive assessment and management of multi-dimensional water risks is championed in the literature, systematic risk assessment at the sub-watershed level using interdisciplinary quantitative and qualitative data and mixed methods was underexplored. Thus, addressing these pertinent gaps, the study has investigated biophysical and social water risks for 38 sub-watersheds in Ontario using publicly available data and developed a novel, locally-attuned, and interdisciplinary water risk assessment framework. Even though at the macro scale, the populous Great Lakes watershed of Ontario *is perceived* to be water secure, upon finer spatial analysis, the study reveals multiple hotspots for biophysical and social risk categories. From the results, while water quantity stress varies across Ontario, water security risks tend to be equally driven by the often overlooked yet key multi-dimensional aspects of water quality, regulatory stringency for allocation and access, and public perception. Thus, considering all risk indicators, the overall water security risk for a sub-watershed can deviate from highly aggregated assessments. Overall, the study empirically challenges the myth of water abundance in the Great Lakes watershed and builds the case for proactive water risk management in Ontario. Moreover, our interdisciplinary water risk assessment framework can help integrate water risks in multi-sector decisions, policies, and practices to foster a water-secure and climate-resilient society and economy.

MANUSCRIPT ENDS

Chapter 4

4. Examining Water Risk Perception and Evaluation in the Corporate and Financial sector: A Mixed Methods Study in Ontario, Canada

Contents of this chapter are published in:

Sandhu, G., Weber, O., Wood, M. O., Rus, H. A., & Thistlethwaite, J. (2023b). Examining water risk perception and evaluation in the corporate and financial sector: a mixed methods study in Ontario, Canada. *Environmental Research Communications*, *5*(10), 105012, 1–26. https://doi.org/10.1088/2515-7620/acff41

As primary users of a socially, economically, and environmentally significant yet increasingly stressed resource like water, the corporate and financial sectors have an important role in sustainable water management. However, extant literature reveals a gap in the empirical assessment of water risk perception and its influence on water risk evaluation and decision-making in the corporate and financial sectors. Our explanatory sequential mixed methods study examined the relationship between water risk perception and risk evaluation (risk ratings), addressing these gaps. We employed a cross-sectional survey (N=25) followed by semi-structured interviews (N=22), with a purposive expert sample of analysts, practitioners, and decision-makers in the corporate and financial sector in Ontario, Canada. Our study finds multi-dimensional risk perception factors, including knowledge, professional experience, perceived controllability, values, trust, location, and gender, that influence water risk ratings and vary with the type of risk. Moreover, the in-depth follow-up interviews reveal multiple drivers of different risk ratings, such as proximity bias, sector differences, trust in various institutions, as well as the influence of tacit knowledge, exposure, the role of regulations, media, and financial materiality. Our study empirically concludes that the water risk perception of analysts, practitioners, and decision-makers in the corporate and financial sectors is highly nuanced and impacts the evaluation of different water risks, and should be systematically integrated into risk assessment and decision-making frameworks. Our study advances knowledge in the fields of risk analysis and sustainable water management and contributes by empirically examining and explaining the complex and underexplored relationship between water risk perception factors and evaluation using novel interdisciplinary Risk Theory and mixed methods approaches. Finally, the study's findings can help integrate sector and location-specific preferences and priorities with analytical data to design contextually-attuned decision support tools for sustainable water management strategies, policies, and practices.

MANUSCRIPT BEGINS

4.1 Introduction

Amidst growing risks to water resources across the globe, Sustainable Development Goal 6 (SDG 6) emphasizes sustainable water management to perpetually safeguard water availability, quality, ecosystems, and access for current and future generations (Sandhu et al., 2021; United Nations, 2018). Water security and sustainable water management are inextricably linked to assessing and managing water risks by all water-using sectors to reconcile competing values, interests, and highly variable water resource supply (Di Baldassarre et al., 2019). Nonetheless, despite the significance of water security and its interconnection with sanitation, health, food and energy security, economic productivity, and environment, the progress on SDG 6 has mainly been unsatisfactory (Sadoff et al., 2020). With impacts of climate change exacerbating variability and uncertainty in water availability along with threat multipliers like population growth, land use change, and industrial and agricultural demand, multi-dimensional water challenges are recognized as significant systemic risks adversely impacting all facets of human society and the environment (Mekonnen & Hoekstra, 2016; Sandhu et al., 2023).

To ensure water security and foster sustainable water management, regional analyses are essential for assessing biophysical and social water risks as well as for improving water management and governance processes that are informed by perspectives, values, and interests of public and private actors and institutions (Dudley et al., 2022; Sandhu et al., 2023). Water risk is a multi-faceted concept defined as the probable occurrence or exposure to different water availability issues (quantity, quality, access, regulatory uncertainty, and multi-user conflicts) that can have adverse consequences for society, economy, and environment (Di Baldassarre et al., 2019; Klinke & Renn, 2012). Social water risks entail legal, political, and social dimensions, including regulatory uncertainty related to how water is allocated, limits to water extraction as well as public perception about water availability and quality, the impact of industrial sectors on water resources, and legacy inequitable access issues, especially in indigenous communities (Sandhu et al., 2021, 2023).

As major water users who impact shared water resources, the corporate sector with businesses in various industries, including manufacturing, agriculture, power generation, mining, recreation, etc., as well as the financial sector that lends, insures, or invests in these businesses are relevant and influential non-state actors in water management and governance (Christ & Burritt, 2018; Klinke & Renn, 2021; Sandhu et al., 2021). Different water risks can lead to increased operational costs, reputational loss, negative public perception, regulatory actions like moratoriums, fines, and increased scrutiny by stakeholders (investors, employees, customers, regulators, civil society organizations, media, and local communities) (Hogeboom et al., 2018; Sandhu et al., 2023; Weber & Saunders-Hogberg, 2018). Water risks also pose significant implications for financial investors, lenders, and regulators through rising operational and regulatory costs, insurance claims, and production disruptions (Sandhu et al., 2021). Thus, the financial sector can potentially drive the inclusion of water risks in investing and lending decision-making, incentivizing and engaging with the corporate sector to create strategies for sustainable water management while identifying opportunities for sustainable water finance aligned with SDG 6 (Hogeboom et al., 2018; Sandhu et al., 2021).

While the exposure to water risks via operational disruptions, reputational implications, and stranded assets due to water issues is acknowledged by the corporate and financial sector (CFS), the urgency of action towards assessing, prioritizing, and managing water risks is largely lagging (CDP, 2022; Christ & Burritt, 2018; Josset & Concha Larrauri, 2021). “Carbon tunnel-vision” has emerged as a prevalent concept, where the myopic focus on carbon emissions overlooks other important interconnected environmental and social development goals, including water security, biodiversity, and social equity that require localized context-based approaches (Gilsbach et al., 2019; Konietzko, 2022; Sandhu et al., 2021). Given these gaps, our study contributes to sustainable water management research and practice by empirically examining the conceptualization, evaluation, and management of different water risks in the CFS (Dobbie & Brown, 2014; Sandhu et al., 2021; Siegrist & Árvai, 2020; Money 2014a,b).

4.1.1. Risk perception of experts and practitioners

Risk is an objective **and** subjective construct that is perceived and interpreted by human actors and is further shaped by the object of risk (source of risk, e.g., water scarcity), perceived impact of risk (what is at risk, e.g., reputation, profits, legitimacy, and health), as well as the affective, trust-based and socio-cultural characteristics of the individual risk perceiver (Dobbie & Brown, 2014; Klinke & Renn, 2021; Siegrist & Árvai, 2020). Decision-making for complex risks entails problem framing, risk assessment, followed by risk evaluation/ characterization where analysts/decision-makers review technical evidence (objective component) and assign a priority based on the acceptability or tolerability of risk (value-based component) (Klinke & Renn, 2012, 2021). Thus, contrary to dominant psychometric paradigms, experts are not a value-free homogenous group but have nuanced cognitive (analytical) and affective (connected to past experiences, feelings, and emotions) risk perception mechanisms that influence risk evaluation and decision-making (Siegrist & Árvai, 2020; Sjöberg, 2002; Slovic, 1999).

It is important to note that "experts" not only include academic experts but also practicing experts, i.e., analysts, practitioners, and decision-makers in corporate organizations, government, or civil society who undertake risk assessments to inform management and decision-making related to the risk problem (Dobbie & Brown, 2014; Sjöberg, 2002). Thus, given multiple decision points, the practitioner/analyst/decision-maker's risk perception informs value-based judgment and prioritization regarding different risks, playing a critical role in risk analysis and management strategies (Dobbie & Brown, 2014). Risk problems, such as water, are multi-faceted, complex, ambiguous, and uncertain, with little or excessive conflicting knowledge (Klinke & Renn, 2021). Thus, practitioners' perception and prioritization of various water risks tend to vary based on their sector, roles, experience, and awareness of impacts (Dobbie & Brown, 2014; Siegrist & Árvai, 2020).

As acknowledged by risk evaluation, management, and governance frameworks, an essential component of comprehensive risk analysis is the examination of the role of water risk perception of practitioners and decision-makers in different water-using sectors and the underlying cognitive and affective factors (Dobbie & Brown, 2014; Renn et al., 2022). However, extant research on attitudes and perception of water risks has mainly focused on the lay public using quantitative methods like surveys (Dobbie & Brown, 2014; Mumbi & Watanabe, 2020; Sandhu et al., 2021; Sjöberg, 2002). Methodologically, mixed methods are an emerging method used to obtain a thorough understanding and explanation of factors underlying risk perception and their relationship with risk evaluation that are underexplored in extant literature (Quinn et al., 2019; Siegrist, 2021; Siegrist & Árvai, 2020). Therefore, our research focuses on the novel application of mixed methods to investigate the perception of biophysical and social water risks by corporate and financial practitioners and decision-makers.

4.1.2. Water risk perception in the corporate and financial sector (CFS) in Ontario

The economy of Ontario in Canada is driven by its large manufacturing and financial sector. Surrounded by the Great Lakes, Ontario is often considered an ideal location for water-reliant production, agriculture, and investment (Sandhu et al., 2020). Despite the perception of abundant freshwater resources, Ontario is rife with water issues, including decreasing flows, quality issues, depleted and /or contaminated groundwater sources, regulatory uncertainty, legacy water access issues in indigenous communities, and controversies/conflicts among competing water user groups, especially the corporate sector (Bonsal et al., 2019; Johns, 2017; Sandhu et al., 2023). Moreover, the role of non-state expert and practitioner risk perception in assessing and managing different water risks largely remains underexplored in Ontario (Sandhu et al., 2021, 2023). Therefore, Ontario is a contemporary and instructive case for empirically examining the underlying facets of water risk perception of practitioners and decision-makers and how biophysical and social water risks are assessed, ranked/prioritized, and integrated into decision-making (Sandhu et al., 2021).

Consequently, our study advances knowledge in risk analysis and sustainable water management. It makes an original and novel contribution by empirically examining and explaining the complex and underexplored construct of water risk perception and its relationship with risk evaluation. Secondly, the study exemplifies the novel application of Risk Theory and explanatory sequential mixed methods approaches for water risks. By analyzing the multidimensional construct of water risk perception and its influence on water risk evaluation and decision-making, multi-sector policies and practices can be designed for sustainable water management. Moreover, this study's research design and analytical procedures can be tested and applied to other regions in future studies beyond Ontario (Creswell & Creswell, 2018).

4.1.3. Research objective and questions

Extant literature reveals gaps in examining the role of water risk perception in evaluating and managing water risks in the CFS in Ontario. Addressing these gaps and using the case of Ontario, Canada*,* our explanatory sequential mixed methods study aims to empirically examine water risk perceptions and priorities of practitioners and decision-makers in the CFS, as well as the relationship of water risk perception with water risk evaluation and decision-making.

RQ 1: What are the factors underpinning the water risk perception of practitioners and decision-makers in the CFS in Ontario?
RQ 2: How does water risk perception relate to water risk evaluation in the CFS?

4.2 Hypotheses and theoretical framework for water risk perception and evaluation in the CFS

For examining a complex, uncertain, and ambiguous risk problem like water and water risk perception, a single siloed theory, method, or disciplinary paradigm may be insufficient (Dobbie & Brown, 2014; Kasperson et al., 2022; Klinke & Renn, 2021). Extant literature highlights the significance of using interdisciplinary approaches to tease out complexities of risk perception and evaluation by integrating multiple physical and social theories and methods across disciplines (CohenMiller & Pate, 2019; Dobbie & Brown, 2014; Klinke & Renn, 2021; Siegrist & Árvai, 2020). Risk Theory is a broad, interdisciplinary, inclusive, and all-encompassing theory that tethers multiple approaches and concepts from disciplines like engineering, psychology, sociology, technology, and political science to get a panoramic systems-based perspective on risk and risk perception (Renn et al., 2022; Roeser et al., 2012). Thus, given the theoretical necessity of interdisciplinary and integrated approaches for examining complex constructs like water risk perception, we chose Risk Theory over other siloed theories to address our research questions.

Using Risk Theory, we can integrate theoretical constructs and hypotheses from psychometric and sociological paradigms to develop our comprehensive interdisciplinary framework for water risk perception and evaluation (CohenMiller & Pate, 2019; Dobbie & Brown, 2014; Klinke & Renn, 2021). For instance, aligned with the psychometric paradigm, risk perception and evaluation can vary with the type and nature of risk and are contingent on the characteristics of hazards (Klinke & Renn, 2021). Moreover, sociological theories like Cultural, Value-Belief-Norm, and Relational Theory state that risk perception is contingent on the risk perceiver (Dobbie & Brown, 2014; Siegrist & Árvai, 2020). Integrating both approaches, we included physical, cognitive, affective, and socio-cultural factors in our hypotheses and framework. Therefore, Risk Theory provides an apt interdisciplinary foundation to extend and apply the analytical-normative framework of risk governance to holistically examine water risk perception factors as well as unearth the complex relationship of these factors with water risk evaluation and management (Kasperson et al., 2022; Renn et al., 2022; Roeser et al., 2012).

4.2.1. Factors underlying water risk perception for risk evaluation and management

Based on Risk Theory and its underlying physical, psychometric, sociological, cultural, and organizational theories, cognitive, affective, and socio-cultural factors of risk perception are expected to act like filters shaping water risk perception of CFS practitioners and influencing risk evaluation (dependent variable), i.e., ratings or priorities assigned to different biophysical and social water risks (Dobbie & Brown, 2014; Sjöberg, 2002; Vasvári, 2015). Water risks relevant from a corporate and financial perspective include water quantity (droughts, groundwater depletion, or reduced flows), quality (contamination), regulatory stringency and uncertainty, location-specific water user conflicts (competing users), source sensitivity (groundwater versus surface water), sector-specific risks, and public and media scrutiny (Sandhu et al., 2023; Money, 2014b).

The factors and corresponding hypotheses are based on general risk perception theories and governance frameworks across multiple disciplines tethered under Risk Theory that we adapted for the risk domain of water in the CFS to develop our study's integrated theoretical framework (CohenMiller & Pate, 2019; Kasperson et al., 2022). Given the research objective, all hypotheses relating risk perception factors (independent variables) to water risk evaluation are associative (explanatory), not causative or predictive. In the case of directional hypotheses, positive association implies that an increase in the factor tends to increase the risk rating, whereas negative association indicates a decrease in ratings.

4.2.1.1. Nature of water risk

"Nature of risk", drawn from the psychometric paradigm, focuses on the risk object, i.e., water risks (Mumbi & Watanabe, 2020). This factor captures the physical conceptualization of different types of water risks, their likelihood, drivers, prioritization, and extent of integration in decision-making that tend to shape risk perception and evaluation (Dobbie & Brown, 2014; Mumbi & Watanabe, 2020). Consequently, our first hypothesis is:

$H1_{\text{Nature of Risk}}$: There are differences in practitioners' conceptualization and prioritization of biophysical and social water risks (Dobbie & Brown, 2014; Klinke & Renn, 2021).

4.2.1.2. Water attitudes

Drawing from sociological theories, attitudes are psychological tendencies about a phenomenon that individuals develop based on their experiences, impacting their evaluation (positive or negative) as well as behavior and actions towards that phenomenon (Eagly & Chaiken, 2007).

Attitudes are domain-specific, i.e., not homogenous across all risks, whereas the Theory of Reasoned Action and the Theory of Planned Behavior can help explain behavioral and perception differences (Weber et al., 2002). Attitudes towards different risks are expressed through multiple variables, including scope, controllability, familiarity (exposure or experience with the issue), concern (dread or worry), urgency, awareness of the negative impact, benefits, and perceived equity of the risk (McDaniels et al., 1997; Mumbi & Watanabe, 2020; Slovic, 1999). For this study, we adapted these variables for water and developed the following hypotheses (Dobbie & Brown, 2014; McDaniels et al., 1997; Mumbi & Watanabe, 2020; Slovic, 1999).

$H2_{\text{Attitude Scope}}$: Perceived scope or extent, i.e., the area and people impacted by the specific water issue, is expected to be positively associated with one's risk perception and, hence, the rating of that water risk. The higher the perceived scope of impact, the higher the risk perception and rating of risk.

$H3_{\text{Attitude Controllability}}$: Controllability is expected to be negatively related to one's risk perception and hence risk rating.

$H4_{\text{Concern}}$: Concern is expected to be a multi-faceted construct encompassing dread, worry, perceived unfairness or inequity related to costs and benefits distribution water of risks, non-substitutability of benefits to offset costs and risk, as well as perceived urgency.

$H5_{\text{Exposure}}$: Direct exposure to water issues is expected to be positively related to risk perception, concern, protective behaviour, and risk ratings (Thistlethwaite et al., 2018).

4.2.1.3. Water-related knowledge

Drawing from the relational theory of risk perception, knowledge is a critical cognitive factor related to core mental processes, where information related to the risk problem is processed to generate risk perception (Dobbie & Brown, 2014; Siegrist & Árvai, 2020). CFS practitioners have individual and collective knowledge as well as interdependent overt and tacit knowledge, which create individual-level differences in perceptions of the same risk. While overt knowledge is connected to formal education and training, tacit or interpretative knowledge is the implicit understanding of phenomena that are gained subconsciously through experience, values, beliefs, and context (Wolfe, 2009; Klinke & Renn, 2021). Tacit knowledge can potentially be impacted by water-related values, attitudes, and previous exposure to issues (Dobbie & Brown, 2014). Integrating the construct of knowledge in our study, water is an interdisciplinary risk problem, and planners, accountants, economists, engineers, ecologists, or management professionals in the same sector may prioritize water risks differently (Dobbie & Brown, 2014). Moreover, while lack of knowledge increases uncertainty, competing claims or multiple interpretations of complex risk phenomena like water may increase risk perception (Aven & Renn, 2019; Weber, 2001). Thus, knowledge and awareness of the complexities of water issues, their impact, and direct exposure tend to increase risk perception (McDaniels et al., 1997; Klinke & Renn, 2021).

H6$_{\textbf{Knowledge}}$: Knowledge encompassing own expertise, awareness of adverse impacts, and experience is expected to be positively associated with water risk ratings.

4.2.1.4. Water values and beliefs

Drawing from the sociological theories like Value-Belief-Norm Theory and Cultural Theory, values and beliefs are expressions of worldviews and overarching sets of goals and principles (distinct but related to attitudes) that guide an individual's behavior and is posited as an explanatory factor for risk perception, especially in conjunction with knowledge (Dobbie & Brown, 2014; Schwartz et al., 2012; Slimak & Dietz, 2006). Domain-specific values, primarily environmental values, have been studied to understand the environmental behavior of different stakeholders (Bøhlerengen & Wiium, 2022; Krewski et al., 2008; Slimak & Dietz, 2006). For such risk domains, values like "Biospheric" (environmental concern); "Altruistic" (concern for others); "Egoistic" (concern for self, assessing costs and benefits); "Technological Optimism" (optimism in technology to address issues) have been identified (Bouman et al., 2018; Krewski et al., 2008). Moreover, biospheric and altruistic values are collectively considered sustainability-centric values (sustaino-centric), and economic benefits-centric values have also been identified in sustainability management, where perceived financial benefits or impacts tend to shape risk acceptability and perception (Gladwin et al., 1995). Adapting these broader environmental values for water, we posit the following hypotheses for risk evaluation:

H7$_{\textbf{Sustainocentric Value}}$: The higher the sustainability-centric values of an individual, the higher the risk ratings due to higher concern for the environment and others, including future generations.

H8$_{\textbf{Egocentric Value}}$: The higher the egocentric values, the lower the perceived risk and ratings for water

H9$_{\textbf{Economic Benefits Value}}$: Economic benefits-centric values are related to risk ratings but are expected to vary across risk types.

H10$_{\textbf{Technological Optimism Value}}$: The higher the optimism in technological solutions, the lower the risk ratings.

4.2.1.5. Trust in various institutions

Drawing from political science and governance paradigms, trust is an increasingly important yet complex explanatory variable of risk perception and evaluation, connected to heuristics, where in case of limited or competing knowledge, individuals may rely on trust to aid decision-making hence impacting risk acceptability (Mumbi & Watanabe, 2020; Siegrist, 2021). Trust can be multi-dimensional and variable, where experiences with an institution and qualities like communication, neutral interests, transparency, and past positive performance can help build (competence-based) trust and confidence. Moreover, social trust can be based on value similarities and group membership (industry) (Dobbie & Brown, 2014; Siegrist, 2021; Slovic, 1999). Therefore, trust is a relevant factor for water risk perception and evaluation.

H11$_{\textbf{Trust}}$: The higher the trust (competence-based) in the government or in an industry (social trust) to assess and manage water risk, the lower the risk perception and risk ratings, i.e., negative association.

4.2.1.6. Sociocultural demographic characteristics of CFS experts and practitioners

Drawing on cultural and relational theories of risk perception, extant literature finds a highly variable impact of sociocultural demographic characteristics like gender, ethnicity, location, professional role, sector, etc., on risk perception that is typically controlled instead of being explored as a part of a theory (Krewski et al., 2006; Siegrist & Árvai, 2020; Slimak & Dietz, 2006). For instance, some studies conclude that women have higher risk perception in some risk domains, but some studies report no effect (Dupont et al., 2014; Mumbi & Watanabe, 2020). Slovic (1999) attributed the higher concern of women about human health, environment, well-being, and safety to the social norm of being entrusted with nurturing and maintaining life. Culture is an interesting factor defined as a dynamic set of shared or group beliefs, norms, meanings, customs, and values that are acquired by an individual (Weber & Hsee, 1998). Therefore, in our study, cultural importance refers to practitioners' shared beliefs, attitudes, or trust related to water bodies, expected to influence risk perception (Dupont et al., 2014; Siegrist, 2021). Other factors include the sector of water use, academic discipline, and location (Dobbie & Brown, 2014).

A location/proximity variable is useful in examining proximity bias, where, interestingly, an individual may discount the occurrence of water issues in their own sub-watershed due to higher perceived control, hence impacting concern, confidence, risk perception, and assessment (Krewski et al., 2008; Money, 2014b; Quinn et al., 2019; Weber et al., 2002). Instead of controlling these sociocultural demographic variables, we empirically examined them as part of our theoretical framework, included as explanatory variables (Mumbi & Watanabe, 2020; Siegrist & Árvai, 2020)

H12$_{\textbf{Gender}}$: Women are expected to have higher water risk ratings than men.

H13$_{\textbf{Cultural Importance}}$: The cultural importance of water is expected to be correlated to trust and confidence.

H14$_{\textbf{Sector}}$: The sector of water use is expected to influence water risk ratings, where water-intensive sectors rate/prioritize water risks higher than others.

H15$_{\textbf{Location}}$: A proximity bias is expected, where an individual may have lower concern and risk perception of their local sub-watershed than the province (as a whole).

4.2.2. Theoretical framework

Based on the investigated risk perception factors and hypotheses (Section 4.2.1) drawn from underlying interdisciplinary paradigms of the Risk Theory that we adapted for water and aligned with the integrated risk analysis stage of the normative-analytical risk governance model of Klinke & Renn (2012, 2019), we developed the study's theoretical framework as depicted in Figure 4.1. These cognitive, affective, social-cultural, and spatial (proximity) factors are posited to shape water risk perception, influence risk evaluation, and, eventually, risk management and decision-making for water. The risk governance model of Klinke & Renn (2012, 2019) is a generic model for all risk domains, encompassing all stages of risk management, including risk pre-estimation, interdisciplinary risk estimation, integrated risk analysis (perception and evaluation), management, and communication. We tested this model by applying it to water risks in the CFS. Then we built it further by expanding the risk analysis/ evaluation stage to purposefully include the integrated water risk perception factors drawn from interdisciplinary theories.

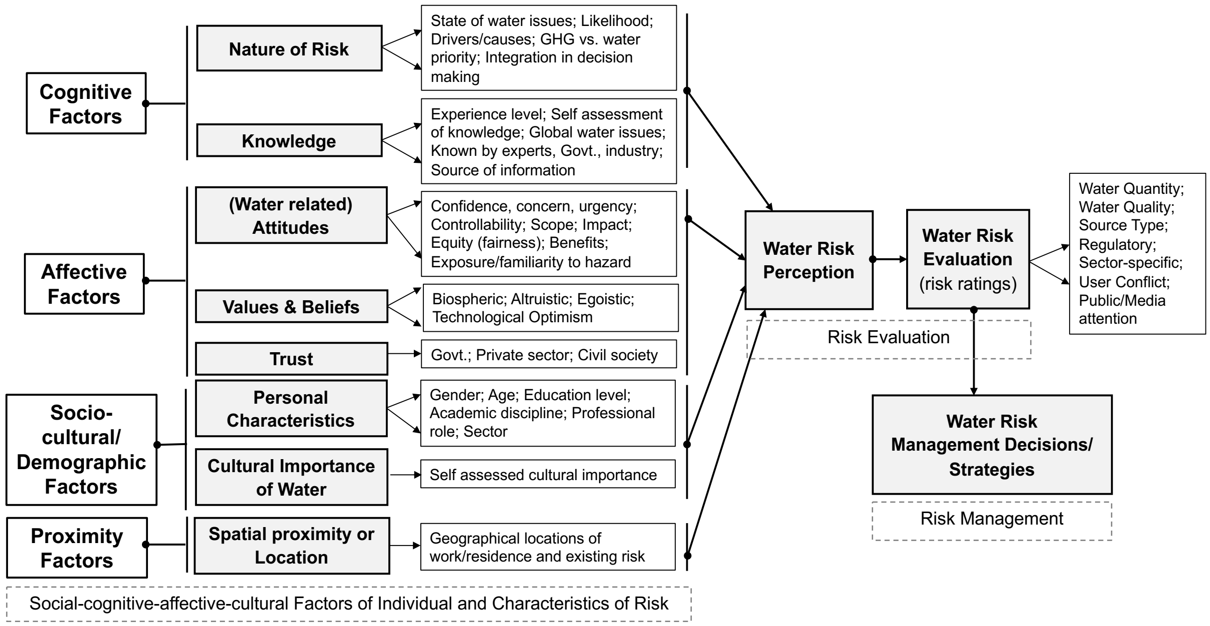

Figure 4.1: Theoretical framework for water risk perception, risk evaluation and management

4.3 Methods and data

Recent literature advocates using mixed methods to address multi-faceted research problems like water risks to ensure quantitative robustness and qualitative depth in tandem (Creswell & Creswell, 2018; Mooney et al., 2020; Quinn et al., 2019). Using a single method will not suffice to examine and understand complex risk perception factors holistically, and there is a paucity of studies employing mixed methods for investigating water risk perception and evaluation (Di Baldassarre et al., 2021; Quandt, 2022; Rangecroft et al., 2021, 2022). Therefore, demonstrating the novel application of mixed methods, we employed an *Explanatory Sequential Mixed Methods research design,* as depicted in Figure 4.2. We combined the quantitative robustness of cross-sectional surveys and the explanatory depth of follow-up qualitative interviews to address our research questions.

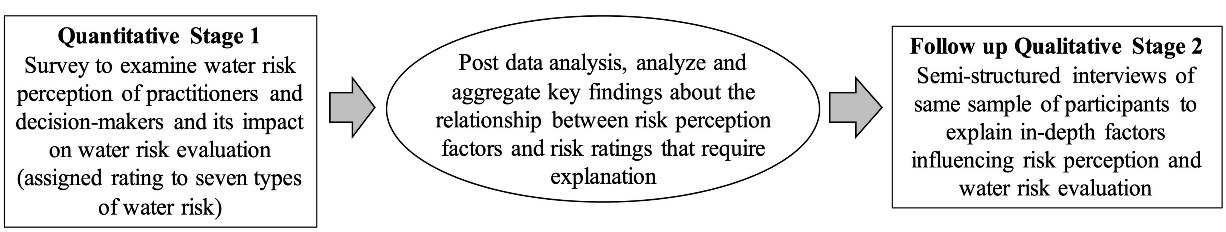

Figure 4.2: Explanatory sequential mixed methods research design

As human participants were involved, the study was reviewed by the University of Waterloo Research Ethics Board (REB# 44065), ensuring ethical recruitment, informed consent, data collection, anonymization, and management. The quantitative stage examined the underlying factors for water risk perception and their relationship with evaluation (captured as risk rating or weights for different water risks). We used a questionnaire-based cross-sectional online survey designed in Qualtrics for data collection (Quinn et al., 2019; Renn et al., 2022). The follow-up qualitative stage with in-depth one-on-one semi-structured interviews was designed to complement the survey. It was conducted with the same sample of participants as the survey (Creswell & Creswell, 2018).

4.3.1. Study participants and sampling strategy

The socio-political landscape for sustainable water management is very diverse with multi-level systems, i.e., a multitude of stakeholder groups including public (state) actors, policy makers, private actors, and civil society, along with their diverse perceptions, values, and interests (Klinke & Renn, 2012; Johns, 2017). However, extant research has primarily focused on the public sector, policy makers, academia, and lay public (Harris-Lovett et al., 2019; Klinke & Renn, 2021; Johns, 2017; Mooney et al., 2020; Quinn et al., 2019). As discussed before, private actors, including CFS, are essential stakeholders in sustainable water management but have been an underexplored population in the water risk assessment and perception research (Christ & Burritt, 2018; Hogeboom et al., 2018; Money, 2014a, 2014b).

Addressing this gap, private sector practitioners and experts, including analysts, managers, and decision-makers from businesses in water-reliant industrial sectors (e.g., food and beverage, aggregate mining, chemical manufacturing, other manufacturing, power production, agriculture, environmental consulting, and research services), and financial sector (e.g., banks, investors, insurance companies etc.), who have expertise in environmental/sustainability risk assessment and operating in Ontario, were chosen as the study's population. An expert-based purposive sampling strategy ensured that the attitudes and perceptions of analysts and decision-makers in different sectors are considered (Mooney et al., 2020). Informed by extant research, purposive sampling is strategic and ensures the representativeness and relevance of the selected sample to the research objective geared toward in-depth context-specific insights (Mooney et al., 2020; Palinkas et al., 2015).

We identified 252 potential participants after research ethics clearance based on publicly available professional profiles on LinkedIn, industry associations, and organizational websites. We used the job title, sector, and location filters to ensure representativeness. The following purposive recruitment criteria were used to screen and select potential participants:

(i) Professional experience or expertise (based on their roles/ work experience) in sustainability, environmental, water assessment, reporting, management, and decision-making
(ii) Job titles including “sustainability”; “environment”; “natural resource”; “water”; “ESG”; “water policy” **AND** “analyst”; “technician”; “engineer”; “manager”; “director”; “lead”; “specialist”; “advisor”; “associate”; “vice president”; “president”; “consultant”
(iii) Current or past work location in Ontario (Northern Ontario; Southern Ontario)

We sent invitation emails along with the information and consent letter to the sample. The information/consent letter provided an overview of the study, objectives, significance, and time commitments. We also provided information about the anonymity and confidential procedure, timelines, scholarly/scientific benefits, consent to record, and the use of quotes. The online survey was available from April 25 to August 10, 2022. Twenty-six participants provided consent to participate, and 25 participants completed the online survey, as presented in Table 4.1. From the recruited sample, 22 participants participated in the follow-up online interviews between October 1 and December 15, 2022. Demographic data of the survey and interview participants are provided in Table 4.1.

Table 4.1: Summary demographic statistics of participants

Participant Demographics	Survey, N=25		Interview, N=22	
	n	%	n	%
1. Gender				
Woman	13	52%	10	45%
Man	12	48%	12	55%
2. Ethnicity				
Others	6	24%	N/A	
White/ Caucasian/ European origin	19	76%		
3. Sector				
Agriculture	5	20%	4	18%
Chemical manufacturing	2	8%	2	9%
Consulting (Research Services, NGOs)	3	12%	2	9%
Financial Sector	7	28%	7	32%
Food and Beverage Manufacturing and Processing	2	8%	3[1]	14%
Mining and milling	2	8%	1	5%
Power Production	2	8%	2	9%
Transportation Equipment Manufacturing	2	8%	1	5%
4. Professional Role				
Analyst	7	28%	N/A	
Director	5	20%		
Manager	7	28%		
Vice President/C Executive/ Co-founder/Owner	6	24%		
5. Discipline of Education				
Arts (Economics, Business, Finance etc.)	2	8%	N/A	
Engineering and Technology	5	20%		

Environment	11	44%
Others (Mathematics, Safety, Agriculture, Health Sciences)	5	20%
Natural and Physical Sciences	2	8%

[1] One additional participant who participated only in the interview stage

Comment on the adequacy of sample size: Studies that employ expert surveys and interviews tend to have a highly specific and small sample (McDaniels et al., 1997; Mooney et al., 2020; Weber, 2001). Arguments about the adequate sample size to ensure representativeness using power analysis, minimum variable-to-case ratios, and restrictions on parametric tests are rife in the literature (Jenkins & Quintana-Ascencio, 2020; Norman, 2010). Nonetheless, the representativeness of a population can be ensured using non-probability based intentional purposive sampling strategies (Mooney et al., 2020; Palinkas et al., 2015). Moreover, parametric tests do not strictly prescribe a minimum sample, and the suggested variable-to-case ratios are rules of thumb varying considerably across disciplines and study designs (Jenkins & Quintana-Ascencio, 2020; Norman, 2010). The emphasis on large samples and power analysis has been criticized for being overly prescriptive, overlooking particularity, i.e., gaining contextual insights of highly specific research populations like experts (Jenkins & Quintana-Ascencio, 2020).

Statistically, a smaller sample size requires larger effects to achieve statistical significance, and thus Type II errors or false negatives might be a concern (Norman, 2010). Nonetheless, in explanatory sequential mixed methods research, the survey's findings are validated and explained in-depth during the follow-up interviews, enhancing the overall research validity and reliability (Creswell & Creswell, 2018; Ivankova et al., 2006). Moreover, parametric tests, including multiple linear regression, are robust for sample sizes as small as 15, provided the basic assumptions of multiple linear regression analyses, i.e., linearity, low multi-collinearity, normality of residuals, and homoscedasticity are met (Norman, 2010). Simulations that matched regression models to data found results to be stable for sample sizes around 25 across variable effect sizes (Jenkins & Quintana-Ascencio, 2020). Thus, in our study with 25 experts, not only are the explanatory variables based on the extensive literature on risk perception but also the follow-up interviews help validate significant and non-significant explanatory variables to address Type II errors (Creswell & Creswell, 2018; Molina-Azorín & López-Gamero, 2016).

4.3.2. Survey questionnaire design

Survey items aligned with variables and measures were drawn from extant risk perception literature and adapted for water risks and the context of Ontario (Bouman et al., 2018; Dupont et al., 2014; Grima et al., 2021; Krewski et al., 2006, 2008; Mumbi & Watanabe, 2020; Robinson, 2018; Slimak & Dietz, 2006; Thistlethwaite et al., 2018). Operationalizing our theoretical framework, water risk perception factors (independent variables) to be examined included *Nature of Risk* (different water issues, likelihood, drivers, extent of integration), *Attitudes* (confidence, scope, controllability, equity, impact awareness, benefits, previous exposure to water issues, overall concern, and urgency), *Knowledge* (assessment of experience, knowledge is different sectors, source of knowledge), *Values and beliefs* (biospheric, altruistic, egoistic, technological optimism), Trust (in institutions to manage water risks), and *Sociocultural demographic characteristics* (cultural importance of water, sector, discipline, professional role, gender, ethnicity, location). Sociocultural demographic questions were self-reported, and the remaining questions were assessed on a 7-point Likert scale. *Water risk evaluation* (dependent variable) was measured by assigning a rating (priority) to seven types of water risks (Figure 4.1) using a 1 to 7 continuous scale based on the perceived importance of the risk to business and investment operations, policies, or decisions (Dobbie & Brown, 2014; McDaniels et al., 1997; Weber, 2001).

Further details on the survey items and scales are provided in the supplementary material as Appendix 4.A. Given the length of the survey, it was not timed and could be filled out by the participants in multiple sittings at their convenience. Moreover, the participants could skip any question they did not feel comfortable answering.

4.3.3. Statistical analysis of stage 1 survey

We used IBM SPSS, V.28 to analyze the survey dataset containing numerically coded values and labels (anchors of rating scale) for each item. We coded the categories manually for text entry options, e.g., Discipline of education, Professional role, Location, i.e., sub-watershed of residence/work. Categories of a few variables were combined into a broader “others” category to ensure at least two cases for each category. A new variable, “Location Conflict Rating” was created from “Location” to link the actual water conflict risk of the participant’s sub-watershed based on the technical water risk assessment by Sandhu et al. (2023) to the perceived risk ratings. The location conflict risk (1: very low to 5: very high) for sub-watersheds is based on the density of water-taking permits, drought potential, high growth regions, the prevalence of drinking water advisories, public and civil society focus, and media attention (Sandhu et al., 2023). For the regression analysis, we created dummy variables for non-ordered categorical variables, i.e., gender, sector, ethnicity, and discipline of education.

4.3.3.1. Exploratory factor analysis for validating theoretical constructs and variable reduction

We employed exploratory factor analysis (EFA) to statistically validate hypothesized constructs based on our theoretical framework and reduce underlying variables (Bouman et al., 2018; Grima et al., 2021; Jung & Lee, 2011). In addition to construct validity, EFA alleviates multi-collinearity issues in statistical tests (Robinson, 2018). The constructs and their underlying items include Nature of Risk (Q1 i-iv, Q2, Q14; Q16 ii), Knowledge (Q15 i-ii; Q16 i; Q18 i-iv; Q17 i-ii), Drivers of Water Issues (Q3 i-vii), Water Values (Q 20 i-x; Q9), Water Attitudes (Q4 i-ii; Q6 i-v; Q7 i-v; Q8; Q9; Q10 i; Q12 i; Q13), Negative Impact Themes (Q5 i-vii), Exposure (Q10i, Q11), and Water Risk Ratings (Dependent Variables) (Q 23 i-vii). Some items (e.g., exposure to water issues and economic benefits) were analyzed under more than one construct (attitudes, exposure, values) due to expected interconnections between values, attitudes, and exposure (Dobbie & Brown, 2014).

Based on extant studies, Principal Component Analysis and Varimax/orthogonal rotation were employed as the factor extraction and rotation method, respectively (McDaniels et al., 1997; Robinson, 2018; Grima et al., 2021). We followed the thresholds of Kaiser-Meyer-Olkin (KMO) >= 0.5 and Bartlett's Test of Sphericity, i.e., $p <= 0.05$ as measures of sample size adequacy and robustness of analysis (Grima et al., 2021; Mumbi & Watanabe, 2020). Items with factor loadings >= 0.40 in the rotated matrix were retained, and the number of factors/components was based on eigenvalues > 1 (Boateng et al., 2018; Slimak & Dietz, 2006). Cross loadings of items, if found, were assessed case by case, leading to either removal or being assigned to one factor based on the theory further validated by reliability tests (DiStefano et al., 2009; Schwartz et al., 2012).

The reliability of each component/construct post-factor analysis was determined using Cronbach alpha (α) (acceptable >= 0.7) (Lam, 2012; Robinson, 2018). Due to the small sample size and the complexity of a few constructs, additional criteria of composite reliability (CR) (acceptable > 0.6) and Average Variance Explained (AVE) (acceptable > 0.4) were used to ensure reliability and convergent validity (Bouman et al., 2018; Fornell & Larcker, 1981; Lam, 2012). The names and definitions of constructs were assigned based on the literature and theory

(Grima et al., 2021; Robinson, 2018). Recent literature on behavioral research suggests that the robustness of sum or mean item scores post-factor analysis is comparable to more refined weighted factor score estimates with the additional advantage of simplicity and consistency across samples (Boateng et al., 2018; Robinson, 2018; Widaman & Revelle, 2022). Thus, upon identification of constructs, the average raw scores of constituent items were used. Since average scores were used, the original scale range (1-7) was retained for the new constructs. Items with negative signs for factor loadings in a construct were reverse-coded and then included in the mean scores before being used in statistical tests (Bouman et al., 2018; Robinson, 2018; Slimak & Dietz, 2006).

4.3.3.2. Statistical tests to examine the relationship between water risk perception and evaluation

After factor analyses, we used Multiple Linear Regression (Ordinary Least Squares estimation method) to analyze and explain the relationship between each water risk type (dependent variable) and hypothesized explanatory risk perception factors measured on the Likert scale (McDaniels et al., 1997; Mumbi & Watanabe, 2020; Shmueli, 2010; Slimak & Dietz, 2006). Past studies have also employed parametric tests for Likert scale data that are considered to be continuous with five or more categories (Bøhlerengen & Wiium, 2022; Mumbi & Watanabe, 2020; Norman, 2010; Slimak & Dietz, 2006; Weber, 2001). Multiple linear regression models were developed for the three water risk ratings, and the models were intended to be explanatory rather than predictive or causal (Shmueli, 2010; Weber, 2001).

For each model, we used the standard method of simultaneous entry of independent variables (ENTER method), listwise deletion of missing data, and dummy variables for non-ordered categorical data (Mumbi & Watanabe, 2020). We calculated standard measures like Variance Inflation Factor (VIF) with a conservative acceptable threshold of < 4 (to minimize multicollinearity), adjusted R^2, F value significance (two-tailed test with alpha of 0.05), and tested all statistical assumptions post hoc (Boateng et al., 2018; Mumbi & Watanabe, 2020; Slimak & Dietz, 2006). Similar to past perception studies, the number of explanatory variables was relatively high for water risk perception and evaluation (McDaniels et al., 1997; Mumbi & Watanabe, 2020; Slimak & Dietz, 2006). Nonetheless, to diagnose overfitting and ensure apt model selection, in addition to adjusted R^2, the PRESS (predicted residual sum of squares) statistic with the total sum of squares of the model was calculated and compared (Allen, 1971).

Additional multiple linear regression models were developed to test the hypotheses related to the factors of Trust and Confidence (as dependent variables) and identify underlying explanatory factors (Mumbi & Watanabe, 2020). Moreover, to test statistically significant mean differences based on gender and sector for variables of interest, we employed independent samples Student's *t*-test (for two groups for gender) and one-way analysis of variance (ANOVA) test (Mishra et al., 2019). We also performed normality (Shapiro-Wilk Test) and homogeneity tests (Levene Test), and the differences were validated in follow-up interviews (Creswell & Creswell, 2018; Ivankova et al., 2006). All significance tests for regression or other tests, i.e., $p < .05$, was a two-tailed test with an alpha of 0.05 (Mishra et al., 2019).

4.4 Stage 1 survey results

4.4.1. Participant demographics and descriptive statistics (mean scores) for variables of interest

A total of 25 (N_{Survey}) participants completed the survey, and 22 ($N_{Interview}$) participated in the follow-up interviews (Table 4.1). For variables of interest, specifically, Trust (degree of trust in different institutions to assess risks, manage or protect water resources), the mean score of all participants was highest for Civil Society Organizations (M = 4.28, SD = 1.14), followed by Government (M = 4.12, SD = 0.73) and least in Private Sector (M = 3.48, SD = 0.87). To explore *Proximity Bias*, we found the mean score of all participants for Confidence (in sufficient and abundant water resources) was higher for one's own sub-watershed of residence/work (M = 5.21, SD = 1.14) than Confidence for Ontario more broadly (M = 5.13, SD = 0.85). Moreover, the mean score for Concern (about water issues, their impacts, and risks) was higher for Ontario (M = 5.25, SD = 1.11) than concern for one's own sub-watershed of residence or work (M = 4.79, SD = 1.18). Therefore, confirming proximity bias, the study finds potential discounting (on average) in perceived water risks in one's own sub-watershed, i.e., less concern and more confidence than in Ontario. While overall Concern for water issues in Ontario is higher than the confidence in water abundance in Ontario, there is more confidence than concern in one's sub-watershed.

4.4.2. Results of factor analysis, final constructs, and mean water risk ratings

We found three constructs for the dependent variable from the EFA based on the seven water risk types. Two constructs, *Indirect Water Scarcity Risk* (i.e., water quality and source type risk) and *Social Water Risk* (regulatory risk, water user conflict, sector-specific risks, and media/public attention), were found with a cumulative explained variance of 66.75% and no cross-loadings. *Direct Water Scarcity Risk* (water quantity) was unidimensional based on the literature and excluded from the EFA. For risk perception factors, individual EFAs were performed due to the complexity of the constructs (Grima et al., 2021). Two constructs were found for *Nature of Risk,* i.e., *Biophysical Aspects* and *Social Aspects,* with a cumulative explained variance of 60.74% and no cross-loadings. Three constructs were found for *Knowledge,* i.e., *Self, General Issues,* and *Experts,* with a cumulative explained variance of 73.32%. *Q15_1_Knowledge_Sustainability Assessment* cross-loaded in *Knowledge_Self* and *Knowledge_General Issues,* but based on the theory, it was retained in *Knowledge_Self.* Following Schwartz et al. (2012), the assignment to a particular factor was validated by comparing α, CR, and AVE values with higher values resulting in the most appropriate scale.

Two constructs were found for *Drivers of Water Issues,* i.e., *Micro* Consumer Level and *Macro* Level, with a cumulative explained variance of 71.30% and no cross-loadings. EFA for Water Values was expected to be complex and iterative, with the final model revealing four constructs, i.e., *Sustaino-centric*, *Economic Benefits centric*, *Ego-centric*, and *Technological Optimism,* and a cumulative explained variance of 78.93%. Cross-loadings were observed for *Q20_7_Efficiency gains can reduce water risks*, loading on Economic Benefits centric and Ego-centric values. However, based on theory, the factor was assigned to Economic Benefits further validated by comparing α, CR and AVE values. Cross-loadings also appeared for *Q20_4_Need to assess both costs and benefits*, loading on *Ego centric values*, *Sustaino-centric,* and *Technological optimism values.* The factor was assigned to *Ego-centric* values, and this assignment resulted in the highest α, CR and AVE values. Ego-centric and benefit-centric values were expected to be complex with relatively low α (Bouman et al., 2018), and hence we relied on CR > 0.7.

Reputational Impacts and *Financial Impacts* were two constructs with a cumulative explained variance of 88.40% and no cross-loadings. A separate EFA was performed for *Sustainability Impacts* with a cumulative explained variance of 86.45% and no-cross loadings. Five constructs resulted for *Attitudes,* i.e., *Scope, Biophysical Controllability, Social Controllability, Overall Concern,* and *Overall Confidence,* with a cumulative explained variance of 73.47%. Cross-loadings were observed for *Q7_5_ Controllability_Water user conflicts,* loading on *Scope* and *Social Controllability*. The factor was assigned to *Social Controllability* that resulted in the highest α, CR and AVE values. Negative factor loadings for items *Q8_Equity of Impact of Water Issues* and *Q9_Economic benefits offset costs and risks* were reverse-coded, alluding to higher concern with higher inequity and non-substitutability of water risks. One construct was found for *Exposure* with a cumulative explained variance of 75.08% and no cross-loadings.

Detailed results of the eight EFAs are provided in Appendix 4.B (Tables 4.B1 – 4.B8), which reports the construct names, underlying items, factor (component) loadings, eigenvalues, % of total variance explained, KMO, Bartlett tests, and reliability tests (α, CR, AVE). All factor analyses yielded KMO values > 0.50 and a significant Bartlett's test of sphericity, i.e., $p < .05$, alluding to the adequacy of the sample and factors. Any item with negative factor loadings was reverse-coded, followed by reliability analysis and averaging for the final construct (Grima et al., 2021; Robinson, 2018). CR > 0.7 was found for all final constructs, which meets the minimum threshold of 0.6 for reliability (Fornell & Larcker, 1981; Grima et al., 2021; Lam, 2012). Before proceeding with the statistical tests, we created a final set of 23 constructs based on average item scores. For example, *Concern* was the average of four survey items (Q12_1, Q13, Q8_REV, Q9_REV), where Q8 and Q9 were reverse-coded due to negative factor loadings.

For the dependent variable, based on the EFA, the highest average score was found to be *Direct Scarcity Water Risk,* i.e., risk of water quantity issues ($M = 4.88$, $SD = 1.68$), followed by *Indirect Water Scarcity Risk,* i.e., scarcity due to degraded water quality and groundwater sources sensitive to contamination ($M = 4.83$, $SD = 1.40$), and least *Social Water Risk* ($M = 4.80$, $SD = 1.19$).

4.4.3. Results of the statistical analysis

We developed three multiple linear regression models for water risk ratings, i.e., *Direct Water Scarcity Risk*, *Indirect Water Scarcity Risk,* and *Social Water Risk* (dependent variables). Based on the theoretical framework and EFA results, our study had 21 explanatory variables. To arrive at a relevant sub-set of explanatory variables (risk perception factors) for each model, we compared VIF, Adjusted R^2, F value, and PRESS statistic. The final models resulted in a significant equation. The *Direct Water Scarcity Risk* multiple regression model (Table 4.2) indicated that the selected twelve risk perception factors explained 87% of the variance (adjusted $R^2 = 0.87$, $R^2 = 0.94$, $F(12, 11) = 13.85$, $p < .001$). The factors, along with their unstandardized

(B), standard errors, standardized coefficients (β), *t* values, *p* values, and VIF, are provided in Table 4.2. Nine out of the twelve explanatory risk perception factors, including *Location Conflict Rating*, *Education Level* (College), *Education Level* (Bachelor, University), *Attitude_Scope*, *Knowledge_Experts*, *Gender* (Woman), *Attitude_Bipohysical Controllability*, *Values_Egoistic*, and *Values_Technological Optimism,* significantly explain ($p < .05$) direct water scarcity risk.

The *Indirect Water Scarcity Risk* multiple regression model results provided in Table 4.3 indicated that the twelve risk perception factors explained 82.6% of the variance (adjusted $R^2 = 0.826$, $R^2 = 0.917$, $F(12, 11) = 10.13$, $p < .001$). Eight out of the twelve factors significantly explain ($p < .05$) indirect water scarcity risk ratings and include *Discipline of Education (Natural Sciences), Discipline of Education (Arts), Discipline of Education (Others), Values_Egoistic, Values_Economic Benefits, Values_Sustaino-centric, Trust in Private Sector,* and *Attitude_Bipohysical Controllability.* The *Social Water Risk* multiple regression model results in Table 4.4 indicated that the ten risk perception factors explained 60% of the variance (adjusted $R^2 = 0.60$, $R^2 = 0.774$, $F(10, 13) = 4.45$, $p = .007$). Six out of the ten factors significantly explain ($p < .05$) social water risk rating and include *Trust in Government, Trust in Private Sector, Discipline of Education (Arts), Attitude_Bipohysical Controllability, Knowledge_Self,* and *Knowledge_Experts.*

Table 4.2: Regression coefficients, t value, significance, and VIF for direct scarcity water risk rating (DV1)

Explanatory Variables[a]	Unstandardized Coefficients B	Std. Error	Standardized Coefficients β	*t*	*p*	VIF
Location Conflict Rating	0.989	0.281	0.353	3.514	0.005	1.790
Education Level[b] (College)	-2.060	0.507	-0.415	-4.066	0.002	1.847
Education Level[b] (Bachelors, University)	-1.758	0.375	-0.528	-4.684	0.001	2.252
Attitude_1_Scope	0.857	0.163	0.539	5.257	<.001	1.865
Knowledge_3_Experts	0.720	0.144	0.490	4.989	<.001	1.711
Gender[c] (Woman)	1.728	0.311	0.526	5.562	<.001	1.587
Trust in Government	-0.438	0.203	-0.194	-2.153	0.054	1.432
Attitude_2_Bipohysical Controllability	-0.453	0.147	-0.288	-3.077	0.011	1.556
Values_3_Egoistic	-1.202	0.212	-0.573	-5.681	<.001	1.800
Values_2_Economic Benefits	0.135	0.123	0.108	1.093	0.298	1.730
Values_4_Technological Optimism	0.433	0.128	0.340	3.387	0.006	1.788
Knowledge_1_Self	-0.093	0.163	-0.063	-0.573	0.578	2.173

[a]Dependent Variable: Direct Water Scarcity Risk
Model Statistics: *Adjusted* $R^2 = 0.87$, $R^2 = 0.94$, $F(12, 11) = 13.85$, $p < .001$, Total Sum of Squares = 64.63, PRESS = 18.98, PRESS < SSTO.
[b] Dummy variable for the level of education (Reference: University Degree or Certificate, Master or PhD level)
[c] Dummy variable for gender (Reference: Man)
[d] Shapiro Wilk Test $p = .941$, Breusch Pagan Test $p = .985$

Table 4.3: Regression coefficients, t value, significance and VIF for indirect scarcity water risk rating (DV2)

Explanatory Variables[a]	Unstandardized Coefficients B	Std. Error	Standardized Coefficients β	*t*	*p*	VIF
Gender[b] (Woman)	0.057	0.267	0.021	0.213	0.835	1.254
Discipline of Education[c] (Natural Sciences)	-1.600	0.494	-0.322	-3.240	0.008	1.307
Discipline of Education[c] (Arts)	2.289	0.748	0.333	3.062	0.011	1.566
Discipline of Education[c] (Others)	-2.469	0.351	-0.730	-7.031	<.001	1.428
Discipline of Education[c] (Engineering)	-0.200	0.427	-0.059	-0.469	0.648	2.109
Values_3_Egoistic	-0.574	0.187	-0.327	-3.077	0.011	1.494
Values_2_Economic Benefits	0.527	0.112	0.504	4.703	0.001	1.524
Values_1_ Sustaino-centric	1.091	0.235	0.588	4.632	0.001	2.139
Trust in Government	-0.380	0.194	-0.201	-1.957	0.076	1.392
Trust in Private Sector (Industry)	0.559	0.203	0.352	2.751	0.019	2.169
Attitude_2_Bipohysical Controllability	-0.527	0.154	-0.401	-3.427	0.006	1.815
Location Conflict Rating	0.354	0.261	0.151	1.358	0.202	1.636

[a]Dependent Variable: Indirect Water Scarcity Risk
Model Statistics: *Adjusted* $R^2 = 0.826$, $R^2 = 0.917$, $F(12, 11) = 10.13$, $p < .001$, Total Sum of Squares= 45.33, PRESS = 17.87, PRESS < SSTO.
[b] Dummy variable for gender (Reference: Man)
[c] Dummy variable for the discipline of education (Reference: Environment)
[d] Shapiro Wilk Test $p = .971$, Breusch Pagan Test $p = .757$

Table 4.4: Regression coefficients, t value, significance and VIF for social water risk rating (DV3)

Explanatory Variables[a]	Unstandardized Coefficients B	Std. Error	Standardized Coefficients β	*t*	*p*	VIF
Trust in Government	-0.799	0.252	-0.497	-3.167	0.007	1.417
Trust in Private Sector (Industry)	0.632	0.232	0.469	2.723	0.017	1.707
Discipline of Education[b] (Arts)	2.480	0.886	0.425	2.799	0.015	1.326
Education Level[c] (College)	1.195	0.631	0.339	1.895	0.081	1.840
Education Level[c] (Bachelors, University)	0.640	0.445	0.270	1.436	0.175	2.040
Attitude_2_Biophysical Controllability	-0.397	0.173	-0.356	-2.295	0.039	1.382
Location Conflict Rating	0.587	0.331	0.295	1.773	0.100	1.591
Knowledge_1_Self	0.596	0.196	0.570	3.036	0.010	2.028
Knowledge_3_Experts	0.755	0.176	0.724	4.284	0.001	1.644
Values_2_Economic Benefits	-0.312	0.151	-0.352	-2.076	0.058	1.656

[a]Dependent Variable: Social Water Risk
Model Statistics: *Adjusted* $R^2 = 0.60$, $R^2 = 0.774$, $F(10, 13) = 4.45$, $p = .007$, Total Sum of Squares = 32.62, PRESS = 25.27, PRESS < SSTO.
[b] Dummy variable for the discipline of education (Reference: Environment)
[c] Dummy variable for the education level (Reference: University Degree or Certificate, Master or PhD level)
[d] Dummy variable for gender (Reference: Man)
[e] Shapiro Wilk Test $p = .146$, Breusch Pagan Test $p = .588$

Using multiple linear regressions, we also examined *Trust in Private Sector* (to manage water risks) and *Overall Confidence in freshwater abundance in Ontario* (as Dependent Variables). The *Trust in Private Sector* multiple regression model (Table 4.5) indicated that the risk perception factors explained 60.6% of the variance (adjusted $R^2 = 0.606$, $R^2 = 0.778$, $F(10, 13) = 4.54$, $p = .006$). Six out of the ten factors significantly explained ($p < .05$) the degree of trust in the private sector, including *Values_Egocentric, Gender, Attitude_Social Controllability, Impact_Financial, Knowledge_Self,* and *Knowledge_Experts.* The results for *Confidence* (Table 4.6) indicated risk perception factors explained 67.7% of the variance (adjusted $R^2 = 0.667$, $R^2 = 0.846$, $F(12, 11) = 5.02$, $p = .006$). Nine out of twelve factors significantly explained ($p < .05$) confidence, including *Values_Technological Optimism, Drivers of Water Issues_Micro, Cultural Importance, Gender (Woman), Discipline of Education, i.e., Arts, Natural Sciences and Others, Location Conflict Rating,* and *Exposure.*

Table 4.5: Regression coefficients, t value, significance and VIF for Trust in Private Sector

Explanatory Variables[a]	Unstandardized Coefficients B	Std. Error	Standardized Coefficients β	*t*	*p*	VIF
Values_1_ Sustaino-centric	-0.208	0.189	-0.178	-1.102	0.290	1.529
Values_2_Economic Benefits	0.068	0.097	0.103	0.703	0.495	1.257
Values_3_Egocentric	0.596	0.208	0.538	2.858	0.013	2.070
Impact_2_Financial	-0.593	0.174	-0.658	-3.413	0.005	2.171
Gender[b] (Woman)	0.600	0.261	0.346	2.301	0.039	1.324
Knowledge_1_Self	-0.593	0.144	-0.764	-4.110	0.001	2.017
Knowledge_2_Experts	-0.283	0.123	-0.365	-2.301	0.039	1.474
Extent of Water Risk Integration	0.157	0.102	0.269	1.533	0.149	1.801
Attitude_1_Scope	-0.202	0.151	-0.241	-1.336	0.204	1.900
Attitude_3_Social Controllability	0.318	0.145	0.349	2.202	0.046	1.467

[a]Dependent Variable: Trust in Private Sector (industry)
Model Statistics: *Adjusted* $R^2 = 0.606$, $R^2 = 0.778$, $F(10, 13) = 4.54$, $p = .006$, Total Sum of Squares = 18.00, PRESS = 13.38, PRESS < SSTO.
[b] Dummy variable for gender (Reference: Man)
[c] Shapiro Wilk Test $p = .359$, Breusch Pagan Test $p = .731$

Table 4.6: Regression coefficients, t value, significance and VIF for Overall Confidence (Attitude_Confidence)

Explanatory Variables[a]	Unstandardized Coefficients B	Std. Error	Standardized Coefficients β	*t*	*p*	VIF
Nature of Risk_2_Social Aspects	-0.288	0.146	-0.312	-1.966	0.075	1.790
Values_4_ Technological Optimism	-0.325	0.144	-0.454	-2.252	0.046	2.900
Drivers of Water Issues_Micro	-0.558	0.110	-0.681	-5.073	<.001	1.282
Cultural Importance	-0.238	0.100	-0.325	-2.375	0.037	1.333
Gender[b] (Woman)	-1.198	0.289	-0.651	-4.143	0.002	1.758
Discipline of Education[c] (Arts)	1.813	0.702	0.394	2.582	0.025	1.655
Discipline of Education[c] (Others)	-0.786	0.336	-0.347	-2.337	0.039	1.567
Discipline of Education[c] (Natural Sciences)	-1.221	0.553	-0.367	-2.207	0.049	1.964
Location Conflict Rating	-0.514	0.232	-0.327	-2.213	0.049	1.554
Exposure	0.341	0.105	0.524	3.245	0.008	1.856

Trust in Government	-0.180	0.165	-0.142	-1.091	0.299	1.210
Trust in Private Sector (Industry)	-0.244	0.189	-0.230	-1.288	0.224	2.261

[a]Dependent Variable: Attitude_Confidence
Model Statistics: *Adjusted* R^2 = 0.667, R^2 = 0.846, $F(12, 11)$ = 5.02, p = .006, Total Sum of Squares = 20.33, PRESS = 12.19, PRESS < SSTO.
[b] Dummy variable for gender (Reference: Man)
[c] Dummy variable for the discipline of education (Reference: Environment)
[d] Shapiro Wilk Test p = .897, Breusch Pagan Test p = .535

To validate the assumed normality, linearity, and homoscedasticity for the linear regression model, the probability plots of regression residuals and scattered plots of predicted values with standardized residual values were visually assessed (Pearson et al., 2010; Slimak & Dietz, 2006). Additionally, post hoc Shapiro Wilk Tests of the residuals (i.e., $p > .05$ if residuals are normally distributed) and Breusch Pagan Tests for residuals were performed (i.e., $p > .05$ for homoscedasticity) (Breusch & Pagan, 1979; Norman, 2010). To overcome overfitting and model adequacy concerns, we calculated the adjusted R^2 values as well as the PRESS statistics, which should be lower than the model's total sum of squares (Allen, 1971). All regression models upheld statistical assumptions, all VIF values were lower than three, and no multi-collinearity issues appeared (Mumbi & Watanabe, 2020; Slimak & Dietz, 2006).

To reveal statistically significant mean differences based on gender and sector, we conducted the Student's *t*–test and an ANOVA, respectively. For the t-test on gender, we tested differences in three water risk perception factors (as dependent variables) *Nature of Risk, Knowledge (self-assessed, general issues, and expert), Drivers of water issues (macro, micro), Water Attitudes (Scope, biophysical controllability, social controllability, concern, confidence) Impacts (reputational, financial, sustainability), Values (sustaino-centric, economic benefits, egocentric, technological optimism), Cultural Importance, Trust (private sector, government, civil society), Exposure*, and *Degree of Water Risk Integration*. Results reveal that only two factors had statistically significant mean differences, i.e., ($p < .05$). Women (M = 2.69, SD = 1.32) reported significantly lower agreement levels with *Value of Technological Optimism* than men (M = 4.00, SD = 1.13), $t(23) = -2.66$, $p = .014$, Cohen's d = 1.06. Moreover, women (M = 4.79, SD = 1.01) reported significantly lower levels of *Confidence* than men (M = 5.54, SD = 0.72), $t(22) = -2.09$, $p = .048$, Cohen's d = 0.85. Shapiro Wilk Test for normality of residuals ($p > 0.05$) and Levene Test for homogeneity of variance ($p > 0.05$) revealed no issues.

We employed a one-way ANOVA to test sector-based differences for some variables of interest like the *Water risk ratings*, *Impacts (reputational, financial, sustainability), Drivers of* *water issues (macro, micro), Trust (private sector, government, civil society),* and *Degree of Water Risk Integration*. Results presented in Table 4.7 demonstrate a statistically significant influence of the sector on the *Macro drivers of water issues,* $F(7, 16) = 3.97$, $p = .011$, *Reputational Impact of water issues,* $F(7, 16) = 2.99$, $p = .033$, *Sustainability Impact of water issues,* $F(7, 17) = 5.85$, $p = .001$, *Degree of Water Risk Integration in organizational decision-making,* $F(7, 17) = 3.39$, $p = .019$. Effect sizes (eta squared) in all cases were > 0.14. We performed the Shapiro-Wilk Test for normality, and sector differences were further explored in the interviews.

Table 4.7: Significant sector based group means and standard deviation

Dependent Variables	Sector based Groups	N	*M*	*SD*
Drivers of Water Issues (Macro)	Agribusiness	5	4.13	0.38
	Chemical manufacturing	2	3.50	1.65
	Consulting, (Research and NGO)	3	4.44	0.84
	Financial Sector	6	6.17	0.62
	Food Manufacturing and Processing	2	4.83	1.18
	Mining and milling	2	4.33	0.94
	Power Production	2	4.67	0.94
	Transportation Equipment/ Automotive Manufacturing	2	5.17	0.71
Reputational Impact	Agribusiness	5	4.50	0.71
	Chemical manufacturing	2	5.50	0.71
	Consulting, (Research and NGO)	2	3.00	1.41
	Financial Sector	7	5.79	0.99
	Food Manufacturing and Processing	2	4.75	1.06
	Mining and milling	2	5.00	0.00
	Power Production	2	5.00	1.41
	Transportation Equipment/ Automotive Manufacturing	2	6.50	0.71
Sustainability Impact	Agribusiness	5	4.00	1.15
	Chemical manufacturing	2	4.17	0.24
	Consulting, (Research and NGO)	3	2.67	0.67
	Financial Sector	7	5.81	0.86
	Food Manufacturing and Processing	2	4.83	1.18
	Mining and milling	2	3.83	1.18
	Power Production	2	4.33	0.47
	Transportation Equipment/ Automotive Manufacturing	2	6.67	0.47
Degree of Water Risk Integration in organizational decision-making	Agribusiness	5	5.40	0.89
	Chemical manufacturing	2	6.00	0.00
	Consulting, (Research and NGO)	3	5.00	1.00
	Financial Sector	7	4.71	1.38
	Food Manufacturing and Processing	2	2.50	0.71
	Mining and milling	2	7.00	0.00
	Power Production	2	5.00	2.83
	Transportation Equipment/ Automotive Manufacturing	2	2.50	0.71

4.5 Stage 2 Interview: Guide Preparation, Thematic Analysis, and Results

After statistically analyzing the survey data, findings were categorized as new, expected, or unexpected based on the literature. New and unexpected findings were used to develop the follow-up one-on-one interview guide, enabling further exploration and interpretation of the survey's findings.

4.5.1. Interview guide design and procedure

The interview guide (Appendix 4.E) included two questions aligned with RQ1, which was intended to explore the conceptualization of different water risks as well as gain explanatory insights on the mean risk ratings found in the survey. Aligned with RQ2, five questions were based on explaining interesting/unexpected risk perception factors or relationships found in the survey including *Value of technological optimism* and *DV 1, Trust in private sector/industry* and *DV 2* and *Knowledge_Self* and *DV 3*. Moreover, we also discussed questions on exposure to water issues, proximity bias, role of trust, sector-specific insights, and gender-based differences.

All interviews were administered online on MS Teams following a standard interview protocol for consistency (Creswell & Creswell, 2018). One research team member conducted all interviews to eliminate inter-interviewee bias. The questions were asked sequentially, but given the semi-structured nature, there was flexibility for change, e.g., additional prompt questions for elaboration if a new concept emerged. All interviews were audio recorded with 817 minutes of data for 22 participants. On average, interview data of 37 minutes per participant were collected, highlighting sufficient details and in-depth engagement (Money, 2014 b). All interview audio files were transcribed into separate documents with timestamps, anonymized for confidentiality, and reviewed for errors.

4.5.2. Qualitative coding and thematic analysis

We employed QSR NVivo 12 to code and analyze the interview data. We followed the coding and analysis procedures by Braun & Clarke (2006) for a priori *theory-driven coding* apt for explanatory sequential mixed methods. Starting with Pass 1 Open Coding, 22 transcripts were reviewed line-by-line and assigned codes or labels to capture the confirmatory or emerging ideas. The codes were named and defined based on the underlying concept (predetermined or expected codes) aligned with our theoretical framework and Stage 1 findings. Data/extracts could be coded under multiple codes to address the concept from various theoretical angles as necessary (codes of conceptual interest) (Braun & Clarke, 2006; Creswell & Creswell, 2018). For Pass 2 Coding, Pass 1 codes were refined and condensed further, and some open-ended codes were retained for further conceptual organization.

For thematic analysis (Axial), Pass 2 codes were reviewed to identify conceptual patterns, and related codes (and their data extracts) were collated into higher-level themes. The themes were refined, defined, and named based on their underlying core concepts (Braun & Clarke, 2006). For the final analysis (Selective), the themes were connected to the theoretical framework and hypotheses (factors of risk perception) and further collated into relevant sub-categories and main categories (Mooney et al., 2020). The broader level of analysis was based on the main concepts drawn from the data, relationships between concepts, and aligned with (answering) the research questions (Mooney et al., 2020). 179 Pass 2 Codes (post phase 2 refining) were collated into 69 Themes under 20 Sub-categories that were further collated under 7 Main Categories. One research team member coded the data, and other team members independently cross-checked the codes and themes (Creswell & Creswell, 2018). The analysis of water risk management strategies and next steps will be part of future work and research questions.

Appendix 4.C illustrates the thematic analysis for a single sub-category (Types of Water Risks) under the Nature of Risk category, along with the codes, the number of files (participants) that were coded under the theme, and an example of data extraction from the transcript.

4.5.3. Stage 2 qualitative results

Key findings from the thematic analysis are reported below, and the themes are italicized. A conceptual map was also developed to visually depict the resulting categories, sub-categories, themes, and sub-themes (Appendix 4.D).

4.5.3.1. Nature of water risk

The introduction questions were exploratory and provided the participants' baseline conceptualization of water risks. Analyses of the responses revealed themes around the different types of water risks, the degree of water risk integration in organizational decision-making, drivers or barriers of water risk integration, prioritization, and management. The first theme of the discussion focused on different *types of water issues and risks*, where there was a conceptual distinction not only between biophysical aspects and social aspects of water risks but also among biophysical aspects of *water quantity* and *quality*. Moreover, temporal importance for water quantity as well as quality (via legacy contamination), location, i.e., spatial variability of water risks across sub-watersheds, and interconnection between quality and quantity emerged as important sub-themes. Nonetheless, the systems-based interconnection between water quality and availability, i.e., quality-driven scarcity, was discussed only by 32% of the participants.

Social water risks also emerged to be multi-dimensional, where themes of *conflict risks, regulatory risks*, and the *perceived impact of water-intensive sectors* (e.g., water bottlers, agriculture, food processing, etc.,) were discussed. Within social conflict risks, sub-themes like barriers to access to water for social, economic, environmental, or drinking water uses, competition among water users, nexus of water and health, concerns around legacy water-related inequity issues in First Nations communities, as well as negative media attention and public concern emerged. Confirming the factor analyses, participants articulated water risks as a multi-dimensional concept with biophysical and social facets further reflecting the nuances of public perception, temporal uncertainty, spatial variability, and sector-specific impacts that have implications for water risk evaluation. Among different risks, water quality is discussed more overtly by participants (91%). Source type risk has been conceptualized as the sensitivity of groundwater to contamination, aquifer productivity, competing demand, and access to the Great Lakes.

The discussion on the *extent or degree of integration of different water risks* revealed two key themes. 50% of the participants mentioned *significant consideration of water risks and their impacts* at the individual organizational level. However, 50% of the participants (mainly from the financial sector) mentioned that water risks were integrated but to a *limited extent at the organizational level*. Participants revealed six potential *water risk integration, prioritization, and management drivers*. Firstly, *organizational-level drivers* focused on alleviating risk to business operations, the impetus of investors, and the individual organization's values and commitment to water-related sustainability targets, goals, assessments, and reporting. A connected yet distinct theme was of *reputational drivers,* where water risk integration is driven to avoid negative reputational impacts due to media, public perception, or water user conflicts, as well as to meet stakeholder expectations to maintain the social license to operate. From an institutional perspective, *government regulations* and compliance requirements were also identified as drivers along with *economic and financial drivers* like increasing costs and financial impacts of water issues. Finally, *biophysical drivers*, such as local water scarcity, contamination, or extreme climate events, followed by drivers related *to individual concern and motivation* were also identified.

Three key themes emerged *when barriers to water risk integration* were discussed stemming from the limited extent of water risk integration. Firstly, a *lack of systems understanding about water* was identified, where participants noted a lack of awareness about the interconnected nexus of water risks, cumulative impacts, efficiency of water use, and articulation of the business case of sustainable water use. Secondly, *siloed business-as-usual* *approaches and inertia* was identified, where participants highlighted the inertia in organizations that tend to focus on the financial bottom line and metrics. Under the inertia theme, institutional issues like lack of transparent, integrated, and attuned or systems-based regulations that drive action and support sustainability-based transitions were highlighted. Moreover, the perception of water abundance in Ontario is discussed as a driver of the status quo. Finally, participants noted that *water tends to be a lower priority/ focus* than carbon and climate change.

4.5.3.2. Different water risk ratings and their reasons

Aligned with the survey, 73% of the participants discussed direct scarcity or water quantity risks being high in Ontario. Nonetheless, 77% of the participants reflected on *water risks other than quantity,* revealing four themes. Firstly, there is a *perception of water abundance* in Ontario, where 41% of the participants mentioned water quantity as relatively secure. Nonetheless, the nuances of variability due to location (proximity to the Great Lakes) or sector-specific differences in water use, were articulated in tandem. Secondly, participants also noted *water quality risks,* including the impact of wastewater contamination, to be equally high and prevalent across Ontario. Thirdly, 32% of the participants considered *social water risks* to be more relevant and challenging for the context of Ontario. Lastly, participants also noted a high *risk of regulatory uncertainty* due to evolving water-related regulations as well as increasing timelines, scrutiny, and level of detail required for water-related permit approvals.

Discussion on the reasons for the assigned water risk ratings revealed three key themes. Firstly, *cognitive knowledge and awareness-based factors* were identified by 86% of the participants, where awareness, knowledge of financial impacts of water issues, perceived impact of certain sectors on water resources, water availability of specific locations, the role of timing, demand as well as the influence of information on issues outside of Ontario (e.g., in the United States), were identified as reasons for higher risk perception and ratings. Moreover, the gap in knowledge and understanding about specific water issues, e.g., emerging contaminants and direct experience of an adverse event (instead of likelihood) were also identified as cognitive factors leading to high-risk perception. Secondly, *internal attitude factors* related to water (controllability, importance, or concern) were identified, where issues of competing water user groups and interests, as well as increasing unpredictability and controllability of water issues beyond one's sphere of influence/control are noted to shape the perception of water risks. Moreover, given the criticality of water, there is higher sensitivity regarding water availability and, hence, higher risk perception. Thirdly, the participants also attributed the reasons for risk ratings to *Trust-based factors,* where media coverage on water issues inside or outside Ontario can spur concern, distrust, and impact risk perception. Moreover, past reactive regulations related to water may create distrust, concern, and higher perceived risk that may be different from actual risk.

4.5.3.3. Explanation of risk perception factors and risk ratings based on survey findings

Firstly, from the survey's analyses (Table 4.2), the direct scarcity water risk rating increased with technological optimism. We wanted to investigate this possible value-behavior disconnect since optimism in technology did not alleviate the perception of direct scarcity (quantity) risk. 82% of the participants mentioned the *cognitive aspects of limits to technology* related to water quantity risks. Under this broad theme, participants identified limitations of relying only on technology due to complexities of timing, demand, biophysical barriers like resource availability, economic barriers, and risks of novel technology that may not be tried and tested. Participants noted that gaps in knowledge and understanding about water quantity issues persist, i.e., scientific uncertainty due to which technology cannot fully mitigate the risk, leading to higher risk perception/ ratings. Moreover, the availability of technology is one aspect, but the lack of incentives and regulatory signals to adopt technology is another driver of risk perception. Participants also noted that there may be higher optimism and the possibility of technology to address water quality issues. Still, in the case of water scarcity or reduced flows, technology may have more barriers. Moreover, increased awareness/exposure to competing information, data, and technology about an issue may also lead to an increased risk perception.

Secondly, the survey's findings (Table 4.3) revealed that the Indirect Water Scarcity Risk Rating increases with the level of Trust of an individual in the private sector (to self-regulate and manage water risks). Since our participants were from the private corporate or financial sector, we wanted to understand why a higher trust in the private sector does not alleviate perception and rating for indirect scarcity risk, i.e., water quality and source type sensitivity. 68% of the participants noted a distinction between trust in one's organization, suppliers, or sphere of influence and trust in the broader industry beyond one's sphere of control or influence. Therefore, thematically, the results suggest that trust may exist in one's own organization and sphere of influence, but *trust may not be generalized to the entire industry*. So, while there is trust to an extent in one's organization to self-regulate, this trust is not extended to all industries without adequate checks and balances. Secondly, 73% of the participants discussed an affective disconnect where the presence of *trust does not alleviate the issue.* While there may be trust and action by the private sector, the indirect water scarcity or quality issues remain a higher priority. Various sub-themes emerged from this aspect, where the role and reliance on government regulations and laws to drive action and compliance in the private sector was highlighted to alleviate risk. Moreover, the self-serving and profit-centric interests of the private sector and the implications of other organizations or sectors that may not be sufficiently self-regulating, may still drive risk. Finally, the complex interaction of information and trust is articulated, where excessive information and negative media coverage tend to increase perceived risk and lead to tacit distrust.

Thirdly, from the survey (Table 4.4), we found that Social Water Risk rating increases as one's own knowledge and professional experience related to water increases. Three key themes emerged from the discussion that explain an increased focus on the social aspects with experience. 82% of the participants mentioned the role of *external drivers of social aspects* like stakeholder awareness, expectations, reputation, regulations, sector-specific impacts, and media, which become more evident with experience. Specific sectors are more prone to social water risks due to the nature of water taking, controversies, and media attention on these sectors compared to biophysical risks. Moreover, certain social aspects like stakeholder engagement and consultation are part of regulations, and broadly, there is more awareness regarding social aspects like the social license to operate. 68% of the participants also highlight that at an individual level, *the connection, awareness, and notions of controllability about social aspects of water risk* increase with one's experiential knowledge and awareness. Finally, 41% of the participants also noted that *tangible biophysical and economic aspects tied with social aspects* might drive the emphasis on social water risks, where biophysical and social risks are increasingly understood to be connected and equally important.

4.5.3.4. Affective, spatial and socio-cultural demographic risk perception factors

Participants also provided insights on other theoretically relevant factors like the role of previous exposure, gender, proximity bias, and trust in various institutions and their influence on water risk evaluation. Firstly, the discussion on *previous exposure to water issues* and its impact on overall confidence, concern, and risk perception revealed four key themes. 77% of the participants highlighted that *direct exposure to water issues increases water awareness, value,* *and importance*. Thus, any exposure to or experience with local water issues like scarcity or quality issues, a first-hand realization of climate change impacts, as well as increasing competition and demand by users could raise awareness and hence relevance and risk perception of water. Participants also noted that *professional experience and disciplinary knowledge related to water increase risk perception.* The disciplinary understanding gained in educational training and the awareness and experiences gained in a professional setting can make an individual more attuned to water issues, increasing risk perception and concern. Another theme addressed the *exposure to non-local water issues that increase the value and confidence of water quality and quantity in Ontario*. In this case, participants articulated that experiences or information about water issues in other regions or countries may also increase the value and relative confidence in water security in Ontario. Finally, the theme of *impact of non-water issues and experiences* highlights that some non-water issues, like inflation, food and fuel prices, etc., may garner higher attention than water. Moreover, negative experiences like regulatory stringency or enforcement may generate a defensive reaction.

Secondly, upon exploring *gender and risk perception* with a subset of participants who identified as women, two broad themes emerged. The first theme highlighted that *women tend to have higher empathy, awareness, and vulnerability to impacts*, hence are more concerned about access to the environment and water. Due to social norms historically, women tend to be more empathetic, aware, and considered as nurturers of families and, broadly, the environment. Moreover, women are increasingly in more front-and-center decision-making roles related to sustainability and water, using collaborative approaches instead of relying on technology alone. Marginalized groups, including women, tend to be more vulnerable to adverse impacts of environmental issues, and this may translate to lesser confidence in freshwater availability, higher concern, and perceived risk. Participants also mentioned that water risk perception may also be influenced by other considerations like the intergenerational concern of people with families or people with professional roles related to the environment.

Thirdly, the discussion on *proximity bias for water issues and risk perception, i.e.,* potential discounting of water risks in one's sub-watershed, revealed three themes. The first theme focused on the *perception of more control over local water issues,* where more engagement with local water issues and proximity to the Great Lakes may lead to the perception of higher control over local issues and reduce risk perception. Moreover, from a cognitive perspective, participants discussed how there might be a general *lack of knowledge about local water issues* and *higher knowledge of the impact of non-local water issues* that may increase concern/ perceived risk outside one's region. The media and public attention on the broader Great Lakes issues like nutrients, water diversion, etc., is more than local water issues. Hence the concern for local water issues may be lowered.

Finally, the survey revealed (Section 4.4.1) that there was, on average, higher trust in civil society organizations and government to assess and manage water risks. In the discussion, 82% of the participants attributed lower trust in the private sector to its profit-centric and *self-serving interests.* 77% of the participants perceived *government and civil society organizations public-centric and neutral institutions*, working for public interests without profit motives, leading to higher trust. Moreover, the experiential theme of *past demonstration, systemic tendencies, and history of water management* also emerged. Participants noted that government and civil society organizations may have demonstrated expertise, collaboration, and transparency, along with considering cumulative impacts leading to higher trust. Nonetheless, trust may taper down due to past negative experiences as well as knowledge/ understanding of the profit-centric motives and self-interests of the private sector. Finally, a *lack of transparency in the private sector may lead to higher trust in non-private actors*. Participants also highlighted the role of media, where the nature of messaging may create distrust in the private sector.

4.5.3.5. Sector-specific insights on water risk ratings

Contrary to the hypothesis, $\mathbf{H14_{Sector}}$, there were no significant sector-based differences for the three water risk ratings from the statistical analysis. However, from the interviews, discussion regarding *sector-specific differences in water risk priorities* revealed nuances of this relationship. Firstly, 41% of the participants noted that there tend to be some sector-based differences in the ranking or prioritization of different water risks due to variability in water use across sectors in terms of water quantity and quality. Nonetheless, they elaborated high heterogeneity of water use even within sub-sectors that other sectors or industries may not completely understand. 32% of the participants emphasized that the location of water use is more important than the sector, where the *location may be more relevant in the water risk ratings* than the sector. Moreover, participants also noted that water risk ratings are contingent on the sector and the location, further highlighting the complexity of sector-based influences on risk ratings.

Discussing different impacts as drivers of how various water risks are rated, prioritized, or managed across various sectors revealed three themes. Firstly, participants noted the *influence and relevance of the financial impact* of risks as the most important (compared to sustainability or reputational impacts) in driving differences in water risk priorities across different sectors. Thus, the extent of the negative financial impact of water issues may be the most critical factor leading to different water risk priorities/ratings across sectors. Secondly, the participants noted that *regulations and compliance may drive a sector's water risk priorities,* especially if the sector (e.g., chemical manufacturing, food and beverage, mining, etc.) is more regulated than others. Finally, *reputational, social, and sustainability impacts may drive sector-based differences,* where the extent of negative impacts on sustainability and reputation rather than just financial implications may lead to differences in prioritization of risks .

4.6 Discussion of results

Our study's findings provide several interesting insights that contribute to the literature on water risk perception, assessment, and management in the CFS. Our study's novelty and contribution to knowledge is the empirical examination and explanation of the complex construct of water risk perception and its relationship with risk evaluation by applying the interdisciplinary Risk Theory to the water domain in the CFS, which has not yet been addressed in the literature. The application of explanatory sequential mixed methods is a major strength of our study that led to enhanced scientific rigor, qualitative depth, and nuanced theoretical understanding of complex constructs, such as water risk perception and evaluation.

The following sub-sections discuss the results with regard to our study's main objectives: firstly, to empirically examine the factors underpinning water risk perception and priorities of practitioners and decision-makers in the CFS in Ontario. Secondly, to explain the relationship of water risk perception with risk evaluation. We discuss the results from both stages based on the study's hypotheses and the current literature. Finally, we discuss the study's contribution to knowledge and practice along with the limitations and recommendations for future work.

4.6.1. Factors underpinning water risk perception of the CFS

Addressing RQ1, our study found technical characteristics of risk as well as more individual-centric cognitive, affective, socio-cultural, and spatial factors that underpin water risk perception of corporate and financial practitioners, analysts, and decision-makers and influence water risk evaluation. From the perspective of the risk object, i.e., water risks, the factor analysis of the ratings of different water risks (Section 4.4.2) and interviews revealed a conceptual distinction between biophysical and social water risks. This distinction was interesting because it confirmed the multidimensionality of water risks as a concept and in decision-making with both biophysical and social dimensions. Thus, supporting $\mathbf{H1}_{\textbf{Nature of Risk}}$, heterogeneity among and within different biophysical and social water risks was confirmed. However, in contrast to Money (2014a) who generated their results from corporate reports, our study used a mixed-methods approach including a survey and follow-up interviews of practitioners and decision-makers that are able to assess individual experiences. Moreover, in contrast to Mumbi and Watanabe (2020), our study focused on Ontario – a seemingly water abundant region, where contemporary water issues emerge locally. Hence, our study broadened the literature through the examination of water risk perception of individual practitioners and decision-makers in different water-using sectors and by using a granular lens on a seemingly water-abundant region as the field of study.

Aligned with the study's theoretical framework, we find that the selection, interpretation, and prioritization of various water risks or framing of water risks is contingent on technical aspects of the risk object but also on the individual's expertise, knowledge, or exposure to issues, internal values and attitudes related to water as well as trust. Our results suggest that the latter is valid for practitioners (Dobbie & Brown, 2014; Mumbi & Watanabe, 2020), analysts, and decision makers in the CFS in Ontario (Klinke & Renn, 2012, 2021). Interestingly, from the interviews, the reasons for the assigned water risk ratings were attributed to cognitive factors like awareness, direct experience with the issue, perceived or known impact of other sectors on water resources, and knowledge of the extent of impacts. Moreover, affective aspects like values and attitudes related to water, i.e., controllability, intrinsic connection to water, perceived criticality, nuances of location, and trust related to media, stakeholders, and perceived sufficiency of regulations, were also articulated. Hence, the results address our first objective by suggesting that a nexus of cognitive and affective factors underpin water risk perception and priorities of practitioners in the CFS, where awareness or knowledge (tacit or acquired), attitudes, and trust (in different institutions to manage water risks) shaped water risk perception.

While sector-based differences in the three water risk ratings were not statistically significant, interviews revealed additional insights. Heterogeneity among sub-sectors, nuances of location, and risk impacts may be difficult to capture using quantitative methods alone. Nonetheless, in line with Dobbie and Brown (2014) and Klinke and Renn (2019), the extent of integration of water risks in decision-making were found statistically to vary across sectors (Table 4.7). From the interviews we found that the extent of water risk integration in decision-making was contingent on individual organizations rather than sector-wide generalization. This emphasizes the need for surveys and interviews at the individual level to assess water risk perception. From the discussion on the drivers for integration, we found a dominance of institutional and stakeholder-related drivers like reputation, organizational risks (operational institutional drivers related to stakeholder risks, investors, etc.), regulations, and economic drivers rather than pure biophysical drivers of local water security in line with the water governance study by Alvarado-Revilla and de Loë (2022).

Additionally, the financial sector tends to be more critical of the limited extent of water risk integration across all sectors. Barriers to water risk integration were related to cognitive gaps in systems understanding of water but also the inertia of business-as-usual approaches. This inertia was attributed to a lack of clarity regarding the business case or economics of sustainable water management, a lack of integrated and attuned regulations, and path dependency on financial metrics and the bottom line. Also, evidence of "carbon tunnel-vision" emerged, where participants articulated the myopic and competing focus on carbon emissions, energy, and climate that overlooks the connection between water, carbon, and climate (Konietzko, 2022). Based on these results, we suggest that transdisciplinary collaboration, training, and knowledge sharing is needed to foster proactive systems-based approaches for assessing and managing different water risks.

Other interesting risk perception factors in our factor analyses include participants' *Concern* about water. Supporting **H4$_{\textbf{Concern}}$**, results (Section 4.4.2) revealed that factors like the urgency of water issues, perceived inequity of issues, and non-substitutability of risks by economic benefits contribute to overall concern related to water issues. Hence, it seems that the participants preferred a strong sustainability approach to water (Dietz & Neumayer, 2007). The construct of Confidence (in abundance and sufficiency of water resources in Ontario) was also interesting. Supporting **H13$_{\textbf{Cultural Importance}}$**, the cultural importance of water was a significant explanatory variable negatively related to confidence (Table 4.6), where higher cultural importance of water tends to decrease overall confidence. This was expected as one's shared cultural beliefs and attitudes connect to higher sustaino-centric values emphasizing protective behavior and preparedness related to water conservation intra and intergenerationally instead of confidence, aligned with Dupont et al. (2014) and Siegrist (2019). However, contrary to **H5$_{\textbf{Exposure}}$**, exposure to water issues increased confidence in freshwater abundance. Theoretically, an increased risk perception, concern, protective behaviour, and decreased confidence was expected (Siegrist, 2021; Thistlethwaite et al., 2018). Nonetheless, the interviews revealed that previous exposure to water issues can evoke complex reactions that are contingent on whether the experience was direct or indirect through information about water issues that affected others. Moreover, non-local water issues may increase risk perception and concern but also tend to increase the value and confidence in the relative availability of water resources in Ontario. This result explains the perception of Ontario's relative abundance of water.

Gender was an interesting demographic variable, in which statistically significant mean differences were found using a *t*–test for technological optimism and overall confidence. From the interviews, women were more concerned about risks to human health, environment, intergenerational well-being, and safety due to the social gender norms of being entrusted with nurturing families. While studies by Slovic (1999) and Dupont et al. (2014) found similar results for perception of other risk domains and Mumbi and Watanabe (2020) report no significant effect, our study confirms the role of gender in the water domain and the specific sample of the CFS in Ontario. Marginalized groups, including women, tend to be more vulnerable to the adverse impacts of risks. Thus, similar to risk domains (Slovic, 1999), women tend to be more sensitized to water risks, explaining the lower confidence in freshwater abundance, higher concern about water issues and their intergenerational impacts, and lower optimism in technology as the sole solution.

4.6.2. Relationship between water risk perception and risk evaluation

Addressing RQ 2, we developed multiple linear regression models and found statistically significant relationships between risk perception factors and water risk evaluation. Water risk perception of analysts, practitioners, and decision-makers in the CFS is highly nuanced, and the underlying explanatory factors/models vary with the type of water risk (Dobbie & Brown, 2014). Interestingly, factors like knowledge, values, attitudes, and trust were important to different extents for the three types of water risks. As reported in Tables 4.2, 4.3, and 4.4, the attitudinal factor of controllability, aligned with the Theory of Planned Behavior and connected to familiarity and dread dimension, was a common significant explanatory variable in all three water risks (Dobbie & Brown, 2014; Weber et al., 2002). Thus, supporting **H3$_{\textbf{Attitude Controllability}}$**, higher perceived controllability of biophysical water issues was associated with a lower rating of water risks. Hence, the study clarified the role of the controllability factor in the Theory of Planned Behavior specifically applied to water risk evaluation.

For the direct scarcity risk rating (Table 4.2), supporting $\mathbf{H6}_{\textbf{Knowledge}}$, Knowledge, specifically in experts about water issues, impacts, risks, and likelihood, was positively associated with direct scarcity risk rating. Hence, the study confirmed the results for water risks in line with the literature on the impact of knowledge on the perception of broader environmental risks (McDaniels et al., 1997; Slimak & Dietz, 2006; Siegrist & Árvai, 2020; Weber, 2001). However, one's own knowledge was not a statistically significant factor but two out of the four values were relevant, where supporting $\mathbf{H8}_{\textbf{Egocentric Value}}$, a negative association between egocentric values and the risk rating was found, where the higher egocentric values of an individual, the lower the risk rating (Bouman et al., 2018). Contrary to $\mathbf{H10}_{\textbf{Technological Optimism Value}}$, higher technological optimism did not alleviate risk but increased the risk ratings. While technological optimism as a significant explanatory variable aligns with the Value-Belief-Norm Theory and Theory of Reasoned Action (Slimak & Dietz, 2006; Weber et al., 2002), the unexpected direction alludes to a possible disconnect between one's values and behavior (captured in risk ratings).

From the interviews, we found a tacit understanding of the limits of technology, i.e., biophysical limitations of resources as input and lack of economic and regulatory signals for adoption. The remaining factors supported our hypotheses, i.e., $\mathbf{H2}_{\textbf{Attitude Scope}}$, the higher the perceived extent or scope, i.e., the area and people impacted by the specific water issue, the higher the direct scarcity risk rating. Moreover, supporting $\mathbf{H12}_{\textbf{Gender}}$, women tended to rate direct scarcity risks higher than men, alluding to gender-based differences in the rating of specific water risks. Hence, our study confirmed that risk perception in the domain of direct water scarcity risk is shaped by individual experiences and subjective factors (Sjöberg, 2002; Slimak & Dietz, 2006).

For the indirect water scarcity risk rating (Table 4.3), based on the survey's findings, in contrast to Siegrist and Árvai (2020), we found no significant influence of one's own or expert knowledge/experience on the risk rating, alluding to the dominance of affective factors like values and trust in the CFS practitioners. Supporting $\mathbf{H7}_{\textbf{Sustainocentric Value}}$, we found that higher biospheric and altruistic values tend to increase risk ratings as well as $\mathbf{H9}_{\textbf{Economic Benefits Value}}$, where economic benefits centric values were positively associated with indirect scarcity risk, unearthing the connection between financial materiality and indirect scarcity risks. **H8$_{\textbf{Egocentric Value}}$**, was also supported where the higher egocentric values, the lower the indirect scarcity risk ratings. Interestingly, as compared to direct scarcity, a more diverse set of values explains indirect scarcity risk ratings, but technological optimism was not an explanatory factor. Nonetheless, the discipline of education was a significant explanatory factor, where participants with an educational background in Arts (including Economics, Business, Finance, etc.,) tend to rate indirect scarcity risks higher than participants with a background in Environment, Natural Sciences, and Other disciplines. Thus, alluding to the role of educational discipline behind differences in risk perception of water quality and source type risks (Dobbie & Brown, 2014). From the interviews, water quality risk is more important from a financial materiality (impact) perspective, especially in the financial sector. Overall, these results suggest a strong influence of affective and individual factors on water risk evaluation. Hence, the risk perception might be highly variable and different from biophysical parameters of water scarcity.

Finally, trust in the private sector/industry was a significant explanatory factor that tended to increase the indirect scarcity risk rating. Given that the sample is predominantly from the private sector, based on the literature, we expected value alignment and risk alleviation based on trust (Mumbi & Watanabe, 2020; Siegrist, 2021). Nonetheless, from the interviews, trust emerged as a nuanced construct operating in different spheres. Higher trust is placed within one's immediate sphere of influence or interaction, i.e., one's own organization, suppliers, etc., but not generalized across the sector or industry resulting in higher perceived risk. Thus, trust is limited to one's immediate sphere and it does not alleviate risk due to the perceived impact of all sectors. Moreover, trust was an explanatory factor in indirect scarcity risk but not in direct scarcity risk, where knowledge was important, confirming reliance on either knowledge or trust for water risk evaluation (Siegrist, 2021).

For the social water risk rating, which was expected to be more contingent on affective values, none of the four values were significant explanatory factors (Table 4.4). On the other hand, supporting **H6$_{\textbf{Knowledge}}$**, i.e., one's self-assessed knowledge, professional experience, and knowledge of experts increases the social water risk ratings. This finding is in line with studies on other types of risks that found a correlation between self-assessed knowledge and risk perception (McDaniels et al., 1997; Slimak & Dietz, 2006; Weber, 2001). Thus, as the awareness and professional experience of the practitioner increases, there is a higher emphasis on social water risks. Moreover, supporting **H11$_{\textbf{Trust}}$**, higher trust in the government to manage water risk by regulations, tends to decrease social water risk ratings. Thus, higher reliance on the government to manage social water risks (competence-based trust) is evident (Siegrist, 2021). Interestingly, knowledge and trust explain the evaluation of social water risks rather than intrinsic affective values. In the interviews, participants explained that cognitive and external factors like stakeholder awareness, expectations, nuances of power, reputation, regulations, sector-specific impacts, and the role of media become more evident with professional experience. Thus, the study reveals a novel insight, where compared to biophysical risks, social water risks were more experiential and the awareness of complexities of social water risks increases risk perception and evaluation. Furthermore, these findings on social water risk perception in the CFS confirm and add to the findings by Alvarado-Revilla and de Loë (2022) who studied external factors influencing water quantity governance in Ontario.

Participants also provided insights on the survey's findings on proximity bias and trust and their interaction with concern, confidence, water risk perception, and evaluation. Supporting **H15$_{\textbf{Location}}$**, evidence for a proximity bias was found, where, on average, overtly stated concern for water issues in Ontario was higher than one's own sub-watershed (Krewski et al., 2008). The interviews explained that a higher perceived locus of control and engagement in one's location (sub-watershed) tends to reduce concern and perceived risk that may be disconnected from actual biophysical water risks. Interestingly, discounting of water risks was also related to cognitive aspects of excessive information about non-local issues or lack of information about local issues, where non-local issues may take cognitive precedence in risk ratings. Since there is high media coverage regarding water issues (Sandhu et al., 2023), this result on proximity bias and higher water risk perception for non-local issues is explained. This finding also adds to the literature about the role of media in risk perception and evaluation that has explored other risk domains (Flynn, 1998; Kasperson et al., 2022; Slovic, 1999) by including the water domain in the CFS.

For trust in different institutions, results revealed that, on average, higher trust is placed in government and civil society organizations. Among private sector (non-state) practitioners, even given their critique on the design and reactive nature of water regulations, public-centric institutions are still predominantly relied upon to provide unbiased oversight, checks and balances, and drive compliance and, thus alleviate water risks. Trust in the industry/ private sector to manage water risks, as discussed before, was limited to one's sphere of influence and not generalized to the entire industry primarily because of the awareness of the self-serving profit-based interests of the private sector more broadly. Thus, aligned with the regression results for trust (Table 4.5), cognitive factors like knowledge, awareness of impacts, as well as the role of media and messaging, and lack of transparency reduce trust in the industry, even among practitioners, thus increasing risk perception. Our study's results for trust and water risk perception is in line with the review by Siegrist (2019) covering other risk domains, where our study adds to the literature by examining the under-explored water domain. The role of media was a consistent theme for driving water risk perception and proximity bias and emerged as an influential institution that influences cognitive factors and affect due to its impact on trust (Kasperson et al., 2022; Mooney et al., 2020; Slovic, 1999).

4.6.3. Study's novel contributions to knowledge and practice

The study makes an original contribution to knowledge by systematically examining and explaining the water risk perception of CFS practitioners and decision-makers and the relationship with water risk evaluation using explanatory sequential mixed methods, addressing a major gap in the current literature (Dudley et al., 2022; Di Baldassarre et al., 2021; Mumbi & Watanabe, 2020; Renn et al., 2022; Siegrist, 2021; Rangecroft et al., 2021, 2022). Firstly, our study expanded and empirically tested the novel interdisciplinary framework of Risk Theory for the water domain with a first-of-a-kind sample of non-state CFS practitioners and decision-makers at the regional scale (Dudley et al., 2022; Klinke & Renn, 2021). The study's novel findings highlight the importance of integrating psychometric, cultural, and relational theories of risk to unearth contextual and multidimensional complexities of risk perception in the assessment and management of water risks. The study concludes that for practically sound and comprehensive water risk management, in addition to quantifying water risks, it is equally important to integrate diverse perspectives of influential actors like CFS who are undertaking water-related decision-making (Christ & Burritt, 2018; Klinke & Renn, 2021). The study's findings have key implications in the fields of risk analysis and governance, sustainable water management, and decision-making. For instance, the interviews revealed that water quality risk tends to be important in the financial sector from a financial materiality (impact) perspective. Moreover, water risk integration in more regulated sectors, e.g., chemical manufacturing, food and beverage, mining, etc., tends to be driven by regulations and compliance. Thus, these diverse sector-specific nuances build a case for an attuned water risk management framework rather than a one-size-fits-all framework based only on biophysical risk data.

Secondly, the study finds that the water risk perception of CFS experts, i.e., analysts, practitioners, and decision-makers, was highly nuanced and shaped by cognitive, affective, socio-cultural, spatial, and trust-based factors that influence the evaluation of different water risks (Dobbie & Brown, 2014; Kasperson et al., 2022). Therefore, by including variables like gender, educational discipline, location, etc., as part of our novel interdisciplinary theoretical framework, we empirically confirmed their impact and importance for water risk assessment. Otherwise, omitting these theoretically relevant variables could have skewed the findings. Moreover, water risk was identified as a systemic risk problem with all three characteristics of complexity (due to a multitude of explanatory mechanisms), uncertainty (due to competing knowledge claims, experience, or lack of knowledge), and ambiguity (due to multiple interpretations, socio-political and normative value differences) (Aven & Renn, 2019; Renn et al. 2020). Consequently, there is a need for a variety of deliberative and discursive risk management, communication, and governance strategies to develop collaborative transdisciplinary knowledge of water risks among all stakeholders (Klinke & Renn, 2021). Finally, methodologically, a key strength and scientific novelty of our study is the successful demonstration of the application of explanatory sequential mixed methods to examine complex constructs like water risk perception and evaluation in a particular expert sample, i.e., the CFS (Di Baldassarre et al., 2021; Siegrist & Árvai, 2020). The follow-up interviews validated the survey's findings and provided much-needed depth and understanding of the drivers of risk ratings, expanding statistical evidence further. Therefore, using mixed methods, our study achieved enhanced rigor, qualitative depth, and theoretical understanding of nuanced water risk perception factors.

Practically, the study is part of a broader interdisciplinary project that aims to develop a locally attuned water risk management framework for the province of Ontario, Canada. Different hydrological and social water risks were investigated for Ontario in a separate study (Sandhu et al., 2023). Our current study engaged CFS practitioners to co-develop knowledge and understanding of water risk perception and evaluation. Water risk ratings analyzed in this study can be used to design contextually-attuned decision support tools for the CFS as well as training strategies for risk assessment and management. Policymakers may find the results on proximity bias, the role of trust and exposure, the need of contextually-attuned regulations, the influence of media, location, and financial impacts as strategic avenues for multi-stakeholder engagement to bridge the science-policy-practice gap in sustainable water management.

4.6.4. Limitations of study and recommendations for future studies

While apt for our explanatory research objective, the cross-sectional survey design does not provide causal interpretations. Nonetheless, the follow-up interviews provided insights into potential causal mechanisms like cognitive (knowledge/awareness), affective (attitude and trust-based), spatial, and sociocultural demographic factors that drive the water risk ratings. The study's findings inform future longitudinal survey designs to establish causality. Moreover, the scales for water attitudes and values developed in the study can be tested further with the lay public and experts in other public or civil society sectors for cross-sample reliability. A large sample size tends to be desirable in risk perception studies. However, given the time-intensive nature of mixed methods, large sample sizes are not always possible, especially with specific expert populations. Nonetheless, even with a specific and small sample, statistical assumptions were upheld, and reliable conclusions were drawn that were further validated by the interviews.

With respect to generalizability, our in-depth case study approach captures locally relevant heterogeneous water risks and perspectives of the CFS scoped to Ontario (Hogeboom et al., 2018). Nonetheless, for future studies, we recommend applying our novel theoretical framework and mixed methods procedures to different geographical contexts for comparative case analysis, appealing to academia, businesses, investors, and policymakers beyond Ontario (Creswell & Creswell, 2018). Secondly, future studies can operationalize our theoretical framework's water risk management stage and investigate management strategies and sector-based preferences to develop a decision support tool. Thirdly, future research can validate our study's framework with other stakeholder groups, including the public, government, and civil society organizations. Finally, future studies can further explore proximity bias, quantifying location-based differences between actual and perceived water risk ratings, operationalizing water risk governance frameworks, and exploring adaptive and resilience approaches for water risk governance (Kasperson et al., 2022; Klinke & Renn, 2021; Koehler, 2023).

4.7 Conclusion

Extant literature revealed a pertinent gap in the empirical assessment of water risk perception and its impact on water risk evaluation and decision-making in the CFS. Our study addresses this gap in knowledge by examining the relationship between water risk perception and evaluation using novel interdisciplinary Risk Theory and explanatory sequential mixed methods approaches consisting of a survey and follow-up interviews. Our study finds heterogeneity among different water risks as well as multi-dimensional cognitive, affective, and socio-cultural personal factors of water risk perception, including knowledge, professional experience, perceived controllability, values, trust, location, and gender of CFS practitioners, analysts, and decision-makers that influence the evaluation of different water risks. Water risk perception, evaluation, and decision-making is a nuanced and subjective process influenced by the risk characteristics and the risk perceiver. Therefore, for comprehensive and sound water risk assessment, management, and decision-making, we find it is critical to systematically integrate water risk perception and priorities of relevant non-state actors like CFS along with quantifying different water risks. Our study contributes and advances knowledge in sustainable water management and risk analysis by empirically applying Risk Theory to the domain of water risks in CFS and successfully demonstrating the novel use of mixed methods for examining complex theoretical constructs like water risk perception and evaluation. Our findings on water risk ratings, relevant water risk perception factors, and sector-specific priorities enable the integration of analytical risk data with practitioner perspectives to inform evidence and context-based decision support tools for water risk management. These outcomes are critical for sustainable water management research, policies, and operational practices to promote water security and resilience in Ontario and Canada.

MANUSCRIPT ENDS

Chapter 5

5. Developing a Transdisciplinary Tool for Water Risk Management and Decision Support in Ontario, Canada

Contents of this chapter are submitted and under review for publication in:

Sandhu, G., Weber, O., Wood, M. O., Rus, H. A., & Thistlethwaite, J. (Under Review). Developing a Transdisciplinary Tool for Water Risk Management and Decision Support in Ontario, Canada. *Environmental Research Communications.* pp. 27. Manuscript ID: ERC-101939

Extant literature reveals limited examination of contextually-attuned risk management strategies and tools for sustainable management and decision support related to water. Given the systemic complexities of water risks, a transdisciplinary approach is necessary that advances interdisciplinary knowledge and develops practical tools for water risk management and decision support by engaging influential actors like the private sector including, businesses and the financial sector. Addressing this gap, the study applied a novel normative-analytical risk governance framework to water, and employed transdisciplinary mixed methods (survey, interviews, and secondary data analysis) to investigate water risk management strategies in Ontario, Canada. It then developed a first-of-a-kind decision support tool, WATR-DST, integrating interdisciplinary data for seven water risk indicators at the sub-watershed scale with practitioner perspectives and priorities, providing location, sector, and context-specific risk information and strategies to inform decisions, practices, policies for sustainable water management. The study finds that a combination of regulatory, voluntary, and multi-stakeholder participatory approaches is needed for water risk management, contingent on the severity of water risks, sector, location, and context. Moreover, the criteria of flexibility, efficiency, strategic incentives, and economic and regulatory signals are essential. The research contributes to knowledge in sustainability management, risk analysis, and environmental management by expanding the novel normative-analytical framework to investigate water risk management and decision-making in the private sector, which was underexplored in extant literature. Using transdisciplinary mixed methods, the study reveals hybrid strategies for water risk management, communication, and trust-building and develops a novel environmental management tool to improve multi-sector water-related decisions and environmental performance.

MANUSCRIPT BEGINS

5.1 Introduction

Anthropogenic activities are at the core of water challenges, adversely impacting the quality, flows, access, and ecological health of water sources (Rangecroft et al., 2021; Sandhu et al., 2023a; Savelli et al., 2022). Social, economic, political, and hydrological systems are inherently interdependent, interconnected, interdisciplinary and complex, hence making water a critical Earth system for sustainability and a fundamental objective for sustainable development (Di Baldassarre et al., 2021; United Nations, 2018; Zipper et al., 2020). While sustainably managing risks to water resources is crucial for addressing the Sustainable Development Goal (SDG) 6, the progress of the global society has been insufficient (Sadoff et al., 2020; UN-Water, 2021). Risks to water security continue to rise, including dwindling flows, groundwater overextraction, deteriorating water quality, inequitable water access, regulatory complexity, and conflicts between water users (Cai et al., 2021; Di Baldassarre et al., 2019; Sadoff et al., 2020; Savelli et al., 2022). Therefore, estimating and managing water risks at the appropriate scale, i.e., sub-watershed scale, is a growing arena of research and application in the fields of sustainability and environmental management (Bilalova et al., 2023; García Sánchez et al., 2023; Sandhu et al., 2023a; Stafford-Smith et al., 2017; Zipper et al., 2020).

Water security challenges are 'wicked' problems in the fields of sustainability and risk analysis, due to high complexity with interdependent systems, high uncertainty, and contextual and normative ambiguity due to various stakeholder interpretations, knowledge claims, values, and interests (Bilalova et al., 2023; Renn & Klinke, 2015; Rittel & Webber, 1973; Sandhu et al., 2023b). The focus of this study is Ontario, a province in Canada, nestled between the Great Lakes, but rife with interconnected hydrological and social water issues and risks (Sandhu et al., 2021, 2023a, 2023b). This makes the region unique and interesting from an academic perspective. Ontario's Climate Change Impact Assessment Report highlights the highly spatially and temporally variable impacts of climate change on water security that threaten societal well-being, productivity of businesses, economy, and the environment (Climate Risk Institute et al., 2023). Thus, safeguarding water security by water risk management is key to achieving is key to a climate-resilient and sustainable society, economy, and environment (Koehler, 2023; Mitchell, 2015; Savelli et al., 2022).

Given the complexities of a coupled socio-hydrological system, a systems-based transdisciplinary approach is needed to develop interdisciplinary knowledge and context-specific environmental management tools by engaging influential actors in the water management and governance landscape (Bansal & Song, 2017; Busch et al., 2023; Christ & Burritt, 2019; Di Baldassarre et al., 2019; Wyrwoll et al., 2018). This landscape consists of multiple institutions, actors, and stakeholders (de Loë & Patterson, 2017; Klinke & Renn, 2012). The term “actors” encompasses the various organizations, institutions, or individuals whose activities, actions, and decisions impact water security (de Loë & Patterson, 2017). An important non-governmental actor in the water management and governance landscape includes the private sector, which can catalyze the progress towards sustainable water management (Busch et al., 2023; Christ & Burritt, 2019; Cosgrove & Loucks, 2015; Garrick et al., 2017; Sandhu et al., 2023b).

The private sector consists of businesses, which operationally depend on a large quantity and specific quality of local water resources, and financial institutions, who invest, lend, or insure these businesses (Hogeboom et al., 2018; van Vliet, 2023). The private sector and its individual organizations are embedded within the broader social, economic, cultural, political, institutional, and environmental (including hydrological) contexts (Sandhu et al., 2023a). Water insecurity is a physical and material risk that can have significant operational, financial, regulatory, and reputational impacts, requiring an integrated socio-economic-ecological approach (Weber & Saunders-Hogberg, 2020). However, the examination of the role of influential actors like businesses and the financial sector in managing water security risks at the local scale and tools that support water-related decision-making is an underexamined yet timely research opportunity in the fields of sustainability, risk analysis, and environmental management (Bilalova et al., 2023; Busch et al., 2023; Chan et al., 2019; Christ & Burritt, 2019; Forin et al., 2018; Sandhu et al., 2023b).

5.1.1 Contemporary risk analysis, management, and governance frameworks for sustainability challenges

The study’s theoretical foundation is risk analysis and management, applied to the ‘wicked’ sustainability and environmental management problem of water. Risk assessment and management are integrated processes consisting of ‘what is the risk,’ i.e., risk identification, estimation, and evaluation, where risks are prioritized based on their acceptability (Klinke &

Renn, 2021). However, extant sustainability and environmental research has been limited to water risk assessment, without addressing how to manage the assessed risk and support practical decision-making (Forin et al., 2018; García Sánchez et al., 2023; Sandhu et al., 2023b) A risk management strategy entails 'what to do about the assessed risk', where options, procedures, rules, or policies to address to risk are described and weighed by analysts and decision-makers (Renn & Klinke, 2015; Vasvári, 2015). Nonetheless, with growing prevalence of wicked risk problems, like water, risk management has evolved into risk governance, which is distributed across multiple decision-making levels (individual, organizational, industrial, or regional, provincial, macro-level economy) with state and non-state actors (Aven & Renn, 2020; Klinke & Renn, 2021).

Risk governance argues that Risk cannot be understood and managed solely on objective information and needs an understanding of how stakeholders, practitioners, and decision-makers perceive risk. Moreover, incorporating perception-based priorities and judgment is crucial for risk management tools, policies, and strategies especially for wicked risk problems (Klinke & Renn, 2012, 2021; Koehler, 2023; Sandhu et al., 2023b). This approach is a contemporary shift away from state-centric top-down command and control approach towards multi-level systems-based approaches, where risk assessment and management is distributed among diverse stakeholders including the private sector (Bilalova et al., 2023; de Loë & Patterson, 2017; Klinke & Renn, 2021). This study adopts a contemporary risk governance approach for water risk management. Thus, analytical risk quantification is integrated with normative deliberative approaches eliciting preferences of the private sector for water risk management (Klinke & Renn, 2021; Renn & Schweizer, 2009).

The normative-analytical model of risk governance put forth by Klinke and Renn (2012) combines quantitative risk estimation with subjective judgment (perception-based) in a comprehensive framework, apt for sustainability and risk problems like water (Klinke & Renn, 2012, 2021; Renn & Schweizer, 2009). The model includes risk framing, interdisciplinary risk estimation with objective and subjective concern assessment, risk evaluation (stakeholder preferences), risk management, and monitoring (Klinke & Renn, 2012; Renn et al., 2022; Renn & Schweizer, 2009). Moreover, risk communication and deliberation are embedded within this cycle, necessitating stakeholder inputs in all stages (Klinke & Renn, 2012). Through deliberation, various management options are identified and evaluated in the decision-making context (Aven & Renn, 2020; Renn & Schweizer, 2009; Wyrwoll et al., 2018).

For managing water risks, the key area of inquiry of this research, the literature identifies three possible strategies (Klinke & Renn, 2012; Renn & Klinke, 2015; Vasvári, 2015). First, linear management approaches include government regulations and risk-informed strategies, including expert deliberation and techno-centric approaches focusing on scientific research and technology for risk mitigation (Aven & Renn, 2020; Klinke & Renn, 2012, 2021; Vasvári, 2015). Then, precaution-based approaches include proactive self-regulatory approaches for resilience building in water-using sectors (Busch et al., 2023; Christ & Burritt, 2018, 2019). Finally, a discourse-based multi-stakeholder strategy entails participatory decision-making (Aven & Renn, 2020; Klinke & Renn, 2012; Renn & Klinke, 2015). However, for managing complex sustainability challenges like water, a monodisciplinary approach, method, or theory may be insufficient and an investigation into systems-based transdisciplinary approaches is necessary (Busch et al., 2023; Garrick et al., 2020; Klinke & Renn, 2021).

5.1.2 Transdisciplinary approaches for water risk management: A decision support tool for Ontario, Canada

Majority of the research in water management is siloed and limited to assessing either biophysical risks in natural systems using hydrological and engineering methods or solely quantifying social water risks of urban water infrastructure (Bansal & Song, 2017; Christ & Burritt, 2019; Forin et al., 2018; García Sánchez et al., 2023). Given this lack of knowledge integration, transdisciplinary systems-based socio-hydrological approaches are novel contributions in the fields of sustainability management, risk analysis, and water resource management (Busch et al., 2023; Christ & Burritt, 2018, 2019; Krueger et al., 2016; Starik & Kanashiro, 2013; Xu et al., 2018). Transdisciplinary approaches to water risk management and governance entail the engagement of multi-sector practitioners and the scientific community using mixed methods to co-develop knowledge, application-based tools, and strategies (Busch et al., 2023; Christ & Burritt, 2019; Krueger et al., 2016; Renn et al., 2022).

To bridge the knowledge-application gap, Decision Support Tools (DSTs) are a broad category of automated tools that compute and display information, variables, and outcomes based on the user’s needs to assist their tasks and decisions (Loucks, 2023; Morales-Torres et al., 2016). DSTs are designed to apply theoretical frameworks in practical decision-making, e.g., comparing different management options in a standardized format and integrate stakeholder priorities, judgments, and preferences by provision of weights or multipliers (Giupponi & Sgobbi, 2013; Yang, 2017). Thus, these application-based transdisciplinary tools can help bridge the gaps between interdisciplinary knowledge, practical implementation and policy-making in sustainability (Costa et al., 2019; Loucks, 2023; Morales-Torres et al., 2016).

Existing methods and tools for water-related decision support, including WWF Water Risk Filter, WBCSD Global Water Tool, Water Footprint Analysis, Global Drought Observatory, etc., have limitations. The underlying data lacks granularity and overlooks the systemic interconnections between water scarcity and quality, sector-specific impacts, role of regulations, conflicts, and stakeholder scrutiny at the local sub-watershed scale (Christ & Burritt, 2017; Dudley et al., 2022; Josset & Concha Larrauri, 2021; Sandhu et al., 2023a; van Vliet, 2023). Moreover, spatially, by focusing on global, cities, or organizational scales, these studies omit the contextual nuances of the social, political, cultural, and institutional environment using basin or sub-watershed boundaries, apt for identification and management of water risks (Di Baldassarre et al., 2021; Dudley et al., 2022; Forin et al., 2018; Sandhu et al., 2021; Savelli et al., 2022; Zipper et al., 2020). Previous research by Sandhu et al. (2023a) quantified different physical and social water risks prevalent across Ontario's sub-watersheds. Sandhu et al. (2023b) studied the relationship between water risk perception and estimation in the private sector in Ontario. However, these studies recommended a transdisciplinary investigation into strategies and development of tools for water risk management and decision support, hence defining our research objective.

5.1.3 Research objective, questions, and contributions

While the sustainability and risk management literature discusses normative-analytical models, a transdisciplinary risk governance approach for water risk management has not yet been operationalized (Bilalova et al., 2023; Koehler, 2023; Rangecroft et al., 2021; Sandhu et al., 2023b). Current literature also reveals limited examination of DSTs and how water risks are managed by the private sector, locally at the sub-watershed scale (Busch et al., 2023; Cosgrove & Loucks, 2015; Forin et al., 2018; Sandhu et al., 2021, 2023b; van Vliet, 2023; Wyrwoll et al., 2018). This study's objective is to address these knowledge gaps by investigating water risk management strategies and preferences of the practitioners (i.e., analysts, decision-makers, or experts) in the private sector in Ontario, Canada. Then, the study develops a decision support tool that provides ratings for interdisciplinary water risk indicators and qualitative public and media scrutiny themes, based on the user's location and sector.

The study's research questions are:

RQ 1: What are the strategies and preferences for water risk management in the private sector in Ontario, Canada?

RQ 2: What are the gaps and opportunities for water risk management in the private sector's decision-making in Ontario, Canada?

RQ 3: How can a transdisciplinary decision support tool be developed for water risk management in the private sector in Ontario, Canada?

The study contributes to knowledge in sustainability management, risk analysis, and environmental management by first-of-a-kind application of the normative-analytical framework to water that tethers Risk Management and Governance Theory with environmental management. Second, it uses transdisciplinary methods to engage practitioners and investigate water risk management strategies, contributing to the methodological development in sustainability and environmental science. Moreover, the comprehensive decision support tool is the key application of the research, that can improve water-related decisions, policies, and operational practices for sustainable water management across multiple sectors.

5.2 Theoretical framework

The theoretical foundation of this work is built upon Klinke and Renn's (2012, 2021) 'normative-analytical risk governance model'. As discussed in Section 5.1.1, literature highlights insufficiency of extant monodisciplinary approaches, and the necessity and novelty of including interdisciplinary data, theories, and transdisciplinary normative perspectives for managing wicked sustainability and risk challenges like water (Klinke & Renn, 2021; Krueger et al., 2016; Renn & Schweizer, 2009; Sandhu et al., 2023b). Thus, we adopted the contemporary theoretical lens of Risk Management and Governance, and developed a normative-analytical model for water risk assessment, management, and decision support (Figure 5.1). The first stage of water risk estimation (pre-estimation and interdisciplinary sub-watershed assessment) combines objective and social concern assessment, quantifying ratings for seven water risk indicators. In water risk evaluation (second stage), the practitioners indicate their preferences and priorities for each water risk indicator based on their perception, contingent on characteristics of the individual water risks. The third water risk management and decision support stage entails integrating the results of water risk estimation and perception-based preferences for the water risk indicators, and explores risk management strategies that inform decisions for sustainable water management.

The interdisciplinary risk estimation and risk evaluation stages (including risk perception) highlighted by grey boxes in Figure 5.1 have been operationalized in previous work (Sandhu et al., 2023a, 2023b). Sandhu et al. (2023a) assessed interdisciplinary water risks, identifying sub-watersheds and sectors with differentiated ratings for seven interdisciplinary water risk indicators. The seven types of water risk are: Water Quantity Risk, Water Quality Risk, Source-specific Risk, Regulatory Risk, Water User Conflict Risk, Sector-specific Risk, and Public and Media (Reputational) Risk (Sandhu et al., 2023a). Sandhu et al. (2023b) examined the nuanced relationship of risk perception and the evaluation of water risks. Their research found that priorities assigned reflect the practitioner's risk perception determined by the characteristics of the water risk and the individual characteristics like knowledge, attitudes, values, trust, experience, gender, location, and sector (Sandhu et al., 2023b).

The water risk management and decision support stage (black boxes in Figure 5.1) is the framework's integrative and conclusive stage, is operationalized in this study to integrate and advance knowledge in risk management and practical decision support for water. The practitioner insights and preferences for water risk management strategies and priorities for different risks were obtained using mixed methods. Then, we integrated the water risk data from the risk estimation stage and priorities from the risk evaluation stage to develop the tangible tool to support decisions for sustainable management of water in the private sector.

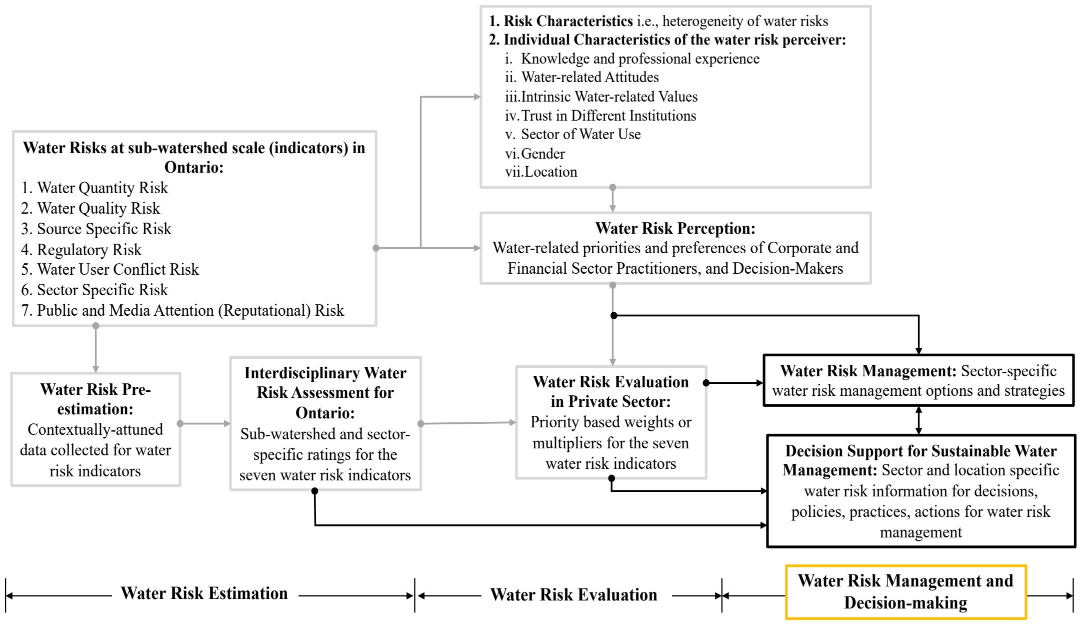

Figure 5.1: Theoretical framework for water risk management and decision-making

5.3 Methods

The sustainability and risk literature highlights the importance and novelty of using participatory transdisciplinary approaches to operationalize analytical and normative risk governance frameworks (Christ & Burritt, 2018; Di Baldassarre et al., 2021; Klinke & Renn, 2021). Consequently, mixed methods (surveys followed by interviews) aligned with transdisciplinary research are recommended for eliciting insights of practitioners (normative component) along with using secondary data analysis for water risk assessment (analytical component) (Di Baldassarre et al., 2021; Sandhu et al., 2023b). Using a transdisciplinary mixed methods design enables the combination of the rigor of quantitative methods and the contextual depth of qualitative data provided by practitioners (Figure 5.2) (Creswell & Creswell, 2018).

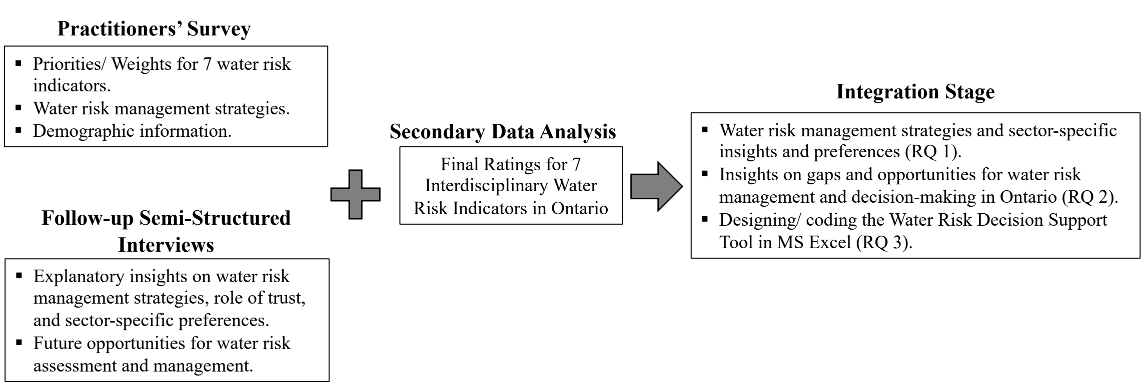

Figure 5.2: Transdisciplinary mixed methods research design

5.3.1 Methodological overview and study's participants

The study addressed RQs 1 and 2 using a survey and semi-structured interviews that provided practitioner insights for water risk management strategies. Since this study is a part of a broader water risk perception, evaluation, and management project (Sandhu et al., 2023b), we included the questions for water risk management in the overall project survey and the same participant sample.

An 'expert purposive sampling strategy' was used for a strategic and representative sample that aligned the participants with the transdisciplinary research objective (Sandhu et al., 2023b). The participants were practitioners with sustainability or environmental risk assessment and management experience in Ontario. The term 'practitioner' encompasses professionals, analysts, managers, and decision-makers in the private sector, i.e., corporations in water-using sectors and financial institutions. We used LinkedIn, websites of industry associations, and organizations for recruitment using strategic filters for roles, sectors, and locations that ensured a representative sample. Table 5.1 lists the demographic information of the participants, who were recruited in accordance with research ethics requirements. The survey was completed by 25 practitioners, and 22 continued with the interviews. The questionnaire-based survey was conducted online on Qualtrics between April and August 2022. The interviews were conducted with the same sample on MS Teams between October and December 2022.

Table 5.1: Study's participants[a]

Demographic Information	Number of Participants, Practitioner Survey (Total = 25)	Number of Participants, Follow-up Interviews (Total N =22)
1. Gender		
Woman	13	10
Man	12	12
2. Professional Sector		
Agriculture	5	4
Chemical manufacturing	2	2
Consulting	3	2
Financial Sector	7	7
Food and Beverage Manufacturing	2	3[b]
Mining	2	1
Power Generation	2	2
Automotive Manufacturing	2	1

3. Role		
Analyst/ Specialist/ Expert	7	Not Applicable
Director/ President	5	
Manager	7	
Owner/ Co-owner/Vice-President	6	

[a] Participant sample for this study is the same as in the overall project (Sandhu et al., 2023b).
[b]Additional participant who contributed exclusively to the interviews.

5.3.2 Practitioner survey and interviews

The questionnaire for the survey included Likert scale questions for eliciting priorities for the water risk indicators, preferences for water risk management strategies, and text entry-based demographic information. The risk management strategies are based on the reviewed literature (Section 5.1.1). Table 5.2 summarizes the survey's questions, items, and scales.

Table 5.2: Items and rating scales of practitioner survey questionnaire

Survey's Question	Survey's Items	Rating Scale
Water Risk Ratings/ Priority Assign a priority (rating) based on your knowledge, experience and relevance/ impact of the water risk on business or investment decisions in Ontario	Water Quantity Water Quality Source Type Regulatory User Conflict Sector-specific Public/Media attention	1-7 (1: Lowest– 7: Highest)
Risk Management Strategy Water risks can be best managed by	Additional regulations More scientific research Proactive private sector approaches Multi-stakeholder participatory approaches	1-7 (1: Strongly disagree – 7: Strongly agree)
Demographic Characteristics	Gender Professional Role Sector	Select one option/ Text entry

We analyzed the survey data using IBM SPSS (Version 28). We used descriptive statistics to determine average ratings (priorities) and preferences. To examine sector-specific differences in risk management strategies, we used a one-way analysis of variance (ANOVA) (Mishra et al., 2019). Moreover, we used interviews to gain in-depth insights into the survey's results and asked open-ended questions on the gaps and opportunities for corporate and financial water-related decision-making in Ontario. The interview guide is provided as Appendix 5.A.

All interviews were conducted using a standard protocol for consistency, were audio-recorded, anonymized, and then transcribed for qualitative analysis (Creswell & Creswell, 2018, Sandhu et al., 2023b). We used QSR NVivo 12 for coding and data analysis following Braun and

Clarke (2006), reviewing the transcripts to assign the first pass of coding based on the underlying theme, pattern, or concept (Braun & Clarke, 2006). For Pass 2, the open codes were condensed into higher-level themes and then organized into categories corresponding to each research question (Sandhu et al. 2023b). One member of the research team coded the interview data and themes while others cross-checked for consistency and reliability Creswell & Creswell, 2018). Appendix 5.B provides an example of the process of coding and thematic analysis.

5.3.3 Developing the "WATR-DST": A water risk decision support tool for Ontario

Aligned with RQ 3, the key output of this study was a water risk decision support tool, i.e., "WATR-DST" as depicted in Figure 5.3. We chose MS Excel to integrate the water risk data, practitioner preferences and code the tool. This choice was due to the ease of use, a friendly graphical interface, and accessibility, with no special training needed for installation (Miles et al., 2023). The detailed description of the design of the WATR-DST is provided in the sub-sections below.

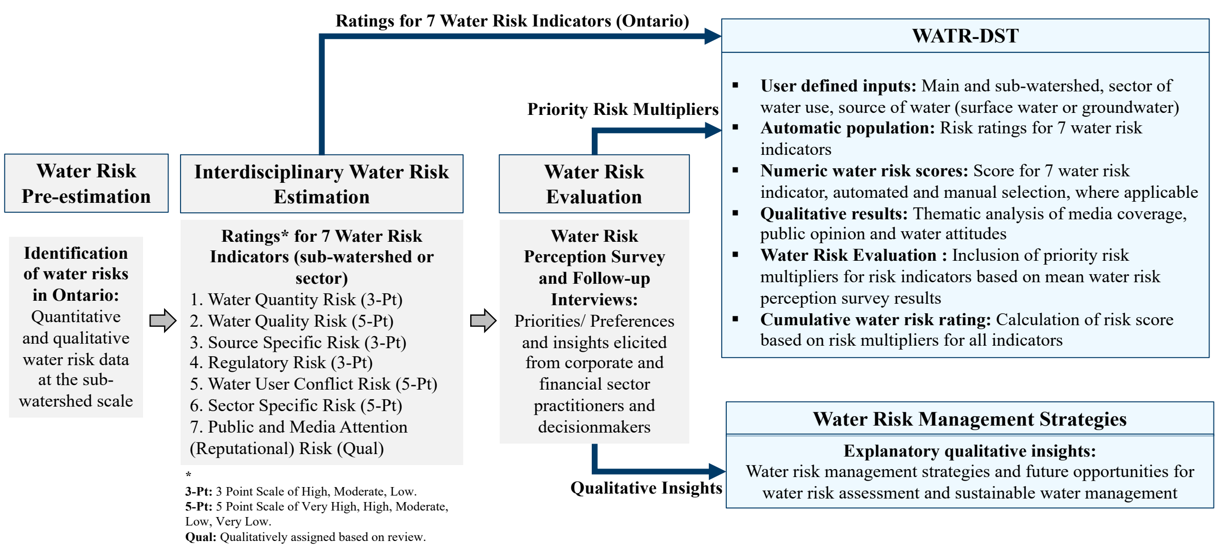

Figure 5.3: Conceptual model for designing the WATR-DST

5.3.3.1 Interdisciplinary water risk estimation: Risk scores for water risk indicators

The data for three and five-point spatial and sector-based ratings and qualitatively analyzed public and media themes for seven water risk indicators are extracted from Sandhu et al. (2023a), coded, and integrated in MS Excel. Based on user-defined inputs chosen from pre-coded drop-down lists for the main and sub-watershed (location), water use sector and sub-sector, and the type of water source, WATR-DST calculates the results for the seven water risk indicators. The user reviews the results and selects scores, if applicable, based on their judgment informed by the evidence provided by the tool. For example, for the water quantity risk indicator, the user selects if their location is listed in the quaternary watersheds at high or moderate risk. Then, based on the user's inputs and the calculated ratings, the tool automatically assigns a numeric risk score for the indicator. The tool has been color-coded such that the user input areas and instructions are clearly demarcated. The score assignment procedures of the tool are detailed below:

i. **Water quantity risk:** Based on the user input of the sub-watershed, the tool populates the quaternary watersheds under four quantity risk sub-indicators, i.e., high surface water quantity risk, moderate surface water risk, high groundwater quantity risk, and moderate groundwater risk. If the user's location is within the identified quaternary watersheds, the user can choose "yes" or "no" from the drop-down options. Then, based on the rating, the tool engages the corresponding numerical risk score. If no watershed is identified, the base score of 1 is used.

ii. **Water quality risk:** The tool calculates the risk rating for water quality (measured on a 5-point scale as Very High to Very Low) based on the user's sub-watershed. The tool then displays the risk score and the information on the quality status of the individual Great Lake. The user can review the data and select an additional score from the drop-down list. Otherwise, the tool uses a base score of 1.

iii. **Source-specific risk:** Since groundwater is a higher-risk water source for contamination and overextraction, and is hydrologically connected to surface water, it is assigned a higher risk score (Sandhu et al., 2021, 2023a). The user can select a score for each source type, and the tool calculates the corresponding score.

iv. **Regulatory risk:** The tool uses the results from the regulatory assessment of Ontario by Sandhu et al. (2023a), with different risk drivers at high and moderate occurrence. Moreover, municipalities and sub-watersheds with a high regulatory focus are also populated (regional regulatory risk). The user selects which risk scores should be engaged and if their location is at high regulatory focus and then the tool engages regulatory risk scores.

v. **Water user conflict risk:** Based on the user's sub-watershed, the tool calculates the water-user conflict risk rating (Very High to Very Low) and the score.

vi. **Sector-specific risk**: Based on the user's main and sub-sector of water use, the tool calculates the sector-specific risk rating (Very High to Very Low) and the score.

vii. **Public and media (reputational) risk:** For the public and media scrutiny (reputational risk), results from Sandhu et al. (2023a)'s analysis and public opinion and attitudes surveys are integrated. Then, the user reviews the information and selects a score.

The pre-defined scores for the indicators are numeric values assigned to the 3 or 5-point ratings. These pre-defined values (Table 5.3) are selected for illustrative purposes only, i.e., to demonstrate a proportional increase in the score as the risk rating (severity) increases proportionally (Sandhu et al., 2020). These values can be updated based on future multi-stakeholder roundtables and consultation.

Table 5.3: Illustrative risk scores for water risk indicator ratings

Water Risk Indicator and Rating	Risk Score
1. Water Quantity Risk	
High	2
Moderate	1.5
Low	1
2. Water Quality Risk	
Very High	3
High	2.5
Moderate	2
Low	1.5
Very Low	1
3. Source-specific Risk	
Groundwater	2
Both groundwater and surface water	1.5
Surface water	1
4. Regulatory Risk	
High	2
Moderate	1.5
Low	1
5. Sub-watershed Water User Conflict Risk	
Very High	3
High	2.5
Moderate	2
Low	1.5
Very Low	1
6. Sector-specific Risk	
Very High	3
High	2.5
Moderate	2
Low	1.5
Very Low	1
7. Reputational Risk	
Very High	3
High	2.5
Moderate	2
Low	1.5
Very Low	1

5.3.3.2 Risk evaluation: Priority risk multipliers for cumulative water risk score

For water risk evaluation, the stakeholder priorities for the seven water risk indicators from the survey are coded as multipliers in the tool to calculate a cumulative risk rating. For an indicator with more than one score, the maximum score was utilized to avoid double counting. For the regulatory risk indicator with high and moderately prevalent risk drivers and a regional score, the geometric aggregation method is utilized, i.e., product of three scores.

The authors developed the following criteria for individual indicators:

$\mathbf{R}_{\mathbf{Quantity}}$ = Maximum of water quantity risk scores calculated by the tool. The average values are used if both surface and groundwater are selected as the source type.

$\mathbf{R}_{\mathbf{Quality}}$ = Maximum of the sub-watershed water quality risk score AND the risk score of the main watershed.

$\mathbf{R}_{\mathbf{Source}}$ = Source risk score.

$\mathbf{R}_{\mathbf{Regulatory}}$ = Risk score for high regulatory drivers x Risk score for moderate drivers x (Maximum of sub-watershed risk score AND municipality risk score).

$\mathbf{R}_{\mathbf{Water\ User\ Conflict}}$ = Conflict risk score.

$\mathbf{R}_{\mathbf{Sector\ Risk}}$ = Sector risk score.

$\mathbf{R}_{\mathbf{Reputational\ Risk}}$ = Reputational risk score.

Once individual risk scores are calculated, the tool engages multipliers based on the average ranking obtained from the survey ($\mathbf{M}_{\mathbf{Priority\ 1\text{-}7}}$). For the cumulative score, an additive or multiplicative aggregation method can be used to combine the weighted scores (Kodell & Gaylor, 1989). However, due to the 'multiplier effect' of systemic risks like water, where the impacts are multiplied and the water risk indicators are interdependent that augment total Risk (Li et al., 2021; Rayer et al., 2021). Therefore, the multiplicative model is better suited for calculating the cumulative score (Diaz-Gallo et al., 2021; Kodell & Gaylor, 1989).

$\mathbf{R}_{\mathbf{Cumulative\ Water\ Risk\ Score}} = [(R_{Quantity} \times M_{Priority\ 1}) \times (R_{Quality} \times M_{Priority\ 2}) \times (R_{Source} \times M_{Priority\ 3}) \times (R_{Regulatory} \times M_{Priority\ 4}) \times (R_{Water\ User\ Conflict} \times M_{Priority\ 5}) \times (R_{Sector\ Risk} \times M_{Priority\ 6}) \times (R_{Reputational\ Risk} \times M_{Priority\ 7})]$

Based on the cumulative score, the tool also calculates the overall rating differentiated on a 5-point scale from Very high to Very low) based on 20% range of the maximum and minimum cumulative score.

5.4 Results

5.4.1 Descriptive statistics for Practitioners' survey

For Water Risk Management Strategies, the average agreement score was highest for Proactive approaches for water resilience in all water-using sectors (*Mean* = 6.12, *SD* = 0.83), followed by Multi-stakeholder participatory approaches (*Mean* = 5.80, *SD* = 1.22), Additional scientific research (*Mean* = 5.72, *SD* = 1.10) and the least for Additional and more stringent Government regulations (*Mean* = 4.76, *SD* = 1.69). The descriptive statistics for the seven water risk indicators are provided in Table 5.4. Water quality risk was, on average, rated highest (*Mean* = 5.29, *SD* = 1.63), and source-specific risk was the lowest (*Mean* = 4.38, *SD* = 1.55).

Table 5.4: Descriptive statistics of water risk ratings (survey)

Water Risk Indicators	N[a]	*Mean*	*SD*
Water Quality Risk	24	5.29	1.63
Sector-specific Risk	24	4.96	1.55
Water Quantity Risk	24	4.88	1.68
Water User Conflict Risk	24	4.83	1.40
Regulatory Risk	24	4.83	1.63
Reputational Risk (Public and Media Attention)	24	4.58	1.93
Source-specific Risk	24	4.38	1.55

[a] Number of valid responses to this question in the survey

5.4.2 Sector-specific preferences for water risk management strategies

The ANOVA test revealed statistically significant sector differences for two out of four risk management strategies (Table 5.5), i.e., proactive private sector approaches, $F(7, 17) = 4.81$, $p = .004$ and regulatory approaches, $F(7, 17) = 3.53$, $p = .016$. The eta squared values for effect size were > 0.14. We discussed these results in the interview stage for an in-depth understanding.

Table 5.5: Significant group means and standard deviation in 1-way ANOVA

Risk Management Strategy	Participant's Sector	N	*Mean*	*SD*
Risk Management Strategy of proactive private sector approaches	Agribusiness	5	5.60	0.55
	Chemical manufacturing	2	4.50	0.71
	Consulting	3	6.33	0.58
	Financial Sector	7	6.57	0.53
	Food and Beverage Manufacturing	2	6.50	0.71
	Mining	2	5.50	0.71
	Power Generation	2	7.00	0.00
	Automotive Manufacturing	2	6.50	0.71

	Agribusiness	5	2.80	1.48
	Chemical manufacturing	2	5.50	0.71
Risk Management	Consulting	3	3.33	2.31
Strategy of regulatory	Financial Sector	7	6.00	1.00
approaches	Food and Beverage Manufacturing	2	5.50	0.71
	Mining	2	4.50	0.71
	Power Generation	2	5.50	0.71
	Automotive Manufacturing	2	5.50	0.71

5.4.3 Explanatory insights from interviews

The themes from the qualitative analysis of the interview are discussed below. A map summarizing the categories and themes is provided in Appendix 5.C.

5.4.3.1 Preferences for water risk management strategies

The survey finds, on average, that the most preferred water risk management strategies, were private sector approaches, and the least preferred were the government regulatory approaches. Interestingly, the water risk perception study by Sandhu et al. (2023b) with the same practitioner sample found that the extent of trust of the participants across institutions to measure and manage water security risks was the least in private sector and higher in the government and civil society organizations. Therefore, the study explored this trust and management strategy disconnect, where despite the least trust in the private sector, private sector approaches for water risk management were most preferred. Four main themes (italicized) emerged from the discussion.

Firstly, participants provided *insights on government regulatory approaches* for water risk management, articulating their benefits and drawbacks. Participants noted that the *benefit of government regulatory approaches* is that they provide a necessary baseline for performance and foster best management practices across all sectors. They also pointed that the government entities provide independent oversight for compliance, checks, and balances that are not motivated by profit-centric interests as in the private sector. Moreover, the government can provide incentives and support to scale and transfer best sustainability practices across all sectors.

On the other hand, participants also discussed the *drawbacks of government regulatory approaches,* including an overload of siloed regulations and cost-associated burdens, especially for water-reliant sectors like agriculture, manufacturing, food and beverage, power production, and mining. There may be unintended consequences when regulations are not attuned to the sector or location, creating opposite outcomes. Moreover, excessive regulations are prescriptive, resulting in a loss of innovation. Participants also noted the reactive nature of regulations based on public concern rather than biophysical evidence, which makes this approach less preferred.

Secondly, participants discussed *proactive private sector approaches*, revealing two sub-themes. Participants noted that the *private sector's efficiency, flexibility, and know-how may be better than other institutions.* The private sector prefers efficiency and strategic approaches with higher flexibility to address issues, which may also be self-serving. Moreover, the know-how, i.e., knowledge, innovation, as well as resources for technology and implementation for risk management, tends to be higher in the private sector. Lastly, the private sector may look at risks and opportunities more strategically than regulators. This preference also reflects the *drive to do the right thing and build accountability,* i.e., benefiting them, society, and the environment, and a strategy to creating more accountability and regaining stakeholder trust.

Thirdly, participants discussed their *insights on multistakeholder participatory approaches.* Firstly, the *benefits* of collaboration to foster change, action, and improvement were articulated. Nonetheless, participatory approaches have *drawbacks,* including issues with self-serving interests alluding to a lack of trust. Moreover, the issues with coordination, implementation, long timelines, and interest alignment highlighted the practical complexities of participatory approaches.

Finally, participants discussed *additional strategies for water risk management*, noting that economic and materiality considerations (financial bottom line), i.e., costs, expenses, and financial implications, may drive the management strategy. Pricing of risks and water was discussed an additional way to elevate the priority of water in decision-making.

5.4.3.2 Sector-specific differences

The study found sector-specific differences between proactive private sector approaches and regulatory approaches (Table 5.5). Within regulatory approaches, the financial sector rates them higher than other sectors. The interviews revealed that the financial sector seeks certainty, standardization, and risk alleviation provided by regulations, but corporations seek flexibility, efficiency, and innovation provided by private sector approaches. Moreover, sectors and organizations under high media or public scrutiny may prefer both government regulatory and proactive private sector approaches to establish accountability and trust.

The participants also discussed corporate sustainability trends, i.e., the triple bottom line. Participants noted a status quo across sectors where the *bottom line (financial impact/*

materiality) tends to dominate decision-making and action. Profitability tends to be critical, where sustainability initiatives compete with other profit-generating initiatives. Moreover, participants noted that social, reputational, or environmental issues are considered as financial risks in decision-making. Thus, the business case for sustainability (including water) is the dominant ethos driving corporate sustainability action. The participants also discussed *potential drivers of sustainability initiatives*, where internal and external stakeholders, including investors, employees, customers, and potential employees (via recruitment) can drive sustainability action. If compensation is tied to sustainability goals, the financial motivation of executives may also drive action. Moreover, the government plays an important role in proactively signalling sustainable practices through regulations and incentives. The barriers to corporate sustainability were attributed to varying degrees of awareness about systemic sustainability issues, inadequate measures, and reporting that overlook sustainability impacts and measure financial impacts.

5.4.3.3 Gaps and Opportunities for water risk management in Ontario

Discussion about the gaps and opportunities for management of water risks in Ontario revealed three categories. Firstly, concerning the *transdisciplinary collaboration between academia and industry,* participants noted the opportunities for *transdisciplinary research projects, funding, and dissemination.* They highlighted the need for collaboration between academia and industry via research projects, brain-storming sessions, funding, and research dissemination activities, where sustainability challenges and data gaps in the industry can be posed as research questions. *Gaps and issues with data* were noted, highlighting the need of real-time and accessible water data that can inform long-term planning and decision-making. Moreover, participants noted the lag in data for emerging contaminants, and the need of quality assurance of reported data. Finally, there is a need to *improve data accessibility, sharing, and coverage* such that valid data is reliably collected and made accessible.

Secondly, under *adaptation versus mitigation approaches for water risk management,* participants highlighted that water risk management is still mitigation driven. However, *adaptation is slowing gaining attention,* where, as the impacts of climate change materialize, adaptation may become more relevant in decision-making. Moreover, the *nuances of adaptation* were also discussed, where the focus on adaptation depends on the sector's nature and extent of water use. Another nuance was that mitigation and adaptation are interconnected for water risks with a need for an integrated focus on consumption and production. Nonetheless, the difficulty and longer timelines for adaptation approaches are a barrier.

Finally, under *opportunities for water risk assessment and management,* participants noted opportunities for *knowledge co-generation and awareness* about water risks across different sectors and industries. Moreover, accounting for public perception as a social risk as well as recognizing water as a systemic interconnected risk problem, was also highlighted. Operationally, the need for *more integrated tools, plans, frameworks, and data for water risks* is highlighted. Moreover, benchmarking water use in all industries across Ontario, quantification of business case of water sustainability, as well as pricing water risks were also identified.

Participants highlighted opportunities for *multi-stakeholder and multi-sector engagement at the watershed level.* It was noted that stakeholders drive action in environmental topics, create demand, and trigger change. Collaborative management of water and locally-attuned regulations are avenues to explore, along with the role of media and public attention that may drive regulations and industry action. Finally, participants noted opportunities for *government regulations, cost-sharing programs, and incentives,* alluding to expanding well-functioning government programs and cost-sharing programs to support water initiatives and technologies.

5.4.4 A transdisciplinary tool: WATR-DST

The WATR-DST was designed as outlined in Section 5.3.3. The sub-watershed data on the seven water risk indicators, 70 sub-sectors of water use, risk scores (Table 5.3), and criteria for cumulative risk score were coded in MS Excel. The priority risk multipliers, i.e., $\mathbf{M}_{\mathbf{Priority\ 1\text{-}7}}$ were calculated based on the survey's average rankings (Table 5.4). The multipliers are provided in Table 5.6, along with the corresponding rank. For equal means e.g., Water user conflict risk and Regulatory risk, an equal rank was assigned. Base priority multiplier of 1 was assigned to the lowest rank, i.e., 6 and each subsequent rank was assigned a multiplier with an increment of 0.5.

Table 5.6: Priority risk multipliers based on the practitioners' survey

Water Risk Indicator	**Average Survey Rating (*Mean*)**	**Rank[a]**	**Priority Multiplier $\mathbf{M}_{\mathbf{Priority}}$**
Water Quality Risk	5.29	1	3.5
Sector-specific Risk	4.96	2	3
Water Quantity Risk	4.88	3	2.5
Water User Conflict Risk	4.83	4	2
Regulatory Risk	4.83	4	2
Public and Media Attention (Reputational) Risk	4.58	5	1.5
Source-specific Risk	4.38	6	1

[a] Rank of 1 is assigned to the highest rated risk, followed by increments of 1 for next rating

WATR-DST displays the ratings and scores for Water Quantity Risk, Water Quality Risk, Water User Conflict Risk, Regulatory Risk, Source-specific Risk, and Sector-specific Risk. The tool also provides information on public and media scrutiny themes, allowing users to assess Reputational Risk, contingent on the context, location, sector, and legacy issues. The tool then displays the cumulative water risk score, a unique score for the user and a rating. To illustrate the features of the WATR-DST, a step-by-step demonstration and user guide using a hypothetical example is provided in Appendix 5.D.

5.5 Discussion

The objective of this study was two-fold: firstly, we explored practitioner insights and preferences for water risk management in the private sector in Ontario. Secondly, we developed a transdisciplinary and comprehensive decision support tool that captures local hydrological and contextual conditions to assist multi-sector water risk management decisions. The study's results make a tangible contribution to the interdisciplinary knowledge and tools for sustainability management, risk analysis, and water resource management. We discuss the study's findings in line with the research questions, current literature and contributions, limitations, and future research.

5.5.1 Strategies and preferences for water risk management

Answering RQ 1, the study's investigation of water risk management (Section 5.4.1) revealed that the most preferred approaches, on average, are proactive private sector approaches, and the least preferred are government regulatory approaches. Moreover, we found sector-based differences in two out of four strategies (Table 5.5). Proactive private sector approaches include a corporation's proactive activities for risk management, including self-regulation, voluntary monitoring, reporting, internal pricing etc., (Busch et al., 2023; Christ & Burritt, 2018). Regulatory approaches are command and control approaches, where public institutions are responsible for managing water risks and their impacts by laws, regulations, policies, and thresholds (Busch et al., 2023; Dobbie et al., 2016; Klinke & Renn, 2021). The preference for proactive private sector approaches is an interesting finding because Sandhu et al. (2023b) found in the same sample that the trust to manage risks by self-regulation in the private sector was the least and in the government was higher.

Interviews revealed (Section 5.4.3.1) that private sector approaches for water risk management are preferred because of efficiency, flexibility, and know-how at the individual organizational level, but the role of the government in providing baseline standardization, certainty, and unbiased oversight remains crucial (Section 5.4.3.2). While there is higher trust in the government, awareness of limitations of regulations due to costs, and restrictions on innovation and flexibility persists. The practitioners articulated the benefits and drawbacks of each approach, and the preference for flexibility and efficiency dominates. These findings diverge from Dobbie et al. (2016), who found that government agencies are considered to be primarily responsible for reducing and managing risk in the urban water sector in Australia. Their results were explained based on risk perception, where trust was directly connected to the choice of risk management strategy. However, for Ontario, alluding to the complexity of trust reported by Sandhu et al. (2023b), trust may be higher in government agencies, individual's own organization, or stakeholders rather than the industry as a whole, hence disconnecting one's organizational risk management strategy preference from trust and revealing future avenues for trust-building among stakeholders in Ontario.

The laissez-faire preference of the private actors over across-sector government regulations can also be explained based on the perceived relative abundance of water resources in Ontario (Sandhu et al., 2023b). In line with Busch et al. (2023), the study (Section 5.4.3.2) finds dominance of "business case for sustainability" in Ontario. There is a weak conceptualization of sustainability, where the financial bottom line and profit-centric self-serving interests, i.e., financial risks, economic signals, efficiency, stakeholder pressure, and incentives, continue to drive action rather than sustainability (Talbot & Barbat, 2020; Weber & Feltmate, 2016). Nonetheless, supporting Busch et al.'s (2023) findings on environmental management, the study also finds a complementary nature of approaches for water, where government regulations can complement private sector and participatory approaches. The study confirms that government regulations and multi-stakeholder engagement are necessary for water risk management, but can be designed more strategically to trigger a large-scale organizational and behavioral change (Busch et al., 2023; Christ & Burritt, 2019).

Aligned with Aven and Renn (2020) and Garrick et al. (2020), we conclude that a combination of linear top-down, proactive private sector, and multi-stakeholder participatory approaches will be required for risk management based on the severity of water risk for that sector, location, and context. Thus, based on the literature and practitioners' insights, the study developed a water risk management spectrum (Figure 5.4) with the increasing risk severity. This spectrum can be employed to choose a risk management strategy corresponding to the cumulative risk rating calculated from the WATR-DST. The overlap between precaution-based and participatory strategy enables flexibility, where the user can choose based on the cumulative risk, sector's risk, context-specific reputational risk, or location-specific conflict potential.

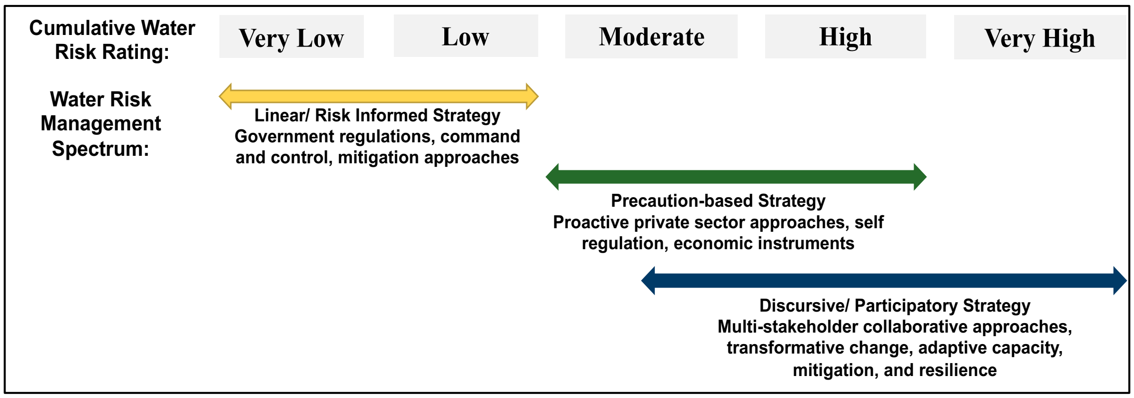

Figure 5.4: Water risk management spectrum

5.5.2 Opportunities for water risk management

Answering RQ 2, the discussion on the next steps for water risk assessment and management (Section 5.4.3.3) revealed three interconnected perspectives that build upon the work of Sandhu et al. (2023a, b). Firstly, from a **cognitive perspective,** opportunities for collaborative transdisciplinary knowledge co-creation with increased awareness, reliable sources of information, and dissemination pertaining to local water risks exist. Therefore, aligned with previous literature, transdisciplinary communication, and dissemination need to attuned to the non-academic audience's needs (Christ & Burritt, 2018, 2019; Krueger et al., 2016; Miles et al., 2023). From a **governance and institutional perspective**, opportunities for multi-stakeholder and multi-sector collaboration at the watershed level and participatory trust-building initiatives are revealed (Dobbie et al., 2016; Mitchell, 2015; Renn & Klinke, 2015). Moreover**,** contextually-attuned regulations and cost-sharing programs are needed.

As argued by Busch et al. (2023), Koehler (2023), and Weber and Feltmate (2016), this study also finds opportunities for hybrid approaches to transition water's business case to the sustainability case. For instance, the private sector's materiality approach for risk management can be expanded to the systems-based combination of inside-out and outside-in approaches (double materiality) for sustainable water management, i.e., assessing, disclosing, and managing overall sustainability impacts of an organization, strategically, with innovation, know-how, and efficiency (Driver et al., 2023; Weber & Saunders-Hogberg, 2020). Moreover, this approach can be combined with collaborative multi-stakeholder participatory approaches that provide institutional diversity and regulatory approaches that provide incentives, certainty, oversight, and standardization (Busch et al., 2023; Klinke & Renn, 2012). Rather than choosing one approach, a spectrum of approaches for water risk management can be selected based on the location, sector, and context. Moreover, the limitations of these approaches can be addressed by transdisciplinary engagement, knowledge sharing, and trust-building (Dobbie et al., 2016; Quandt, 2022; Wyrwoll et al., 2018).

From an **operational perspective,** opportunities for collecting interdisciplinary data, benchmarking of water use across sectors and sub-watersheds, pricing tools, and quantifying the business case for sustainable water management are revealed. Aligned with other studies, the importance of transdisciplinary accounting and decision support tools like WATR-DST was established (Busch et al., 2023; Christ & Burritt, 2018).

5.5.3 Salient features of WATR-DST for sustainable water management

Answering RQ 3, the study developed WATR-DST, synthesizing interdisciplinary water risk data and transdisciplinary practitioner priorities for water risks (Table 5.4, 5.6) overcoming the weaknesses of previous research (García Sánchez et al., 2023; Xu et al., 2018). The WATR-DST has multiple salient features for multi-sector water-related decision-making. The tool provides ratings for seven water risk indicators in an integrated format, attuned to the user's location, sector, source type, and preferences (Loucks, 2023). For instance, if an organization in a water-intensive sector has an existing or new facility, the user, who can be an analyst, decision-maker, or manager, can input their facility's information in the WATR-DST. The tool provides the ratings and scores for seven water risk indicators, a cumulative rating, and corresponding water risk management strategy. Based on the outputs, the user can strategically compare locations, design sustainable water management policies, invest in water efficiency, conservation, treatment technology, or nature-based solutions, and undertake stakeholder engagement based on the key public and media scrutiny themes.

A major gap in tools like WWF Risk Filter, Water Footprint, etc., is the lack of integrated biophysical and contextual risk data to assist decision-making (Dudley et al., 2022; Forin et al., 2018). WATR-DST not only quantifies context-specific regulatory and reputational risks but also provides qualitative themes on crucial reputational issues. The qualitative details inform the user's judgment, which is systematically integrated into this tool for decision-making. Therefore, the combination of quantitative scores and qualitative details at the sub-watershed scale is a salient and unique feature of the tool that were obscured in extant assessments (Dudley et al., 2022; García Sánchez et al., 2023). Moreover, using the water risk management spectrum, a strategy can be chosen based on the cumulative risk score rather than siloed risk scores of extant tools.

5.5.4 Novel contributions of research to knowledge and applications

The research contributes to the knowledge and application-based tools in sustainability management, risk analysis, and environmental management, specifically water resource management, by applying the normative-analytical model to water risk management in the private sector, which had not been done in extant literature. The study's novelty is the use of transdisciplinary mixed methods approaches, to investigate strategies, sector-specific differences, and develop tools for managing risks to water, a key Earth system. By integrating analytical interdisciplinary water risk data with perspectives and concerns of an influential stakeholder like the private sector, the study reveals unique insights and inclusive approaches for water risk management, environmental accounting, and risk communication that challenge the status quo of corporate sustainability management (Busch et al., 2023; Klinke & Renn, 2021; Koehler, 2023). Finally, using the case of Ontario, the decision support tool, "WATR-DST" advances knowledge by integrating Risk Management and Governance Theory with environmental management, highlighting the importance of contextuality in sustainable water management and overcoming the weaknesses of monodisciplinary methods and tools (Loucks, 2023; Renn & Klinke, 2015; Sandhu et al., 2023b).

The WATR-DST (step-by-step demonstration in Appendix 5.D) is a comprehensive environmental management tool for businesses, investors, and regulators that can improve water accounting, decisions, and production practices, by identifying individual water risks, public and media issues, and cumulative risk based on the user's location, sector, and context (Christ & Burritt, 2019; Di Baldassarre et al., 2019; Garrick et al., 2020). This enables strategic comparison of locations and identification of collaborative multi-stakeholder partnerships for sustainable water management, hence improving sustainability performance and accountability for SDG 6 (Christ & Burritt, 2019; Weber & Saunders-Hogberg, 2020). The management of climate-related impacts on water security is one of the pillars of the International Financial Reporting Standards' (IFRS) Sustainability Disclosure Standards that amalgamate the Task Force on Climate-related Financial Disclosure's and the industry-based Sustainability Accounting Standards Board's standards (IFRS, 2023b, 2023a). Since Ontario's climate change adaptation strategies rest on long-term planning, dialogue, and collaboration between stakeholders to manage water-related risks, our study's findings and WATR-DST have key implications for the government, public, and private organizations (Climate Risk Institute et al., 2023).

5.5.5 Research limitations and future recommendations

The risk scores and multipliers used to convert ratings into numerical values in the WATR-DST are illustrative and are not modelled or elicited. Nonetheless, future work can employ multi-stakeholder round-tables to deliberate risk scores for the tool (Sandhu et al., 2020). Second, the study used past data for the baseline risk assessment, which needs to be updated every five years to keep the tool current. However, since the methods and data sources for the tool are well-documented, updating data is not expected to be time-consuming. Third, sensitivity analysis for the scores, quantifying the impact of illustrative scores on the ratings, was out of scope for this study, but future work can delve into data modelling and sensitivity analysis (Dudley et al., 2022). Finally, the study focused on Ontario and the private sector, to reveal the importance of contextuality and local scale for water management (Bilalova et al., 2023; García Sánchez et al., 2023; Zipper et al., 2020). Nonetheless, for generalizability, the study's methods, framework, and tool's design can be applied in future work to other provinces, countries, and stakeholder groups (Creswell & Creswell, 2018).

5.6 Conclusion

While transdisciplinary normative-analytical frameworks are discussed in the literature, operationalizing this approach for management of water risks and decision support in the private sector was a research gap. Addressing this gap, the study applied a normative-analytical model and transdisciplinary mixed methods to engage with corporate and financial practitioners and investigate strategies and preferences for water risk management. Moreover, the study designed a decision support tool, which integrated interdisciplinary analytical water risks and practitioner perspectives for the case of Ontario to assist practical decision-making. The study concludes that to manage wicked sustainability challenges like water, a one-size-fits-all risk management strategy may be insufficient. Thus, a combination of regulatory, voluntary, and multi-stakeholder participatory approaches is recommended contingent on the severity of interdisciplinary water risks, context, sector, and location. Moreover, flexibility, certainty, efficiency, strategic incentives, and economic and regulatory signals are essential for water risk management.

Aligned with inclusive approaches for sustainability management and risk governance, the private sector is an influential actor in the water management and decision-making landscape, where diverse interests, values, knowledge, and preferences, must be considered in risk management frameworks. The study reveals multiple opportunities for transdisciplinary knowledge co-development, dissemination, and collaboration between industry, academia, civil society, and government agencies that can help build trust and risk communication platforms for critical sustainability challenges like water. The study's transdisciplinary investigation into water risk management strategies and development of the WATR-DST is a key theoretical and practical contribution that can help businesses, investors, and regulators identify and manage sub-watershed and sector-specific water risks. Thus, the study's findings and tool can improve strategies, practices, and actions for sustainable water management.

MANUSCRIPT ENDS

Chapter 6

6. Conclusion

A review of literature revealed limited investigation of the interdisciplinary assessment of water security risks at the local watershed scale, and how these water risks are evaluated and managed by influential actors in the water management and governance landscape like the corporate and financial sector (Cai et al., 2021; Christ & Burritt, 2017a, b, 2018; Di Baldassarre et al., 2019, 2021; Rusca & Di Baldassarre, 2019; Savelli et al., 2022). Addressing these gaps, the dissertation successfully executed its three-fold objective, and investigated its phenomenon of interest, i.e., water security risks, specifically, water risk assessment, risk perception and evaluation, management, and developed a transdisciplinary decision support tool at the sub-watershed scale for Ontario, Canada. Overall, the dissertation has five key outcomes discussed in Section 6.1, which overcome the weaknesses of siloed approaches used in extant literature on water risk assessment, management, and decision-making. Moreover, it advances knowledge by integrating social-ecological approaches of sustainability management with risk analysis for the contemporary case of Ontario, Canada (Di Baldassarre et al., 2021; Mitchell, 2017; Quandt, 2022; Rangecroft et al., 2021; Renn & Schweizer, 2009; Xu et al., 2018).

This dissertation is the first comprehensive scholarship to focus on the multi-faceted wicked risk and sustainability problem of water security in Ontario, using Risk Theory, intersecting multiple disciplinary paradigms to develop a novel normative-analytical theoretical framework (Figure 1.2) for water assessment, perception, evaluation, and risk management, for a non-state influential actor like corporate and financial sector (Alvarado-Revilla & de Loë, 2022; Dobbie et al., 2016; Kasperson et al., 2022; Klinke & Renn, 2021; Roeser et al., 2012; Siegrist & Árvai, 2020). This novel theoretical framework contributes to the literature and theory in the fields of sustainability management, risk analysis, socio-hydrology, and environmental management, specifically, water resource management (Busch et al., 2023; Christ & Burritt, 2019; Cosgrove & Loucks, 2015; Klinke & Renn, 2021; Weber & Saunders-Hogberg, 2020).

6.1 Key outcomes of the research: Empirically challenging the scholarly myths

The dissertation's overarching outcomes are discussed below. The scholarly arguments and gaps revealed in the literature are presented as scholarly "myths" and how this dissertation empirically challenged these myths.

i. ***Challenging the myth of water abundance in Ontario:*** The literature revealed a lagging global performance on the targets of SDG 6, highlighting exacerbating risks and impacts of water insecurity (Sadoff et al., 2020; UN-Water, 2021). The province of Ontario, Canada is an interesting case study from an academic perspective (Sandhu et al., 2020a, b). It is perceived as water-abundant with the Great Lakes watershed, apt for water-reliant industries, trade, and investment, but the nuances of quality, regulatory complexity, and public perception are often overlooked (Bonsal et al., 2019; Johns, 2017; Mitchell, 2017; Sandhu et al., 2020a; Sprauge, 2006). The dissertation argues for a comprehensive definition of water security risks, going beyond the biophysical quantity of water and including the nuances of quality, spatial and temporal variability, regulatory accessibility, public perception, legacy issues, and conflicts. Thus, the dissertation defines and assesses water security risks as a multi-dimensional construct using integrated biophysical and social approaches, interdisciplinary data, and transdisciplinary methods with practitioner perception, insights, and a local disaggregated scale (Cosgrove & Loucks, 2015; Evers et al., 2017; Krueger et al., 2016; Signori & Bodino, 2013; Wheater & Gober, 2015; Xu et al., 2018).

   Intersecting key concepts of transdisciplinary approaches for water management (Cai et al., 2021; Cosgrove & Loucks, 2015; Krueger et al., 2016; Wyrwoll et al., 2018) with risk governance (Dobbie et al., 2016; Klinke & Renn, 2021; Koehler, 2023; Renn, 2021; Renn et al., 2022), the research finds that considering biophysical quantity and quality alone, without contextual aspects of regulatory access, legacy issues, public perception, and practitioner insights, can lead to underestimation of total water risk (Cosgrove & Loucks, 2015; Gilsbach et al., 2019; Sandhu et al., 2020a; Signori & Bodino, 2013). Moreover, using siloed disciplinary approaches further fuel the myth of water abundance in Ontario, skewing trust, confidence, and risk management strategies and decision-making towards reactive and laissez-faire preferences (Evers et al., 2017; Gilsbach et al., 2019; Mitchell, 2017; van Vliet, 2023). Challenging extant aggregated assessments, theories, data, and methods, dominant in water management and sustainability literature, Chapter 2 and 3 find moderate to high risk in all water risk categories in at least half of the studied areas in Ontario (Dudley et al., 2022; Morgan et al., 2020; WWF, 2021).

ii. ***Challenging the myth of superiority of generalizability over contextuality in the water management and governance landscape:*** A key facet of water risk assessment and management, is the relevance of a disaggregated sub-watershed scale, context, values, and interests of diverse actors rather than aggregated and generalized assessments (Bilalova et al., Cosgrove & Loucks, 2015; Evers et al., 2017; Quandt, 2022; Wheater & Gober, 2015; Xu et al., 2018; Zipper et al., 2020). Extending Renn's (1998) conclusion, of "context matters," for general risk perception, to the domain of water risks, the contextual nuances of knowledge, values, interests, trust, gender, and location are found to be important considerations for water risk assessment, evaluation, and management (Dobbie et al., 2016; Dobbie & Brown, 2014; Klinke & Renn, 2021; Siegrist, 2021; Siegrist & Árvai, 2020).

Moreover, the water management and governance landscape is diverse, where in addition to state actors like governments, non-state actors like the private sector, civil society, and local communities, impact (inside-out) and are affected (outside-in) by water security issues (Alvarado-Revilla & de Loë, 2022; Christ & Burritt, 2018, 2019; Evers et al., 2017; Klinke & Renn, 2021; Loucks, 2017; Wheater & Gober, 2015). The dissertation finds the private corporate and financial sector (CFS) is an influential yet underexplored actor in water risk management, where its operations and decisions impact local water security (Christ & Burritt, 2018, 2019; Klinke & Renn, 2021; Loucks, 2017). Thus, Chapter 2 and 3 provide an interdisciplinary and comprehensive framework to quantify physical, regulatory, reputational, and inside-out impact-based sector-specific risks at the sub-watershed scale that are overlooked by extant tools (Christ & Burritt, 2017; Gilsbach et al., 2019; Josset & Concha Larrauri, 2021). Chapters 4 and 5 find that risk perception, priorities, and preferences of analysts, managers, and decision-makers in the private sector is also a context-specific construct that impact water risk evaluation and management, having important implications for designing transdisciplinary tools and strategies for sustainable water management.

iii. ***Challenging the myth of a simple model of expert risk perception:*** The dissertation challenges the simple and fully rational model of risk perception in experts, including analysts, managers, and decision-makers for a wicked risk problem like water (Dobbie & Brown, 2014; McDaniels et al., 1997; Mumbi & Watanabe, 2020; Sjöberg, 2002; Slimak & Dietz, 2006; Vasvári, 2015; Weber, 2001). Moreover, the dissertation extends the definition of experts to include practicing experts or practitioners who analyze risk, prioritize and evaluate options, and make decisions related to water (Aven, 2016; Dobbie & Brown, 2014; Sjöberg, 2002; Vasvári, 2015). Chapter 4 argues that, humans, whether lay or expert are not value-free and their overt and tacit experiences, knowledge, attitudes, and beliefs impact how they perceive and prioritize risk (Aven, 2016; Dobbie & Brown, 2014; Klinke & Renn, 2021; Siegrist & Árvai, 2020; Sjöberg, 2002; Slovic, 1999). As risk problems become wicked, data and certainty reduce, the role of social variables, interests, and values, take precedence in risk analysis and decision-making. It finds that cognitive, affective, socio-cultural demographic, trust-based, and spatial factors generate risk perception and affect water risk evaluation to varying extents contingent on the type of water risk. Thus, revealing the complex underlying mechanisms of expert risk perception and its impact on risk evaluation, management, and decision-making (Dobbie & Brown, 2014; Klinke & Renn, 2021; Siegrist, 2021; Siegrist & Árvai, 2020; Slimak & Dietz, 2006; Slovic, 1987, 1999).

iv. ***Challenging the myth of a panacea strategy for water risk management:*** The dissertation argues that a one-size-fits-all panacea strategy will be insufficient for water risk management (Aven & Renn, 2020; Busch et al., 2023; Koehler, 2023; Money, 2014a, 2014b). The findings of Chapter 5 highlight that a water risk management strategy needs to be a combination of multiple strategies, tailored based on the sector, location, and context as well as severity of water risks at the local sub-watershed scale. Moreover, flexibility, efficiency, and strategic-ness of market-based self-regulatory private sector approaches can be complemented by checks and balance, oversight, and standardization of regulatory approaches as well as institutional diversity of multi-stakeholder participatory approaches (Busch et al., 2023; Dobbie et al., 2016; Garrick et al., 2020; Klinke & Renn, 2012, 2021; Renn & Klinke, 2015; Vasvári, 2015). Finally, the dominant ethos of business case of sustainability for financially relevant risks is confirmed for water, which needs to transition into the double materiality and sustainability case (Busch et al., 2023; Driver et al., 2023). The dissertation upholds the arguments by Busch et al. (2023), Koehler (2023), and Weber and Feltmate (2016) for water, and emphasizes using hybrid approaches for water risk management to transition the business case of sustainable water management to the sustainability case, also bringing socially and environmentally-relevant risks to the forefront of corporate and financial decision-making.

The dissertation maintains that the private sector is an influential actor in the water management and decision-making landscape, where their diverse interests, values, knowledge, and preferences, should be considered in risk management. Moreover, transdisciplinary collaboration for knowledge co-development, communication, and trust-building between industry, academia, government, and the civil society are identified as key opportunities for water risk management and governance (Busch et al., 2023; Christ & Burritt, 2018; Krueger et al., 2016; Renn, 2021; United Nations, 2023). Finally, WATR-DST, the decision support tool for water risk management exemplifies the social-ecological systems-based integration of interdisciplinary water risks with transdisciplinary practitioner priorities, preferences, and insights to improve decisions and practices for sustainable water management, corporate sustainability, and accountability (Christ & Burritt, 2018, 2019; Loucks, 2023; Weber & Saunders-Hogberg, 2020). It is a key output that can help identify water risks, risk management strategies, and opportunities for collaboration and risk communication (Miles et al., 2023; Wyrwoll et al., 2018; Yang, 2017).

v. ***Challenging the myth of superiority of siloed disciplines, methods, and theories for water risk assessment, management, and decision-making:*** Amidst calls for interdisciplinary approaches for addressing wicked sustainability challenges and risk problems like water security, the predominant strategy in the literature is the use of siloed disciplinary approaches, where there is a divide between natural sciences, applied sciences, and social sciences, as well as quantitative and qualitative approaches (Di Baldassarre et al., 2021; Evers et al., 2017; Krueger et al., 2016; Renn 2021). Bringing together quantitative and qualitative datasets, hydrological and social indicators, and using an integrated interdisciplinary social-ecological perspective and transdisciplinary approaches was a major gap (Di Baldassarre et al., 2019, 2021; Josset & Concha Larrauri, 2021; Loucks, 2015; Renn, 2021; Xu et al., 2018). The dissertation successfully addressed this gap by applying an interdisciplinary social-ecological systems approach for water risk assessment and management. It intersected normative-analytical theoretical frameworks, synthesized interdisciplinary data and knowledge from fields of hydrology, political science, economics, psychology, sociology, sustainability management, and corporate management, using diverse methods like secondary data analysis, surveys, and interviews with practitioners to co-develop knowledge and practical tools.

The dissertation confirms that a single discipline, approach, theory or method is largely insufficient in assessing total water risk, teasing out conceptual complexities of expert risk perception, and its influence on risk evaluation, management, and decision-making (Di Baldassarre et al., 2021; Kasperson et al., 2022; Koehler, 2023; Krueger et al., 2016; Renn, 2021, Roeser et al., 2012; Siegrist & Árvai, 2020; Vasvári, 2015). The rigor of quantitative approaches, data, and methods were successfully combined with the depth and nuances of qualitative approaches, data, and methods enhancing the validity, reliability, and novelty of the research (Creswell & Creswell, 2018; Harris-Lovett et al., 2019; Quinn et al., 2019).

Similarly, rather a single disciplinary theory, the dissertation applied the interdisciplinary Risk Theory that draws constructs, variables, and hypotheses from theories in sociology, psychometric theory, cultural theory, organizational and management theories, such that the phenomena of interest could be explored and examined from multiple disciplinary angles and gain a comprehensive understanding (CohenMiller & Pate, 2019; Dobbie & Brown, 2014; Roeser et al., 2012; Slimak & Dietz, 2006). Thus, rather than controlling for variables, the dissertation intentionally considered multiple constructs to reveal their impact on water risk evaluation and management (Mumbi & Watanabe, 2020; Siegrist & Árvai, 2020). Using this approach, Chapter 4 revealed the cognitive, affective, spatial, socio-cultural factors, and nuances of gender and trust, that shape expert risk perception and impact evaluation of different water risks. The dissertation hence validated the normative-analytical theoretical framework for water and corporate and financial practitioners, using mixed methods.

6.2 Contributions to knowledge

Given the five broad outcomes, the dissertation makes several novel contributions by advancing knowledge in the fields of sustainability management, risk analysis, environmental management, specifically, water resource management, and socio-hydrology.

First, the dissertation developed and operationalized a first-of-a-kind normative-analytical risk governance theoretical framework for water risk assessment, management, and decision-making. Moreoever, the novel application of Risk Theory, intersecting interdisciplinary social-ecological systems perspective and risk analysis, to define, assess, evaluate, and manage water risks using granular biophysical and social water risk data and mixed methods, had not been done in the literature (Di Baldassarre et al., 2019, 2021; Dobbie & Brown, 2014; Quandt, 2022; Rangecroft et al., 2021; Renn & Schweizer, 2009; Roeser et al., 2012; Xu et al., 2018). The dissertation's comprehensive and interdisciplinary definition and assessment of water security risks using the systems concept of *wickedness*, integration of risk analysis with social, ecological, and hydrological dimensions, as well as methodological novelty of combining hydrological, regulatory, media coverage, public concern, conflict, and sector-specific data, provided a realistic estimation of the total water risk at the sub-watershed scale. Thus, broadening extant siloed approaches of hydrology, risk assessment, corporate water accounting and management, and advancing knowledge in the fields of sustainability management, socio-hydrology, and risk analysis (Aven & Flage, 2020; Di Baldassarre et al., 2019; Gladwin et al., 1995; Evers et al., 2017; Klinke & Renn, 2021; Quandt, 2022; Xu et al., 2018).

Second, the dissertation makes a contribution to knowledge in the field of risk analysis by examining and explaining the underexplored construct of expert risk perception and its relationship with water risk evaluation (Dobbie & Brown, 2014; Siegrist & Árvai, 2020; Slovic et al., 2004). By examining the impact of cognitive, affective, trust-based, location-based, and socio-cultural demographic factors of risk perception on risk evaluation, the dissertation highlights their importance for comprehensive risk analysis and decision-making. While extant research has primarily focused on risk perception of lay public, academic experts, and the public sector, for environmental problems as a whole, the dissertation's comprehensive theoretical approach and findings on risk-centric and individual-centric factors of perception for the risk domain of water security and influential actors like the corporate and financial sector as practicing experts is a novel addition to the knowledge of risk perception and analysis (Dobbie et al., 2016; Mumbi & Watanabe, 2020; Siegrist & Árvai, 2020; Slimak & Dietz, 2006).

Third, the dissertation makes a contribution to knowledge in risk analysis, sustainability management, environmental (water resources) management, by applying and validating the normative-analytical risk governance model for water risk management and decision-making in the CFS using transdisciplinary mixed methods (Christ & Burritt, 2018; Klinke & Renn, 2021; Koehler, 2023; Krueger et al., 2016; Renn, 2021; Slimak & Dietz, 2006; Vasvári, 2015). The spectrum of strategies developed for water risk management, and insights revealed on communication, deliberation, and trust-building to improve corporate sustainability and environmental performance, build a case for integrating transdisciplinary normative-analytical risk governance approaches in sustainability and environmental management (Busch et al., 2023; Klinke & Renn, 2021; Starik & Kanashiro, 2013). Moreover, the development a first-of-a-kind transdisciplinary tool, "WATR-DST", is an application-based contribution to the field of risk analysis and sustainability management (Dudley et al., 2022; Loucks, 2023; Renn, 2021).

Finally, the dissertation's research design, theoretical framework, and methods based on interdisciplinary theories, data, and transdisciplinary inputs of practitioners are important methodological contributions to advance the field of sustainability management and risk analysis

(Busch et al., 2023; Christ & Burritt, 2018, 2019; Krueger et al., 2016; Renn, 2021). The dissertation successfully synthesized quantitative rigor and qualitative depth, to enhance the understanding of complex concepts and relationships of wicked systems-based water challenges, water risk perception, and water risk management strategies that are often obscured in single method quantitative studies (Di Baldassarre et al., 2021; Quandt, 2022; Shan, 2022). Follow-up interviews validated the survey's findings, provided nuanced theoretical understanding, and revealed underlying causal mechanisms that informed future work (Creswell & Creswell, 2018; Quandt, 2022). For instance, interviews revealed the prevalence of a "carbon tunnel-vision" , where the dominant focus on carbon emissions, energy, and climate overlook equally relevant and interconnected sustainability challenges like water (Konietzko, 2022). Transdisciplinary approaches are often proposed as a pertinent approach in sustainability and water management as well as risk management literature, but were yet to be used (Christ & Burritt, 2018, 2019; Evers et al., 2017; Krueger et al., 2016; Renn, 2021). This dissertation demonstrates the application of transdisciplinary methodological approaches, to co-develop knowledge and applications with the CFS practitioners, advocating for its widespread use in sustainability management research.

6.3 Contributions to theory

The dissertation makes a novel theoretical contribution by applying and validating the interdisciplinary Risk Theory for the domain of water and developing the normative-analytical water risk assessment and management theoretical framework (Aven & Renn, 2020; Dobbie & Brown, 2014; Klinke & Renn, 2021; Roeser et al., 2012). Existing literature in the fields of sustainability management, risk analysis, and water management, use theories confined by disciplinary norms (Busch et al., 2023; Christ & Burritt, 2018; Renn et al., 2022; Renn & Schweizer, 2009; Slimak & Dietz, 2006; Starik & Kanashiro, 2013; Xu et al., 2018). Occupying the niche of interdisciplinary theories, this dissertation integrated Psychometric, Cultural, Relational, Social-ecological, Decision, and Organizational and Management theories (e.g., theories of Sustainability Management, Corporate Sustainability, and Environmental Management), to develop constructs, hypotheses, and finally the theoretical framework for water risk assessment, perception, evaluation, and management (Busch et al., 2023; CohenMiller & Pate, 2019; Dobbie & Brown, 2014; Renn & Klinke, 2015; Roeser et al., 2012).

First, using the normative-analytical theoretical framework, the dissertation revealed the nuanced risk perception of practicing experts, shaped by cognitive, affective, socio-cultural, demographic spatial, and trust-based factors that influence the risk evaluation contingent on the type of water risk. The structure of expert risk perception has important implications for Risk Perception Theory, Decision Theory, and Dual Process Theory, where experts were considered to be value-free, context-free, and fully rational decision-makers (Dobbie & Brown, 2014; Roeser et al., 2012; Siegrist, 2021; Siegrist & Árvai, 2020; Slovic et al., 2004). The dissertation challenged this generalized notion, and advanced Risk Perception and Decision Theory by emphasizing on the value-based model of expert risk perception, contingent on the context and complexity of the risk problem. Both System 1 (implicit and affect based, i.e., "risk as feelings") and System 2 (explicit and cognitive based, i.e., "risk as analysis") thinking models can be evoked in decision making by experts, analysts, and decision-makers (Sjöberg, 2002; Slimak & Dietz, 2006; Slovic et al., 2004; Vasvári, 2015). Thus, rationality, cognition, and reason are inextricably connected to an individual's emotions, affect, feelings, and experiences, for wicked risk problems like water (Roeser et al., 2012; Siegrist & Árvai, 2020; Slovic et al., 2004).

Second, by including socio-cultural demographic variables like gender, educational discipline, location, cultural importance, role, sector, etc., as a part of the interdisciplinary theoretical framework in Chapter 4, their impact on water risk evaluation was confirmed (Mumbi & Watanabe, 2020; Slimak & Dietz, 2006; Slovic, 1999). Otherwise, omitting these theoretically relevant variables could have skewed the findings. In terms of specific theoretical constructs, the role of gender, trust, exposure, location (proximity), and their relationship with water risk evaluation and management are interesting contributions from a theoretical perspective (Dobbie & Brown, 2014; Dupont et al., 2010; Krewski et al., 2008; Siegrist, 2021). For instance, Chapter 4 finds proximity bias, i.e., lower concern and higher confidence of water security in one's own location compared to Ontario. This discounting was related to cognitive aspects of excessive information about non-local issues via media or lack of information about local issues, where non-local issues may take cognitive precedence in risk ratings, confirming the role of media in water risk perception, in line with the broader environmental risk perception literature (Flynn, 1998; Kasperson et al., 2022; Slovic, 1999). Building upon the work of Siegrist (2019) and Kasperson et al. (2022), the dissertation also finds trust to be a theoretically nuanced construct, where trust is placed in government agencies, individual's own organization, and immediate stakeholders rather than the industry as a whole. Moreover, trust may be disconnected from one's organizational risk management strategy due to preference of business-as-usual financial bottom line approaches for risk management, further skewed by the perception of relative water abundance in Ontario (Dobbie et al., 2016; Weber & Saunders-Hogberg, 2020).

Finally, the dissertation makes a contribution to Decision and Risk Governance Theory by operationalizing and validating the normative-analytical risk governance model for water risk management and decision-making in the CFS (Koehler, 2023; Renn & Klinke, 2015; Weber & Saunders-Hogberg, 2020). Moreover, by considering the insights and preferences of an influential stakeholder like the private sector for water risk management, communication, and trust-building can help advance theoretical development in the fields of sustainability management and inclusive risk governance (Busch et al., 2023; Klinke & Renn, 2021; Renn & Schweizer, 2009; Siegrist, 2021; Weber & Saunders-Hogberg, 2020).

6.4 Contributions to practice

The dissertation's findings and the transdisciplinary decision support tool, WATR-DST, have several important implications for practice. First, the findings of Chapter 3 on interdisciplinary water risk assessment, provide location and sector-specific water quantity, quality, and conflict hotspots, sector-specific risk ratings, and public concern and media themes, which can be used by businesses, investors, insurers, lenders, policy-makers, and civil society to identify severity of different water security risks and prevalent issues of concern and conflicts in their sub-watersheds. Moreover, the general public is a key beneficiary, who can use the findings to hold the state and non-state actors accountable for improving and managing local water security risks. Hence, informing decisions, policies, practices, and investments for sustainable water management and catalyzing progress on SDG 6 (United Nations, 2023). The higher total water risk found across Ontario further highlights the weaknesses of popularly used water accounting tools like WWF Water Risk Filter and the risks of using aggregated data, to the private sector.

Second, Chapters 4 and 5 were based on a transdisciplinary approach, focused on co-developing interdisciplinary knowledge with practitioners on water risk perception, evaluation, and management and applying that knowledge to design practical decision support tools that helps bridge the academia-policy-practice gap. The findings revealed that water risk evaluation, management, and decision-making is not a purely objective and value-free process and the nuances of individual-centric cognitive and affective factors and influence of regulatory signals, economic signals, stakeholder expectations, reputation, media, location and trust, should be considered in multi-sector decision-making frameworks. Moreover, the cognitive, affective, trust-based, and spatial factors inform strategies for practitioner trainings, multi-stakeholder engagement, and risk communication. The prevalence of the carbon-tunnel vision, dominance of financial bottom line and business case arguments for water-related decision-making, signals the status quo to the private sector. Nonetheless, the findings also guide the private sector how to consider systems-based social-ecological and double materiality approaches to overcome the status quo and improve corporate water performance.

Third, the findings on proximity bias, the role of trust, contextually-attuned regulations, the influence of media, location, and financial materiality have important implications for state actors and policy-makers, developing sustainable water management strategies for climate adaptation and resilience. The findings highlight the criticality of strategically designed and contextually-attuned government regulations for water risk management. Moreover, multi-stakeholder trust-building, knowledge sharing, and collaboration at the sub-watershed scale are identified as important avenues for inclusive water governance in Ontario. Canadian Securities Administrators' "National Instrument 51-107 on the Disclosure of Climate-related Matters," reflects a major impetus towards mandatory disclosure and risk management of key climate-related and sustainability challenges like water (Canadian Securities Administrators, 2021). Thus, the findings can inform Ontario and Canada's climate change adaptation strategies and foster multi-stakeholder dialogue, collaboration, and partnerships to manage climate and water security risks (Climate Risk Institute et al., 2023).

Finally, Chapter 5 developed a transdisciplinary decision support tool, an important practical application of this dissertation to guide multi-sector sustainable water management policies and practices. The WATR-DST was developed as a comprehensive application-based and user-friendly tool for multi-sector businesses, investors, lenders, insurers, and regulators, to apply the dissertation's findings and assist water-related decision-making. As demonstrated in Appendix 5.D, the practitioners (analysts, managers, decision-makers) can enter their location, sector, and source type using pre-defined lists and instructions, and the tool displays results for individual water risks, cumulative rating, and water risk management strategies in a simple and effective manner. Moreover, it provides qualitative information to assist evidence-based judgment for contextual risk indicators like reputational risk. Based on the tool's results, the practitioners can identify individual risk issues in need of attention, strategically compare locations, make investment decisions regarding water efficiency, treatment, or nature-based solutions, undertake stakeholder engagement based on the public and media scrutiny themes. Hence, fostering implementation of relevant water risk management strategies for sustainable water management and improving corporate sustainability performance and accountability (Christ & Burritt, 2019; Weber & Saunders-Hogberg, 2020).

6.5 Limitations of research

In line with the research objective, the water risk assessment is based on secondary past baseline data, which was not modelled or forecasted. Thus, the data needs to be updated to keep the assessment current. Moreover, the multipliers used in the tool are illustrative but can be deliberated in future work using multi-stakeholder roundtables. Second, the research objective and theoretical framework were designed to be explanatory, examining relationships between risk perception factors and ratings and not predictive or causal (Shmueli, 2010). The interviews provided causal insights, but causality needs to be empirically established in future work using a causal research objective. Third, in a highly specific and purposive sampling of participants, the relevance of the sample to the research objective takes precedence over the sample size (Mooney et al., 2020; Palinkas et al., 2015). Small samples require large effect sizes to be statistically significant, hence being prone to false negatives (Type II errors) (Norman, 2010). Nonetheless, this weakness is overcome by conducting additional statistical tests and follow-up interviews, where the findings were explained and validated (Creswell & Creswell, 2018; Ivankova et al., 2006). While a large sample is desirable in surveys, the strong theoretical foundation of risk perception enabled appropriate regression models and interviews provided further validity and reliability of the findings (Jenkins & Quintana-Ascencio, 2020; Norman, 2010).

From a generalizability perspective, the research is spatially scoped to Ontario. However, the literature emphasizes using an in-depth case study-like approach to capture locally-relevant water security challenges, conflicts, regulatory trends, and perspectives of stakeholders, (Christ et al., 2016; Hogeboom et al., 2018). Nonetheless, even with the intended objective of particularity and a purposive practitioner sample for Ontario, the dissertation provides the general method to design the water risk assessment and management framework that can be extended and applied (research transferability) to different geographical contexts and other stakeholder groups for comparative case analysis beyond Ontario (Creswell & Creswell, 2018).

6.6 Future research directions

In addition to the contributions to knowledge, theory, and practice, the dissertation identified research avenues to further advance scholarship and applications for sustainable water management. First, future work can expand the baseline water risk assessment of Chapter 3 by delving into dynamic and predictive socio-hydrological modelling at the sub-watershed scale, comparing different temporal, spatial, and climate change scenarios and quantifying systemic impacts on stakeholders (Di Baldassarre et al., 2019). Sensitivity analysis is another area for enhancing the robustness of the risk assessment framework and WATR-DST.

Second, institutional aspects of water risk governance is a promising area to integrate concepts of resilience, vulnerability, and political ecology (Evers et al., 2017; Koehler, 2023; Linkov et al., 2014). Future research can focus on how local communities, indigenous communities, socially vulnerable groups, governments, and corporations can assess and manage resilience, vulnerabilities, and adaptive capacity under growing water risks (Xu et al., 2018). The relationship between water risk governance, resilience, and adaptation can be explored using in-depth case studies and participatory research (Kasperson et al., 2022; Quandt, 2022).

Third, future work can investigate the underlying causal mechanisms between water risk perception factors and risk evaluation using longitudinal analysis. Similarly, in-depth examination of proximity bias, trust, role of media, and carbon-tunnel vision and their role in water risk perception in different stakeholder groups are pertinent research areas. Moreover, transdisciplinary water risk communication, double materiality considerations for water risks in multi-stakeholder decision-making, benchmarking water use and integrating real-time quantity, quality, and emerging contaminants of concern data at the sub-watershed scale, risk perception centric training strategies, and multi-stakeholder trust-building and collaboration are key transdisciplinary topics in water. Future studies can also investigate the underlying causal models for water risk management strategies to reveal if the preferences are based on values, attitudes, and socio-cultural demographic characteristics.

Finally, future work can expand the dissertation's theoretical framework to other stakeholders, provinces, and countries to establish a suite of transdisciplinary case studies that advance knowledge and understanding of water security risks and sustainable water management.

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Appendices

I. Appendix A: Figure A.1 for Chapter 3

The supplementary information consists of Figure A.1 (1-3), which is the alternative long form three part flowchart layout for the information presented in Table 3.1 (i.e., the detailed methodological overview of Stage 1).

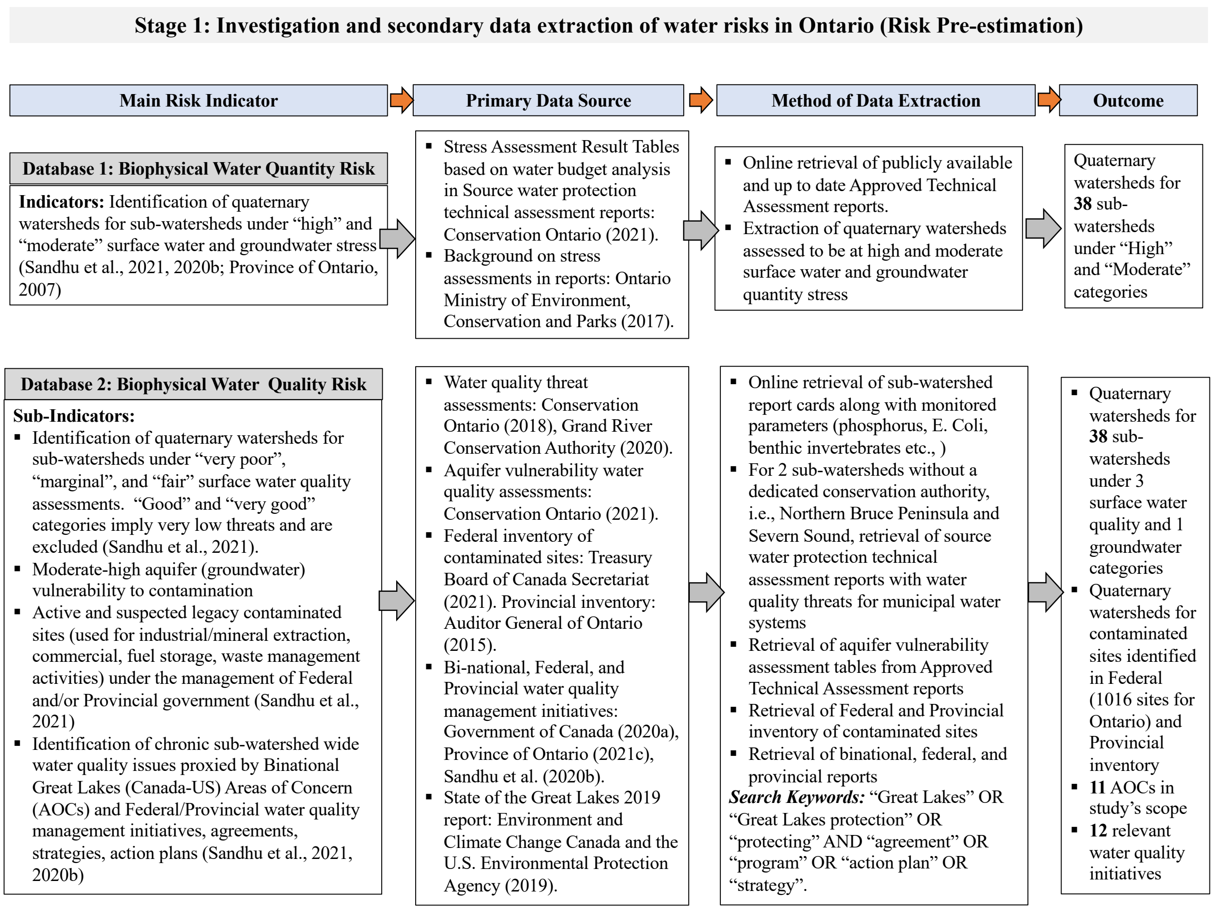


Figure A.1-1. Methodological overview of secondary data extraction for Stage 1 water risk pre-estimation (Alternative flowchart for Table 3.1)

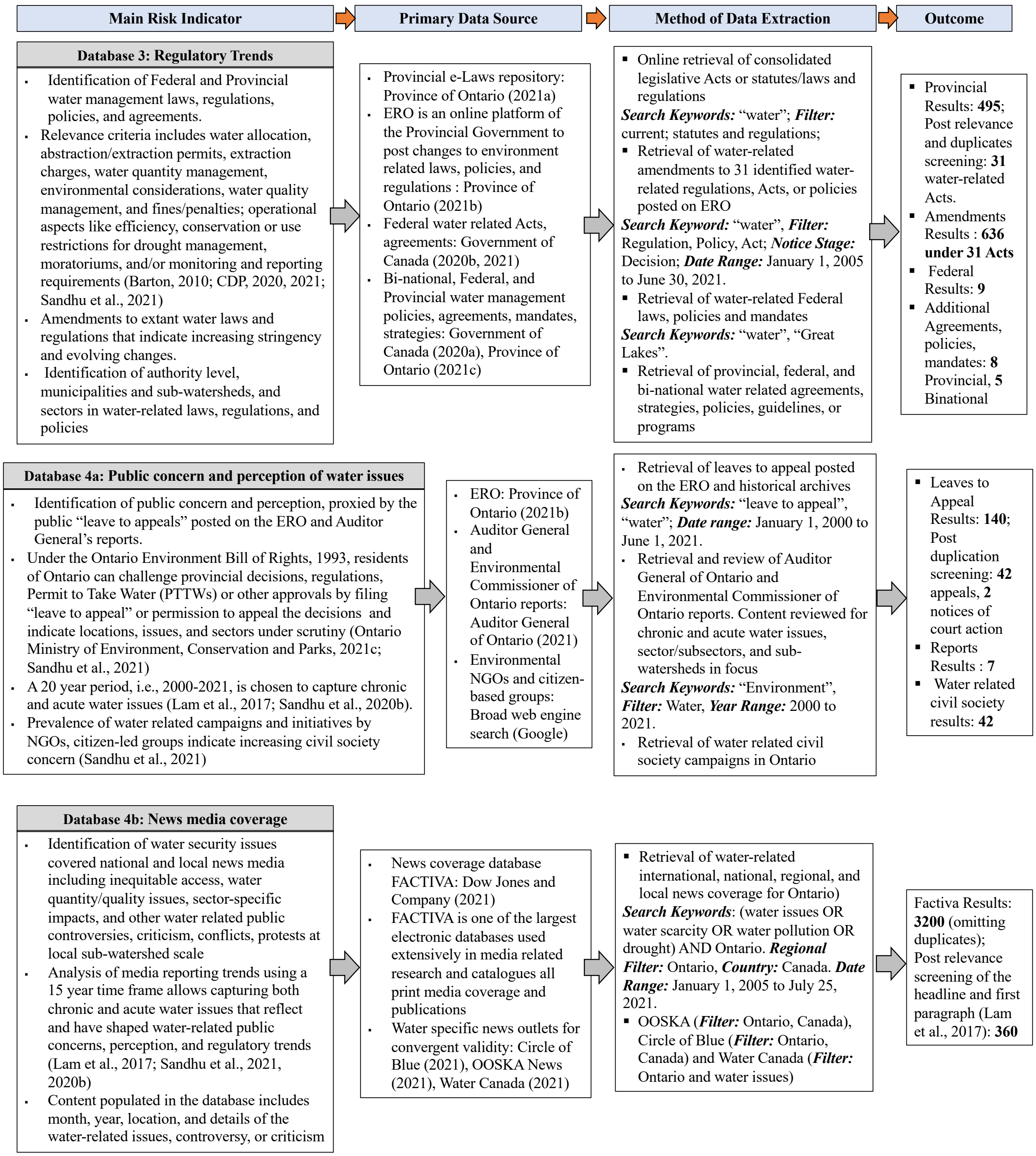


Figure A.1-2. Methodological overview of secondary data extraction for Stage 1 water risk pre-estimation (Alternative flowchart for Table 3.1)

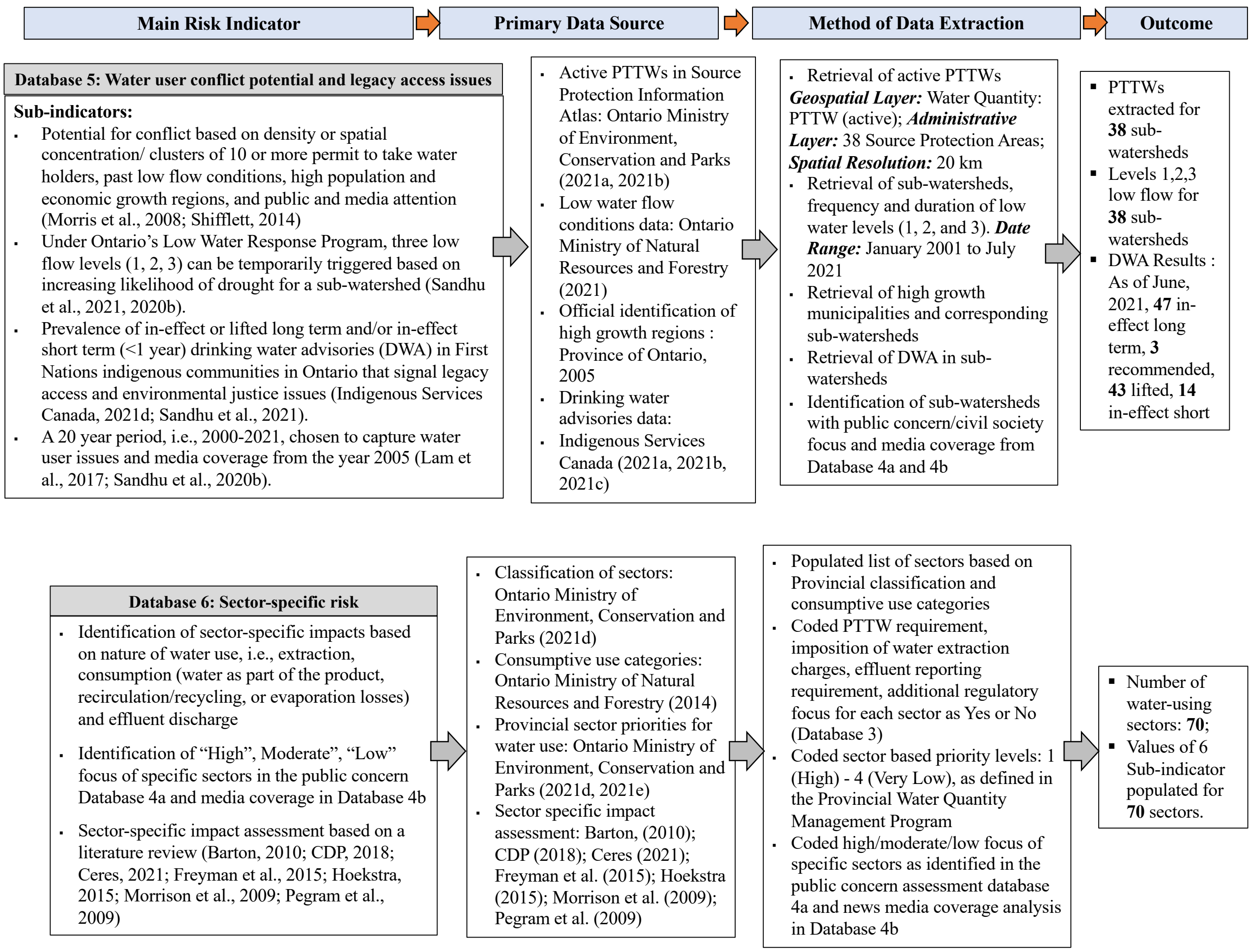


Figure A.1-3. Methodological overview of secondary data extraction for Stage 1 water risk pre-estimation (Alternative flowchart for Table 3.1)

II. Appendix B: Appendices 4.A to 4.E for Chapter 4

Appendix 4.A: Variables, Items, and Rating Scales of Water Risk Perception Survey Questionnaire

Study Variable	Type of Variable	Items on Survey	Brief Description	Rating Scale (Numerical Value and Anchor Labels)	Reference
Nature of Risk	Independent Variable	Q1 (i-iv) Q2 Q3 (i-vii) Q14 Q16 (ii)	Main water issues Likelihood 7 Drivers of issues GHG vs. Water Decision-making	1-7 (Strongly disagree – Strongly agree) 1-7 (Very low – very high) 1-7 (Very low – very high) 1-7 (Very low – very high) 1-7 (Strongly disagree – Strongly agree)	Krewski et al., 2006, 2008; McDaniels et al., 1997; Mumbi & Watanabe, 2020
Attitudes	Independent Variable	Q4 (i) Q4 (ii) Q5 (i-vii) Q 6 (i-v) Q7 (i-v) Q8 Q9 Q10 (i) Q10 (ii) Q11 Q12 (i) Q12 (ii) Q13	Confidence (in Ontario) Confidence (own sub-watershed) Adverse impact Scope Controllability Equity Benefits Exposure-self Recency Exposure-others Concern (in Ontario) Concern (own sub-watershed) Urgency	1-7 (Very unconfident – very confident) 1-7 (Very unconfident – very confident) 1-7 (Very low – very high) 1-7 (Very small – very large) 1-7 (Very uncontrollable– very controllable) 1-7 (Very inequitable – very equitable) 1-7 (Strongly disagree – Strongly agree) 1-7 (Never – Frequently) 1-7 (<2 yrs – >20 yrs, N/A) 1-7 (Never – Frequently) 1-7 (Totally unconcerned – Totally concerned) 1-7 (Totally unconcerned – Totally concerned) 1-7 (Not at all urgent –Very urgent)	Dobbie & Brown, 2014; McDaniels et al., 1997; Dupont et al., 2010; Eagly & Chaiken, 2007; Mumbi & Watanabe, 2020; Thistlethwaite et al., 2018 Bouman et al., 2018; Dupont et al., 2014; Slimak & Dietz, 2006
Knowledge	Independent Variable	Q15 (i-ii) Q16 (i) Q17(i-ii) Q18 (i-iv)	Experience Global water issues Knowledge-other Self assessment	1-7 (No experience –Very experienced) 1-7 (Strongly disagree – Strongly agree) 1-7 (Very little– High amount) 1-7 (Strongly disagree – Strongly agree)	Krewski et al., 2006, McDaniels et al., 1997; Mumbi & Watanabe, 2020; Slimak & Dietz, 2006; Thistlethwaite et al., 2018
Source of Information	Independent Variable (Future)	Q19	Source of information	Select one option/ Text entry	Krewski et al., 2006, 2008
Values and Beliefs	Independent Variable	Q20 (i, ii, iii, ix, x) Q20 (v), Q9 Q20 (iv, vii,viii) Q20 (vi)	Biospheric+ Altruistic Economic Benefits Egoistic Tech Optimism	1-7 (Strongly disagree – Strongly agree) 1-7 (Strongly disagree – Strongly agree) 1-7 (Strongly disagree – Strongly agree) 1-7 (Strongly disagree – Strongly agree)	Bouman et al., 2018; Gladwin et al., 1995; Krewski et al., 1995, 2008; Sjöberg, 2000a, 2000b

Cultural Importance	Independent Variable	Q21	Cultural importance	1-7 (Not at all –Very important)	Dobbie & Brown, 2014; Dupont et al., 2014
Trust	Independent Variable	Q22 (i) Q22 (ii) Q22 (iii)	Government Private sector Civil Society	1-7 (Not at all – Very high) 1-7 (Not at all – Very high) 1-7 (Not at all – Very high)	Dobbie & Brown, 2014; Krewski et al., 2008; Mumbi & Watanabe, 2020
Socio-cultural Demographic Characteristics	Independent Variable	Q24 Q25 Q26 Q27 (i-ii) Q27 (iii) Q27 (iv)	Age Gender Ethnicity Education Professional Role Sector	Select one option Select one option/ Text entry Select one option/ Text entry Select one option/ Text entry Text entry Select one option/ Text entry	Dobbie & Brown, 2014; Dupont et al., 2014; Krewski et al., 2006; Mumbi & Watanabe, 2020; Slimak & Dietz, 2006; Weber, 2001
Proximity	Independent Variable	Q28 (i-ii) Q29 (i-ii) Q30	Location (sub-watershed) Time spent Location (outside Ontario)	Text entry Text entry Text entry	Dupont et al., 2014; Krewski et al., 2006; Mumbi & Watanabe, 2020; Money, 2014b
Water Risk Ratings/ Priority/ Weight	Main Dependent Variable	Q23 (i-vii)	Water Quantity Water Quality Source Type Regulatory User Conflict Sector specific Public/Media attention	1-7 (1: Lowest rating– 7: Highest) 1-7 (1: Lowest rating – 7: Highest) 1-7 (1: Lowest rating – 7: Highest) 1-7 (1: Lowest rating – 7: Highest) 1-7 (1: Lowest rating – 7: Highest) 1-7 (1: Lowest rating – 7: Highest) 1-7 (1: Lowest rating – 7: Highest)	McDaniels et al., 1997; Mumbi & Watanabe, 2020; Slimak & Dietz, 2006; O. Weber et al., 2001; Olaf Weber, 2001
Risk Management Strategy	Exploratory Dependent Variable (Future Study)	Q16 (iii-vi)	Regulation Research Private sector approaches Participatory	1-7 (Strongly disagree – Strongly agree) 1-7 (Strongly disagree – Strongly agree) 1-7 (Strongly disagree – Strongly agree) 1-7 (Strongly disagree – Strongly agree)	Klinke & Renn, 2012; Krewski et al., 2008; McDaniels, 1997

Appendix 4.B: Results from Exploratory Factor Analysis of Water Risk Perception Survey

Table 4.B1: Results from exploratory factor analysis of water risk ratings (dependent variable)

Final Construct	Survey Items	Components 1	Components 2	
Social Water Risk, DV 3	Q23_6_ Sector specific	0.892		
	Q23_5_ User Conflict	0.765		
	Q23_4_ Regulatory	0.735		
	Q23_7_ Public Media Attention	0.523		
Indirect Water Scarcity Risk, DV 2	Q23_3_ Source Type		0.881	
	Q23_2_ Water Quality		0.865	
Direct Water Scarcity Risk (quantity risk), DV 1	Q23_1_ Water Quantity			Excluded
Eigen Values		2.42	1.58	N/A
% of Total Variance Explained		40.35	26.41	N/A
KMO		0.53		N/A
Bartlett's Test of Sphericity		44.22 ($p < .001$)		N/A
Cronbach α		0.70	0.71	N/A
Composite Reliability (CR)		0.83	0.87	N/A
Average variance explained (AVE)		0.55	0.76	N/A
Number of items in construct		4	2	1

Rotated Component Matrix, Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. Factor loadings >=0.4 are retained and reported.

Table 4.B2: Results from exploratory factor analysis of perception construct: Nature of risk

Final Construct	Survey Items	Components 1	Components 2
Biophysical Aspects, Nature of Risk (NR) 1	Q1_1_Quantity Issues,	0.860	
	Q2_Likelihood of occurrence	0.755	
	Q1_Quality issues	0.723	
	*Q16_2_Risk Integration in organizational decision making	-0.708*	
Social Aspects, NR 2	Q1_Regulatory Uncertainty		0.855
	Q14_Priority of Water over GHG		0.713
	Q1_Increasing Competition		0.699
Eigen Values		2.52	1.74
% of Total Variance Explained		35.93	24.81
KMO		0.55	
Bartlett's Test of Sphericity		44.57 ($p = .002$)	
Cronbach α		0.76	0.63
Composite Reliability (CR)		0.74	0.80
Average variance explained (AVE)		0.58	0.58
Number of items in construct		4	3

Rotated Component Matrix, Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. Factor loadings >=0.4 are retained and reported.
*Item codes reversed before further processing for construct, reliability and AVE

Table 4.B3: Results from exploratory factor analysis of perception construct: Knowledge

Final Construct	Survey Items	Components		
		1	2	3
Knowledge_1_Self (level of experience and self assessment of own knowledge of specific water risks and issues)	Q15_2_Water Risk Assessment	0.888		
	Q18_2_ Regulations	0.885		
	Q18_4_Sector Impacts	0.852		
	Q18_3_Water User Conflicts	0.753		
	Q18_1_Water quantity quality	0.729		
	Q15_1_Sustainability Assessment	0.619		
Knowledge_2_General Water Issues (knowledge about broader water issues)	Q16_1_Global Water Issues		0.799	
	*Q17_2_Water Knowledge in Industry		-0.756*	
Knowledge_3_Experts (Knowledge of water issues, risks, impacts in experts)	Q17_1_Water Knowledge in Experts			0.954
Eigen Values		3.95	1.51	1.15
% of Total Variance Explained		43.84	16.76	12.72
KMO			**0.75**	
Bartlett's Test of Sphericity		85.88 ($p < .001$)		
Cronbach α		0.88	0.44	N/A
Composite Reliability (CR)		0.91	0.75	N/A
Average variance explained (AVE)		0.63	0.61	N/A
Number of items in construct		6	2	1

Rotated Component Matrix, Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. Factor loadings >=0.4 are retained and reported.
*Item codes reversed before further processing for construct, reliability and AVE

Table 4.B4: Results from exploratory factor analysis of perception construct: Drivers of water issues

Final Construct	Survey Items	Components	
		1	2
Drivers of Water Issues_2_Micro (Drivers at the micro or individual consumer level)	Q3_4_Inefficient Individual Water Use	0.877	
	Q3_7_Lack of Knowledge in Public	0.864	
	Q3_5_Population Growth	0.696	
Drivers of Water Issues_1_Macro (Drivers at the broader macro or meso institutional level)	Q3_3_Regulatory Lapses		0.904
	Q3_1_Climate Change		0.844
	Q3_2_Industrial Water Use		0.654
Eigen Values		2.98	1.23
% of Total Variance Explained		49.65	21.64
KMO		0.73	
Bartlett's Test of Sphericity		45.31 ($p < .001$)	
Cronbach α		0.79	0.78
Composite Reliability (CR)		0.86	0.85
Average variance explained (AVE)		0.67	0.65
Number of items in construct		3	3

Rotated Component Matrix, Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. Factor loadings >=0.4 are retained and reported.

Table 4.B5: Results from exploratory factor analysis of perception construct: Values

Final Construct	Survey Items	Components 1	2	3	4
Values_1_Sustaino-centric (pro environmental and sustainability values including biospheric and altruistic elements)	Q20_9_ Protect water resources for benefits to all	0.936			
	Q20_3_Fair and equitable access to water	0.810			
	Q20_1_Prevent environmental issues	0.809			
	Q20_2_Ensure environmental sustainability for future generations	0.808			
	Q20_10_ Ecological health and dependent wildlife	0.796			
Values_2_Economic Benefits (economic benefits increase risk acceptability)	Q9_Economic benefits of water taking can offset costs and risks		0.882		
	Q20_5_Economic benefits increase risk acceptability		0.833		
Values_3_Egoistic (egoistic/ self centric benefits and propensity for efficiency gains)	Q20_8_Protect water for organizational benefits			0.877	
	Q20_7_Efficiency gains can reduce water risks			0.559	
	Q20_4_Need to assess both costs and benefits			0.549	
Values_4_Technological Optimism	Q20_6_Fully rely on technological solutions to address all water issues				0.922
Eigen Values		3.90	2.09	1.59	1.1
% of Total Variance Explained		35.46	19.02	14.46	9.99
KMO		**0.60**			
Bartlett's Test of Sphericity		135.36 ($p < .001$)			
Cronbach α		0.88	0.72	0.54	N/A
Composite Reliability (CR)		0.92	0.85	0.71	N/A
Average variance explained (AVE)		0.70	0.74	0.46	N/A
Number of items in construct		5	2	3	1

Rotated Component Matrix, Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. Factor loadings >=0.4 are retained and reported.

Table 4.B6: Results from two exploratory factor analyses: Negative impact themes

Final Construct	Survey Items	Components 1	2	Separate Analysis
Impact_1_Reputational (extent of negative impact of water issues/risks on reputation, social license to operate)	Q5_7_Social license to operate	0.965		
	Q5_6_Reputation and brand image	0.951		
Impact_2_Financial (negative impact on economic growth, profitability)	Q5_1_Economic Growth		0.924	
	Q5_5_Profitability		0.806	
Impact_3_Sustainability (impact on social well being, human health, environmental sustainability	Q5_3_Human health			0.970
	Q5_2_Social well being			0.917
	Q5_4_Environmental sustainability			0.900
Eigen Values		2.64	1.07	2.59
% of Total Variance Explained		61.61	26.79	84.45
KMO		**0.60**		**0.66**
Bartlett's Test of Sphericity		51.39 ($p < .001$)		55.21 ($p < .001$)
Cronbach α		0.95	0.69	0.92
Composite Reliability (CR)		0.96	0.86	0.95
Average variance explained (AVE)		0.92	0.75	0.86
Number of items in construct		2	2	3

Rotated Component Matrix, Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. Factor loadings >=0.4 are retained and reported

Table 4.B7: Results from exploratory factor analysis of perception construct: Attitudes

Final Construct	Survey Items	Components 1	2	3	4	5
Attitude_1_Scope (scope i.e., area and people impact by different water issues)	Q6_5_ Scope_Water user conflicts	0.900				
	Q6_3_ Scope_Groundwater Quality Issues	0.845				
	Q6_4_ Scope_Drinking water advisories	0.839				
	Q6_1_Scope_Water Quantity Issues	0.634				
	Q6_2_ Scope_Water Surface Water Quality Issues	0.537				
Attitude_2_Bipohysical Controllability (controllability i.e., ability of entities to control and manage biophysical water issues)	Q7_2_Controllability_ Surface Water Quality		0.885			
	Q7_3_ Controllability_Groundwater Quality		0.798			
	Q7_1_ Controllability_Water Quantity Issues		0.699			
Attitude_4_Concern (overall concern/dread, urgency of issues, inequity, non-substitutability of risks by economic benefits)	*Q8_Equity of Impact of Water Issues			-0.824*		
	Q12_Overall concern of water issues in Ontario			0.816		
	Q13_Urgency of water risks			0.718		
	*Q9_Economic benefits offset costs and risks			-0.660*		
Attitude_3_Social Controllability (controllability of social water issues and own exposure)	Q7_4_ Controllability_Drinking Water Access				0.867	
	Q10_1_Own exposure to water issues				0.781	
	Q7_5_ Controllability_Water user conflicts				0.412	
Attitude_5_Confidence (Overall confidence in sufficient freshwater to meet all demands)	Q4_1_Confidence in water abundance in Ontario					0.781
	Q4_2_ Confidence in water abundance in own sub-watershed of residence					0.412
Eigen Values		3.99	2.96	2.27	1.79	1.49
% of Total Variance Explained		23.46	17.40	13.33	10.54	8.74
KMO				**0.51**		
Bartlett's Test of Sphericity				177.73 (p = .009)		
Cronbach α		0.86	0.80	0.75	0.56	0.85
Composite Reliability (CR)		0.87	0.84	0.84	0.74	0.91
Average variance explained (AVE)		0.58	0.64	0.57	0.51	0.83
Number of items in construct		5	3	4	3	2

Rotated Component Matrix, Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. Factor loadings >=0.4 are retained and reported.
*Item codes reversed before further processing for construct, reliability and AVE

Table 4.B8: Results from exploratory factor analysis of perception construct: Previous exposure

Final Construct	Survey Items	Component 1
Exposure (frequency exposure of self or relatives to water issues)	Q11_Exposure of Others	0.867
	Q10_1_Exposure of Self	0.867
Eigen Values		1.5
% of Total Variance Explained		75.08
KMO		0.50
Bartlett's Test of Sphericity		6.52 (p = .011)
Cronbach α		0.67
Composite Reliability (CR)		0.86
Average variance explained (AVE)		0.75
Number of items in construct		2

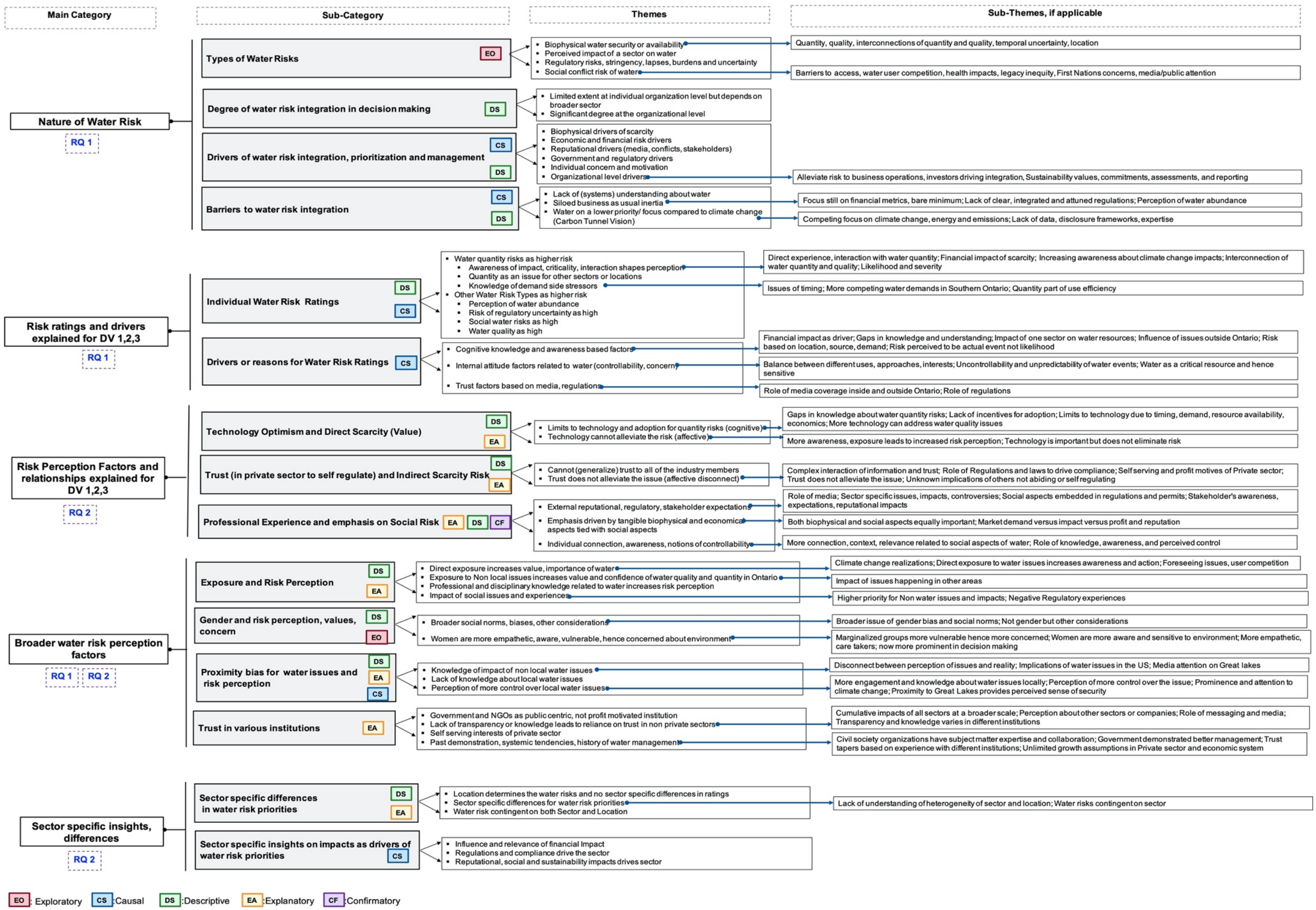
Extraction Method: Principal Component Analysis. No rotation for one component. Factor loadings >=0.4 are retained and reported.

Appendix 4.C: Thematic Analysis Example with Themes, Codes, and Data Extract for one sub-category

Main Category	Sub-Category	Themes/ Files Coded	Codes	Code Description	Example of Data Extract Coded
Nature of Water Risk (RQ1)	**Types of Water Risks (Exploratory)**	1. Biophysical water security or availability **Files Coded: 21**	▪ Scarcity, Interconnected quantity and quality	Water scarcity can be due to quantity and quality. The articulation of the interconnection of water issues i.e., availability of water and access can be impacted by quantity or quality.	"I think that goes for whether you're taking it or whether you're polluting it. If there's a concern and, the water becomes polluted, it's essentially the same as taking it because it's no longer potable and there for use." (D10)
			▪ Uncertainty in temporal water availability	Participant mentions issues of timing of water availability as a water risk related to either droughts or flooding. Too much or too little, extreme weather events that are now more unpredictable.	"I think quantity is a big issue and timing. So yeah, when are droughts hitting? When are floods hitting?" (A2)
			▪ Water Quality Risks	Participant mentions water quality issues as water risks in Ontario.	"But of course, we hear a lot about groundwater contamination." (F4)
			▪ Quality risks due to legacy contamination, issues	Risks to water quality and of water quality due to past legacy contamination or lax regulations around water quality	"I think back in the day in the 1970s, there were a lot of buried tanks and fuel tanks and those had very high (risk) potential and most of them leaked back in the day and those could easily impact any nearby aquifers and neighboring wells." (P1)
			▪ Water Quantity Risks	Participant mentions droughts and flooding as a water risk in Ontario, risk to water supply, availability, low flows-high flows events etc.	"Well, I think the number one is the misconception or the assumption that we have copious amounts of water supply." (D2)
			▪ Quantity risk Contingent on main source	Groundwater vs. Surface water and access to lakes will determine water risks and competition of users	"We do have the Great Lakes but not everybody has access to the Great Lakes." (C1)
			▪ Water intensive sectors	High amount of water use and consumption by a sector	"Whereas if you're taking water and you're processing it and then it has to be treated at a minimum full wastewater treatment plant and that wastewater treatment plant may have only so much capacity." (P1)
			▪ Water risks are sub-watershed dependent	Water risk vary by locations specifically sub-watershed	"So of course, it will be location specific and where I am. I'm not close enough to the Great Lakes but we still have best management practices" (A4)
Nature of Water Risk (RQ1)	**Types of Water Risks (Exploratory)**	2. Perceived impact of a sector on water **Files Coded: 14**	▪ Perceived impact of a sector on water	Issue of negative perception about a sector (public perception of one's own or participant's perception about other sectors), industry or organization adversely impacting the availability, quality or overall	"Because at the end of the day if there's public outcry on an industry or a permit or something that really actually impacts the outcome of the whole thing and even it impacts the regulation." (D3)

				sustainability of water resource/supply or social impact overall of the activity.	
			▪ Concern about water bottlers	Concern of water bottling organizations or water taking by water bottlers	"But we definitely see it in certain areas, (where) the water bottlers become a potential area of conflict over water use and concerned that farmers might impact their ability to access irrigation water" (A2)
Nature of Water Risk (RQ1)	**Types of Water Risks (Exploratory)**	3. Regulatory risks, stringency, lapses, burdens and uncertainty **Files Coded: 12**	▪ Regulatory risks, stringency, lapses, burdens and uncertainty	Regulations around water are unpredictable, siloed, too stringent and not attuned to sector and location. Burdens, lapses and gaps of regulations	"Regulatory uncertainty I would also agree, the timelines on permit approvals are just increasing, the scrutiny and the level of details required for permit approvals, either water taking our water discharge is, so the level of effort is extreme." (D7)
Nature of Water Risk (RQ1)	**Types of Water Risks (Exploratory)**	4. Social conflict risk of water **Files Coded: 19**	▪ Barriers to access and use of water	Participant mentions any barrier to access to water sources for multiple social, economic, recreational or environmental uses and the risks impacting the sustainability of the water source. Includes issues of lack of access to clean drinking water in rural and indigenous communities across Ontario	"I think just on a higher level, like looking at other sectors, tourism and that component of social water risk. I think you often hear people are upset when beaches are closed and all sorts of things. So, I think those components do have an impact on other water users." (A5)
			▪ Competition among water users	Participant mentions issues of competition among different water users, issues of whether there is enough resource for everyone, conflicts due to competing uses in general	"water taking is really the volume of water, which an organization needs in order to utilize in their operations. And at times this this could be a risk for nearby communities and stakeholders." (D7)
			▪ Health impacts of water issues	The health related impacts and consequences of water issues that is a risk in itself, socially centric and systems based. The water, sanitation, and health nexus articulated	"So, I think that social component of impacting tourism, but also people wellness is a piece behind it, so I guess that that would be my perspective on that" (A5) "or can impact health. If that water becomes unavailable then everything else basically becomes a non-issue because water is even more essential than food." (D5)
			▪ Legacy inequity issues, First Nations concerns	The intersection of a facility, water taking, land access with First Nations. Overall concerns of First Nations around water, boil water advisories, access etc.,	"In terms of water risk is on the availability of clean water on the First Nations land because we have quite a few First Nations areas in Ontario and that's something that they struggle with." (D8)
			▪ Media and public attention	Negative media attention and public concern. Includes any scrutiny, concern, attention, backlash for a sector that can be a water-related risk	"Like if I take a look at the water issues that have gone down in Lake Erie. All of a sudden it depends on the messaging, and sometimes that comes out from media." (A4)

Appendix 4.D: Conceptual map based on thematic analysis of the interview Stage



Appendix 4.E: Follow-up Semi-structured Interview Guide

1. **[Introduction question] [Aligned with RQ 1]:** According to you, what are the different types of biophysical and social water risks in Ontario, Canada?
   - Are different biophysical and social water risks assessed and integrated in your sector's decision making in Ontario?
     - If yes: To what extent? How are these water risks prioritized and managed? What is the prime driver behind this integration?
     - If not or to a low extent: Why? Where are the gaps (sector, organizational, individual)?
2. **[Average Risk Ratings based on survey] [Aligned with RQ1]:** According to the survey's results, we found that average rating/weight assigned to different water risks in Ontario, was highest for **direct scarcity** (water quantity) followed by **indirect water scarcity** (water quality and source type) and least for **social water risk (**regulatory uncertainty, conflict potential, sector type, media/public attention).
   - What are your insights on why water quantity risks are rated higher?
   - Conversely, incidence of social water issues (increasing user competition) is rated highest, followed by water quality issues and regulatory changes. Water quantity issues were rated the least. Why biophysical risks are rated higher even though social water issues are more prevalent in Ontario?
3. **[Predictors of risk ratings based on survey] [Aligned with RQ2]:** We also found that the ratings/weights depend on different factors.
   - Direct Scarcity: Among others, as perceived knowledge of experts, scope of impact, participant's location risk and optimism in technology increase, direct scarcity risk rating increases.
     - If there is optimism in technology to address water issues, why is quantity risk more?
   - Indirect Scarcity: As economic benefit centric values, location's risk, and trust in private sector (to self regulate) increases, the indirect water scarcity risk rating increases.
     - If there is higher trust in private sector, why would this risk be rated high?
   - Social risks: As own knowledge/experience, knowledge of experts, location risk, trust in private sector increase, social risk rating increases.
     - Why would social risks be rated higher as one's professional experience increases?
4. **[Previous exposure or experience with water issues] [Aligned with RQ2]:** According to you, what is previous exposure to, or experience with, water issues or risks?
   - Do you think previous exposure to water issues can influence values, attitudes, trust and water risk perception? How and why?
5. **[Proximity bias] [Aligned with RQ2]:** We found that on an average, there is more concern than confidence (in freshwater abundance) for Ontario but concern for own sub-watershed is lower and there is more confidence.

- Why do you think water risks are perceived lower in own sub-watershed, even though the location may be prone to higher water risks especially in Southern Ontario?

6. **[Role of trust/ affect] [Aligned with RQ2]:** Another interesting factor is the role "Trust" in various institutions to assess and manage water risks.
   - Trust, on an average, was higher in the civil society (assess and signal issues) and Government (by regulations) and least in private sector (self regulation). Why is trust in Government and civil society more?
7. **[Sector specific insights] [Aligned with RQ2]:** Would you and your sector rate the three water risks differently than other sectors?
   - Would your sector rate financial, sustainability, reputational impacts of water issues differently than others? Why?
   - Can there be an influence of one's sector on overall concern? How?
8. **[Water risk management] [Aligned with Future Study]:** We found on an average, most agreed upon water risk management strategy was proactive approaches by all water using sectors, then participatory multistakeholder approaches, additional research, and least was additional Government regulations.
   - Why do you think, private sector approaches are highest, even though the trust in private sector is lowest?
   - For Govt regulatory approaches, some sectors agreed more than others. Why? What do you think is driving these sector-based differences?
9. **[Conclusion Question] [Aligned with Future Study]:** According to you, how can water risks and water risk perception be brought to the forefront of decision making in your sector?
   - How can a water risk management framework and decision support tool be designed for your sector?
   - Is there focus on risk mitigation or adaptation/resilience or both?
   - How can academia-industry gap in knowledge sharing be bridged?

III. Appendix C: Appendices 5.A to 5.D for Chapter 5

Appendix 5.A: Follow-up Semi-structured Interview Guide for Water Risk Management

(covering the water risk management and decision-making part of the broader guide for the entire project)

1. **Exploratory and explanatory insights about water risk management strategies, connection with the role of trust, sector based differences for preference of water risk management strategy.**

Main Question: We found on an average, most agreed upon water risk management strategy was proactive approaches by all water using (private) sectors, then participatory multistakeholder approaches, additional research, and least was additional Government regulations.

- Why do you think, private sector approaches are most preferred, even though based on previous study findings, the trust in private sector is lowest?
- For Government regulatory approaches, some sectors agreed more than others. Why? What do you think is driving these sector-based differences?

2. **Open ended exploratory discussion about the gaps and opportunities in water risk assessment and decision making, insights on bridging academia-industry gap, insights on mitigation versus adaptation approaches for water risks.**

Main Question: According to you, how can water risks be brought to the forefront of decision making in your sector?

- How can a water risk management framework and decision support tool be designed for your sector?
- Is there focus on water risk mitigation or adaptation/resilience or both?
- How can academia-industry gap in knowledge sharing be bridged?

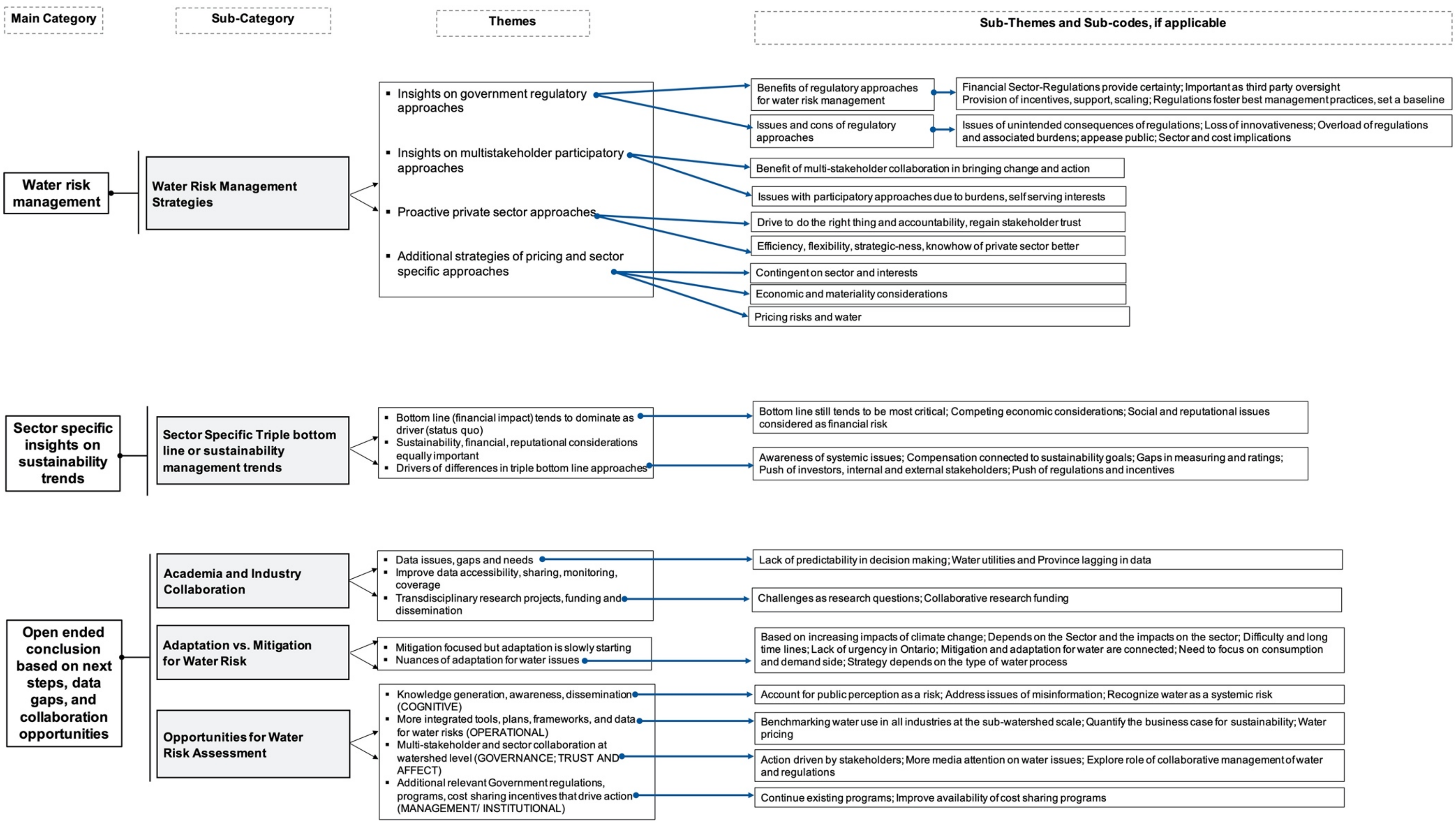
Appendix 5.B: Example of Coding and Thematic Analysis of Interview Data for Water Risk Management

Category	Themes/ Files Coded	Codes	Code Description	Example of Coded Data (Interview Transcript)
Water Risk Management Strategies (descriptive, exploratory and explanatory based on survey findings and open ended discussion)	1. Insights on government regulatory approaches **Files (participants) coded: 22**	**Benefits of regulatory approaches:**	Participant mentions different benefits of regulatory approaches	
		▪ Regulations provide certainty	Financial sector's preference for regulatory approaches. Regulations alleviate risk and provide certainty	"For some water issues or environmental issues that I think, (it's important) having some type of certainty. Things like certainty, reliability are things that investors will look at in a positive perspective." (F3)
		▪ Important as third party oversight	Role of regulations and regulators as independent oversight for compliance	"Others may not have the same company values and standards. And so therefore, would they meet more stringent effluent limits? Probably not. So that's why I think in general, as a whole, regulations are very important and they're needed. It sets that that baseline approach." (D4)
		▪ Provision of incentives, support, scaling	Government needs to provide enabling incentives, support and scaling effort to transfer best practices across the industry	"Yeah, I think that's where incentives could be offered. Maybe that's something that the government could help out with again like when I was saying protection of rivers and streams around farm lands. If they could offer incentives for the farmers to protect those areas, because rather than just putting on the farmers all of a sudden, there's a regulatory requirement to have a 30 foot buffer of vegetated land between your field and stuff. It's going to be here and you're immediately hitting the pocketbook of the farmers who are already working on thin margins." (P1)
		▪ Regulations foster best management practices, set a baseline	Need regulations to set the baseline, foster best management practices	"I think there's a positive side to it because it allows us to improve our best management practices with our water use." (A4)
		Issues or cons of regulatory approaches	Participant mentions different cons of regulatory approaches	
		▪ Issues of unintended consequences of regulations	Unintended consequences of broad sweeping regulations that are not attuned for the sector or location. The implementation is not consistent	"But within the Ministry of the environment, there are people who regulate water, there are people that regulate air, there are people that regulate waste, and they're all operating in their own individual silos. And they don't think about the other silos or what the impact of their decisions could be having on the other silos." (C1)
		▪ Loss of innovativeness	Issue of regulations as barrier to innovation	"I also think when you rely more heavily on government and regulations and that "stick" component, I think you lose a lot of the innovativeness that comes about because it becomes very prescriptive." (A2)

		▪ Overload of regulations and associated burdens	Too many regulations that burden some sectors more than others	"Over time, those regulations have changed and there's many, many more regulations. When I look back at 20-25 years ago there was only a couple of regulations that really, I paid attention to. Now there is multiple regulations that we have to know and we have to keep track of. So, it's very time consuming, it's very cumbersome but to a certain extent needed." (D4)
		▪ Regulations to appease public	Stringent regulations to alleviate public concern and backlash	"Yeah, but I think those regulations were put in to try and appease the public, and I think the government is trying more and more to get the facts out there and help people understand what's happening." (D3)
		▪ Sector and cost implications of Stringent regulations	Sector based preferences and stringent regulations for companies lead to higher expense and cost implications	"For example, where it would be more expensive for their company to have to abide by more stringent regulation. Because that's just companies tend to see more regulation as, not always but often, as more as of a bigger expense." (F4)
Water Risk Management Strategies (descriptive, exploratory and explanatory based on survey findings and open ended discussion)	2. Insights on multi-stakeholder participatory approaches **Files (participants) coded: 4**	▪ Benefit of Multi-stakeholder Collaboration brings change, action	Collaboration brings about change, fosters action and proactive improvement	"So, creating collaboration through private sector and public sector is probably the greatest opportunity because everyone is looking to achieve the same goal and everyone has a different way to get there. And I think that form of collaboration and trying to think outside the box and multiple perspectives is going to yield the best result." (A5)
		▪ Issues with participatory approaches	More burdens, red tape, self-serving interests of all parties involved	"A lot of it could also come down to the burden and red tape as you get more into a participatory approach. And so, I know that has been a challenge in a couple of instances when you have other people that want to be involved in the decision making. They bring their own perspectives and they bring their own interests. They're not necessarily backed up by facts and science." (P2)
Water Risk Management Strategies (descriptive, exploratory and explanatory based on survey findings and open ended discussion)	3. Proactive private sector approaches **Files (participants) coded: 18**	**Drive to do the right thing and accountability**	Participant mentions the drive to do the right thing that benefits their organization, society and the environment	
		▪ Way to be accountable and regain stakeholder trust	Proactive approaches to regain stakeholder trust and accountability	"I could say that regardless if we were being made to do what we do or not, we would (still) do it because it's the right thing to do." (D3)
		Efficiency, flexibility, strategic-ness, knowhow of private sector better	Participant mentions efficiency, flexibility, strategic-ness, knowhow of private sector better	
		▪ Flexibility	Ability of private sector to understand their problems and address it in their own way	"So yeah, I think that's a big reason why they like to let us solve our problems in a way that works for us. We would love to help to work towards the society benefit, but let's do in a way that we can do it. And you don't get that as much when you rely on government through regulation and laws." (A2)

		▪ Private sector know how is better	Private sector innovation, knowledge and resources for risks, action, technology	"I think it's because we are the subject matter experts of what we do. The government doesn't have the expertise to tell us how to reduce our water consumption So, if anyone is going to make that a reality, it's going to be us." (D2)
		▪ Self-serving and efficiency based gains of private approaches	Interest of the private sector to do their own thing but implementation is an issue	"When it comes to private sector like I trust my company to make the right decisions and to consult with whoever is necessary in order to make those decisions, but I don't know if I necessarily trust every other business to be as ethical and thorough. So potentially that could be why." (D8)
		▪ Strategic action in Private sector	Regulations not as strategic but private sector looks more strategically	"But also Regulations do not usually ask company to think strategically about their business and how their business will be shaped in the future with risk. A lot of like the things that fits with climate or TCFD kind of framework of looking strategically around this issue, driving towards solutions, often those things, I don't know if they're really coordinated through government regulations right now in Ontario." (F3)
Water Risk Management Strategies (descriptive, exploratory and explanatory based on survey findings and open ended discussion)	4. Additional strategies of pricing and sector specific approaches. **Files (participants) coded: 7**	▪ Contingent on sector and interests	The water risk management strategy depends on the sector and cost implications	"The difference between the finance community and the issuers or the Corporates was night and day. And there's some real statistical evidence there that you can highlight if you wanted to highlight this obvious difference of interests and really conflicting interests." (F4)
		▪ Economic and materiality considerations	Economic considerations, expense, costs drive the type of management strategy	"So, any kind of impetus towards let's say water conservation or an improving effluent discharge quality or changing efficiency of water use, it'll happen as a risk weighted decision on the private sector. If any kind of changes in those behaviors are also going to be tied with the cost and whether the cost of that is going to be worth it versus any kind of regulatory penalties that they are going to face. So, action will only come in the face of regulatory penalties." (F7)
		▪ Pricing risks and water	Need to price risk, water to elevate priority	"The other aspect that's important, though, is sometimes and I don't like to do this, but in order to make a risk of priority you associate a cost to it and you say if we don't do this, this is the cost to the operation, this is the impact to our reputation. And sometimes you have to do that to elevate that risk and to get the feedback and the back up to implement those mitigations. So those are kind of strategies that I've used in the past as well." (D4)

Appendix 5.C: Summary map of themes from interview analysis

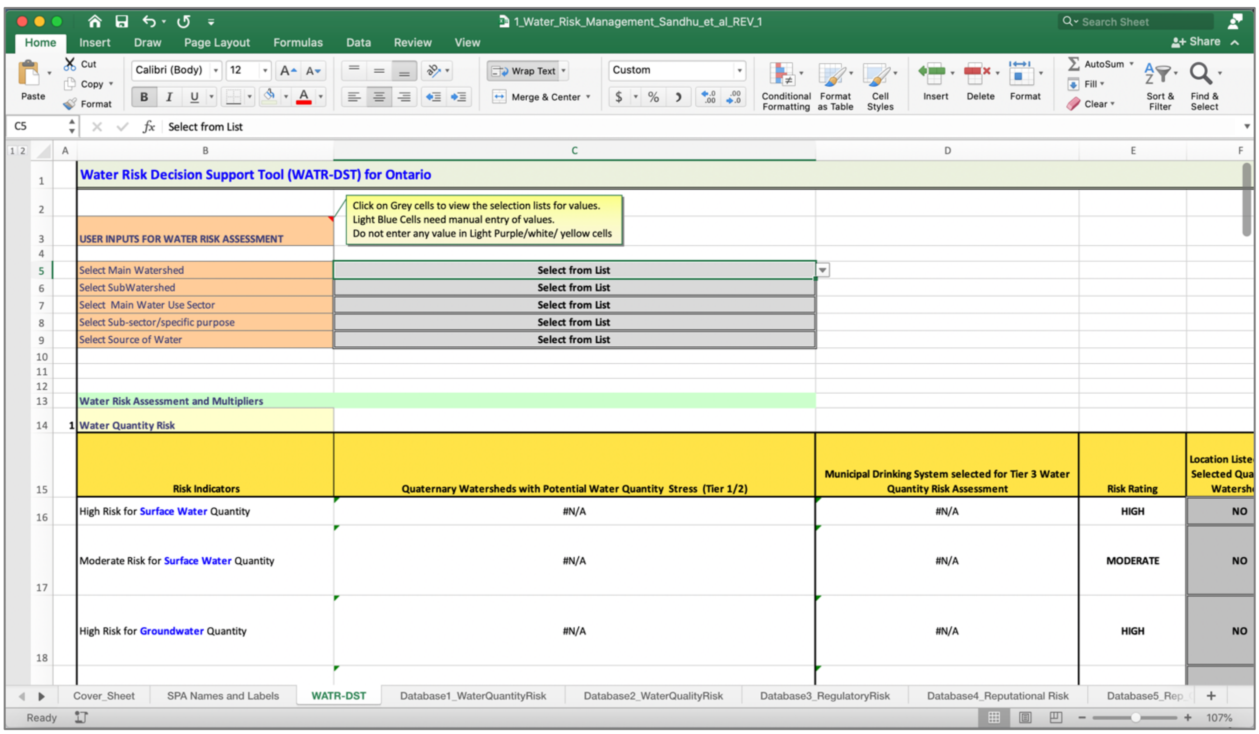


Appendix 5.D: User guide and demonstration of the WATR-DST

Step by Step demonstration and user guide of the WATR-DST, the Decision Support Tool for Water Risk Assessment and Management in Ontario. We have used a hypothetical user for the ease of demonstration of the key features of the tool. The screen shots of the tool input areas and outputs have been provided as a guide for the user.

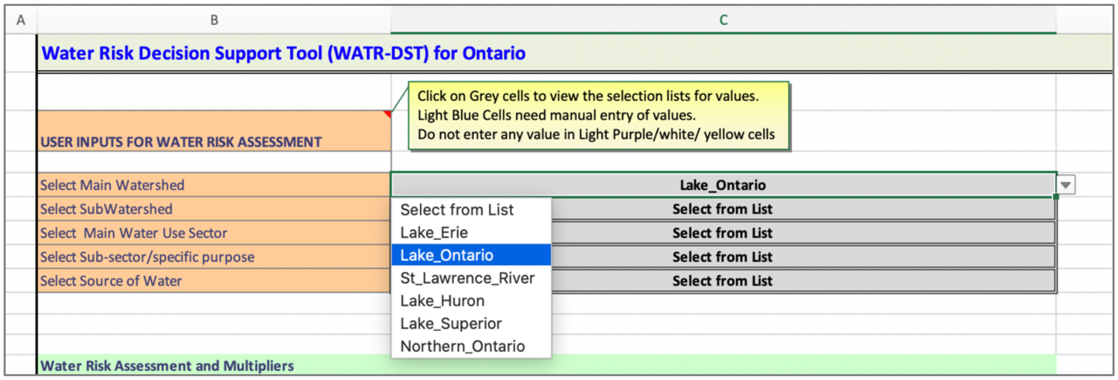
5.D.1. Landing page of WATR-DST in MS Excel

This is the general layout of the tool as displayed in the "WATR-DST" worksheet for a new user. The supporting databases and information are provided in other worksheets of the workbook. The databases are locked for editing to preserve the integrity of underlying data.

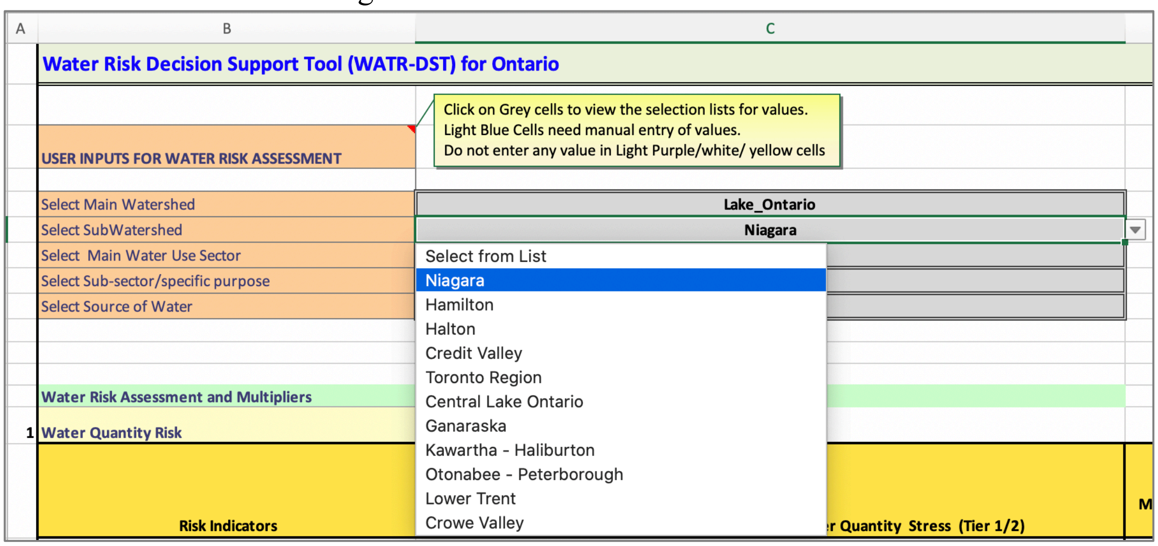


5.D.2. User Inputs for Interdisciplinary Water Risk Estimation/ Assessment

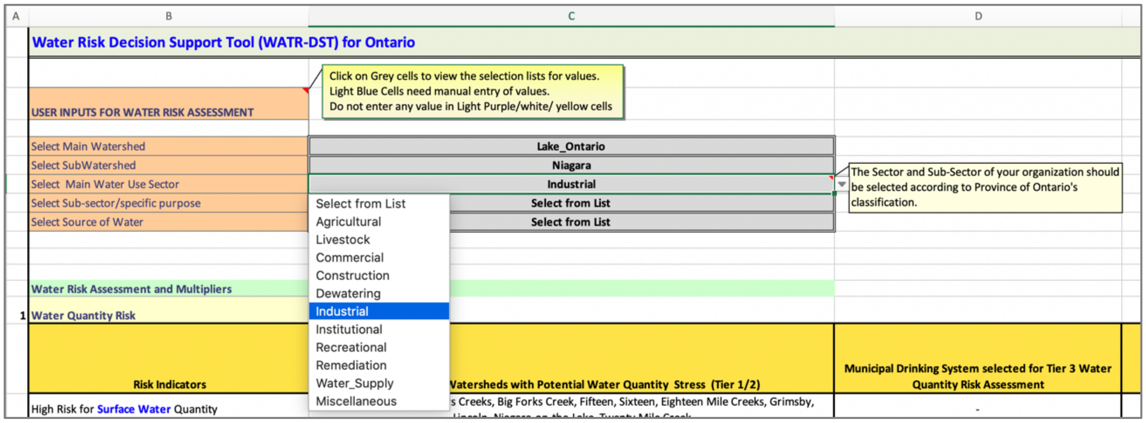
5.D.2.1. As instructed by the tool in the yellow call out comment, the user is required to make selections in Grey colored cells using corresponding drop-down lists. Any manual entry is done in Light blue colored cells and there should not be entry of values in the other cells (colored purple, yellow, white). The user then proceeds to select the **Main Watershed** from the pre-coded dropdown list based on the location of their operation or facility or property. In this case, the user chooses **Lake Ontario.**



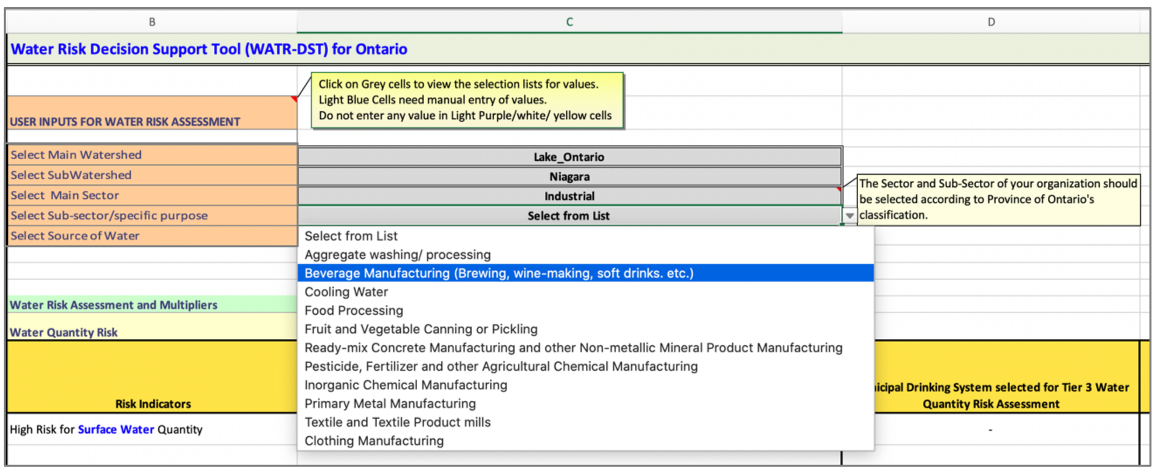
5.D.2.2. The user selects the **Sub-watershed** of the location from the pre-coded drop-down list that the tool automatically filters based on user's Main Watershed. In this case, user's sub-watershed is Niagara.



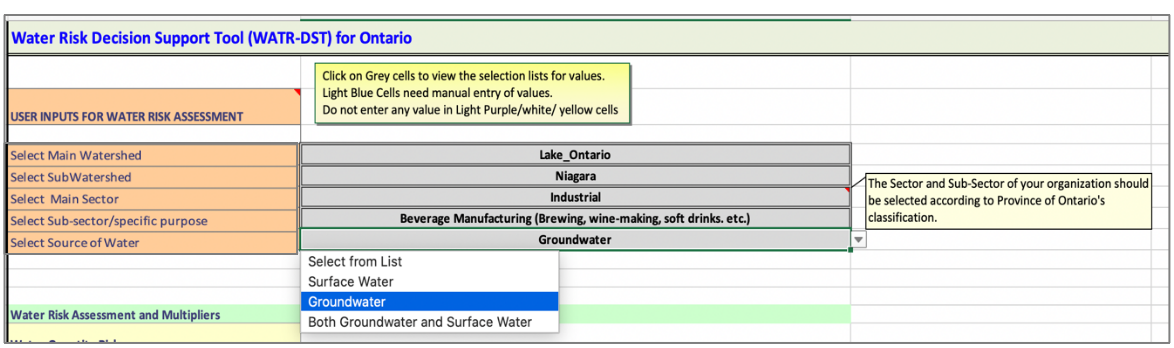
5.D.2.3. User selects their organization's industrial or sectoral classification for the **Main Water Use Sector** from the drop-down list. The user is remined to select their sector aligned with the Province of Ontario's classification, which is also used in Ontario's Permit to Take Water applications. In this case, the user's organization is a beverage manufacturing organization, which is classified under the "Industrial" sector by Ontario. The user can also refer to Database 6 in the workbook for the list of sectors and sub-sectors. The financial sector can make a selection based on the sector of the issuer/ borrower/ insured they wish to assess.



5.D.2.4. The user then selects the specific **Sub-sector or specific purpose** from the pre-coded and filtered list that is automatically populated based on user's prior selection of main sector. In this case, user selects, "Beverage Manufacturing".



5.D.2.5. The user then selects the **Source of Water** from the drop-down list based on the type of water source their organization uses i.e., surface water or groundwater or both. In our case, the user's organization uses and hence selects "Groundwater".



5.D.3. WATR-DST Output 1: Interdisciplinary Water Risk Estimation/ Assessment for the seven water risk indicators based on user inputs selected in Step 2.

5.D.3.1. Water Quantity Risk: Based on the sub-watershed selected by the user in Step 2.2, the tool populated the quaternary watersheds at high and moderate surface water quantity risk as well as groundwater quantity risk, as applicable. The tool also displays the quaternary watersheds where the municipal drinking water systems have been identified at water quantity risk and that is another proxy indicator for water risk. The user then selects if their location of water extraction and use is in the quaternary watersheds identified at risk or not based on the displayed information for their source type, i.e., groundwater. In this case, the user's facility using groundwater is situated in the Lake Erie North Shore quaternary watershed identified under high groundwater quantity risk.

The tool calculates the **Water Quantity Risk Score: 2** for our hypothetical user.

Interdisciplinary Water Risk Estimation/ Assessment

1 Water Quantity Risk

Risk Indicators	Quaternary Watersheds with Potential Water Quantity Stress	Quaternary Watersheds with Municipal Drinking System selected for Tier 3 Water Quantity Risk Assessment	Risk Rating	Location Listed in Risk-Selected Quaternary Watershed?	Location in Vicinity of Municipal DW System selected for Tier 3	Water Quantity Risk Score
High Risk for Surface Water Quantity	Beaverdams and Shriners Creeks, Big Forks Creek, Fifteen, Sixteen, Eighteen Mile Creeks, Grimsby, Lincoln, Niagara-on-the-Lake, Twenty Mile Creek	-	HIGH	NO	NO	1
Moderate Risk for Surface Water Quantity	Central Welland River, Fort Erie Creeks, Lake Erie North Shore, Lower Welland River, South Niagara Falls, Upper Welland River	-	MODERATE	NO	NO	1
High Risk for Groundwater Quantity	Lake Erie North Shore	-	HIGH	YES	NO	2
Moderate Risk for Groundwater Quantity	Fort Erie Creeks, Fifteen, Sixteen, Eighteen Mile Creeks	-	MODERATE	Select from List YES NO	NO	1

5.D.3.2. Water Quality Risk: The tool populates the water quality risk rating for the selected sub-watershed based on the analysis of Sandhu et al. (2023a). Based on the water quality risk rating, the tool calculates the risk score. Moreover, the water quality status, long term trend, and qualitative information on the indicators for the Great Lake, i.e., the main watershed of the user's location (if in one of the Great Lakes' watersheds) is also populated. The user is instructed to review this information and select a score from the drop-down list, if the location is in close vicinity of the main Great Lake and the quality is an additional consideration. Otherwise, the base score 1 can be engaged for the main watershed.

The tool populates the **Water Quality Risk Rating** of **Very High** and a corresponding score of **3**. The user selects additional score of 2 for Lake Ontario watershed based on the qualitative information populated.

2 Water Quality Risk (sub-watershed and main watershed)

Risk Category	Area of Assessment	Risk Rating	Water Quality Risk Score	
Cumulative Sub-Watershed Water Quality RISK Rating	Niagara	VERY HIGH	3	
Water Quality Indicator for the Individual Great Lake: Current Quality Status: (Fair, Poor) + Long Term Trend (Improving, Unchanging, Deteriorating, Undetermined)	Lake_Ontario	1. Contaminants in Edible Fish (Fair and Improving), 2. Toxic Chemicals in Sediment (Fair and Improving), 3. Toxic Chemicals in Water (Fair and Unchanging), 4. Toxic Chemicals in Whole Fish (Fair and Unchanging), 5. Coastal Wetland Fish (Fair and Improving), 6. Coastal Wetland Amphibians (Fair and Improving), 7. Coastal Wetland Birds (Fair and Improving), 8. Coastal Wetland Plants (Fair and Unchanging), 9. Aquatic Habitat Connectivity (Poor and Improving), 10. Nutrients in Lakes (Fair and Deteriorating), 11. Harmful Algal Blooms (Fair and Deteriorating), 12. Cladophora (Poor and Undertermined), 13. Water Quality in Tributaries (Fair and Unchanging), 14. Impacts of Aquatic Invasive Species (Poor and Deteriorating), 15. Terrestrial Invasive Species (Poor and Deteriorating), 16. Watershed Stressors (Poor and Unchanging), 17. Climate Indicator and Trend: Water Levels (Increasing), 18. Climate Indicator and Trend: Surface Water Temperature (Undetermined), 19. Climate Indicator and Trend: Ice Cover (Decreasing)	2 Select from List 3 2.5 2 1.5 1	Self Select if applicable from Drop-down List based on qualitative information provided here for the main watershed and if your location is close to the main Great Lake. If you do not want to consider this additional indicator, you can select base score of 1

5.D.3.3. Source Type Risk: The user is instructed to select the scores for different source types, if a different value is desired. Since groundwater is at higher risk for overextraction and contamination, further connected to surface water sources, it is expected to have the highest score. Based on the source type selected by user, the tool displays the Source Type Risk Score. In our hypothetical case, the tool calculates the

3 Source Type Risk

Source Risk Score:	2	
Groundwater as Main Source	2	Self select scores here from Drop Down Lists for all source types, if different values are to be engaged. The higher value for groundwater is due to the higher risk of over-extraction, contamination, and connection of groundwater to surface water via base flow (Sandhu et al., 2021, 2023a)
Both GW and SW as Main Source	1.5	
Surface Water as Main Source	1	

Source Type Risk Score: 2.

5.D.3.4. Regulatory Risk: The tool populates the results from the regulatory trend analysis by Sandhu et al. (2023a). In the first two rows of the section, the tool displays the regulatory risk drivers at high and moderate prevalence in the regulatory framework of Ontario. Then instructs the user to select if the regulatory risk score for the prevalent risk drivers should be engaged or not. For last two rows, the tool populates the sub-watersheds as well as municipalities at high regulatory focus for water in Ontario based on the analysis. Then the user is instructed to select if their location is under high regulatory focus or not. Finally, the user selects the appropriate regional risk score if the location is under high regulatory focus.

In our case, the user engages the regulatory risk scores as well as the regional risk score as their location is in the municipality identified under high regulatory focus. For the regulatory risk drivers, the tool calculates a **Regulatory Risk Score** of **2** and **1.5** for high and moderate risk respectively and the additional user selected **Regional Regulatory Risk Score** of **3.**

4 Regulatory Risk					
Prevalence Rating	Cumulative Regulatory Risk Drivers	Engage Score for Regulatory Risk and is Location in high regulatory focus municipalities/sub-watershed?	Regulatory Risk Score	Select Regional Risk Score, if Applicable	Regulatory Risk Score
HIGH Prevalence Regulatory Risk Drivers	Consideration for the Environment, Implications for Effluent treatment/ management costs, Tighter regulatory standards, Regulatory uncertainty due to future changes	YES	2	N/A	2
Moderate Prevalence Regulatory Risk Drivers	Requirements for water abstraction permits, volumetric water extraction charges, monitoring and reporting; Increased difficulty in obtaining withdrawal/operations permit ; Lake or River basin/catchment management ; Possibility of short-term or long-term changes to water withdrawal limits/increased monitoring (e.g. Drought Management); Water efficiency, conservation, recycling or process requirements; Regulation of discharge quality/volumes; Violations resulting in fines, enforcement orders, and/or penalties; Potential Impact (consultations, engagement, etc.) from Evolving Laws and Rights like UNDRIP (Bill C-15), Human Right to Water.	YES	1.5	N/A	1.5
HIGH Regulatory Focus in Sub-watersheds	**Lake Erie, Lake Simcoe, Wabigoon River basin (tertiary) and English River Basin (main sub-watershed)**	NO		1	1
HIGH Regulatory Focus in Municipalities	**City of Toronto, Greater Golden Horseshoe Area for Greenbelt Act:** Township of Brock, City of Kawartha Lakes, Town of Georgina, Town of Innisfil, Town of East Gwillimbury, Township of Uxbridge, Township of Scugog, Township of King, Municipality of Clarington, Town of Mono, Township of Adjala-Tosorontio, Town of New Tecumseth, County of Simcoe, Town of Whitchurch-Stouffville, City of Pickering, Town of Whitby, City of Oshawa, Municipality of Port Hope, Town of Orangeville, Town of Caledon, City of Vaughan, Town of Richmond Hill, Town of Aurora, City of Markham, Town of Ajax, Town of Erin, Township of East Garafraxa, City of Toronto, City of Brampton, Township of Guelph/Eramosa, Town of Halton Hills, City of Mississauga, Town of Milton, Township of Puslinch, City of Hamilton, Town of Oakville, City of Burlington, Town of Grimsby, Town of Lincoln, Town of Niagara-on-the-Lake, City of St. Catharines, Town of Pelham, City of Niagara Falls, Township of West Lincoln, City of Thorold and and City of Welland. **GGH Area:** Brant, Dufferin, Durham, Haldimand, Halton, Hamilton, Kawartha Lakes, Niagara, Northumberland, Peel, Peterborough, Simcoe, Toronto, Waterloo, Wellington, York. **Northern Ontario Area covered:** Algoma, Cochrane, Kenora, Manitoulin, Nipissing, Parry Sound, Rainy River, Sudbury, Thunder Bay, Timiskaming. **Niagara Escarpment:** Niagara Region, City of Hamilton, Halton Region, County of Dufferin, Municipality of Peel, County of Simcoe, County of Grey, Bruce County. **Oak Ridges Moraine:** Section 1: Caledon, Adjala-Tosorontio, Mono, New Tecumseth, Section 2: Township of King, Section 3: Aurora, Newmarket, Richmond Hill, Vaughan, Section 4: East Gwillimbury, Markham, Whitchurch-Stouffville, Section 5: Pickering, Uxbridge, Section 6: Oshawa, Scugog, Whitby, Section 7: Clarington, Section 8: Cavan-Millbrook-North Monaghan. **Lake Simcoe:** City of Kawartha Lakes, Section 9: Hamilton, Port Hope, Section 10: Alnwick-Haldimand, Cramahe, Trent Hills. City of Kawartha Lakes, Township of Algonquin Highlands, United Townships of Dysart, Dudley, Harcourt, Guilford, Harburn, Bruton, Havelock, Eyre and Clyde, Township of Minden Hills, City of Barrie, City of Orillia, Town of Bradford West Gwillimbury, Town of Innisfil, Town of New Tecumseth, Township of Oro-Medonte, Township of Ramara, Township of Severn, District Municipality of Muskoka, Regional Municipality of Durham, Regional Municipality of York	YES		3 Select from List 3 2.5 2 1.5 1	3

5.D.3.5. **Water User Conflict Risk:** The tool populates the results for the water user conflict potential analysis based on the user's sub-watershed. The tool displays the conflict risk rating and calculates the corresponding risk score. In our case, the tool populates a **Water-user Conflict Risk Rating** of **Very High** and a corresponding risk score of **3**.

5 Water User Conflict Risk (sub-watershed specific)									
Sub-Watershed	PTTW Density Analysis	Drought Potential	High Growth Region	Prevalence of Short term or Long Term DWA	Public Attention: Leave to Appeal/ ERO Report/ Civil Society Focus	Media Attention/Coverage: Drought/ FNs/ Industrial water taking/ water quality issues	Generic Watershed wide Media Attention Issues	Potential for Conflict	Conflict Risk Score
Niagara	High	Low	Y	0	YES	YES: Droughts/low level	Lake Ontario: Low water levels, level control by IJC, Great Lakes Basin: Water quality, groundwater issues (quantity, quality and contamination), low levels, effects of climate change, concerns of bulk water export, nuclear waste burial	VERY HIGH	3

5.D.3.6. Sector-specific Risk: The tool populates the results of the sector-specific risk assessment for the user's organizations' main industry and sub-sector. The tool then displays the risk rating for the sector as well as the corresponding risk score. In our hypothetical case, the sub-sector of the organization is beverage manufacturing and the **Sector-specific Risk Rating** is **High** and the risk score is **3**.

6 Sector Specific Risk

Main Sector of Water Use	Sub-Sectors/Specific Purpose	Consumptive Water Use Category	Effluent Reporting Requirements and Fines	Additional Regulatory Focus specific to the sector	Leave to Appeal Focus on Sector	Citizen group/NGO Focus on Sector	Media Attention on Sector	Cumulative Sector Specific Risk Assessment	Sector Risk Score
Industrial	Beverage Manufacturing (Brewing, wine-making, soft drinks, etc.)	High	No	No	Low	Moderate	Yes	High	2.5

Sector/Sub-sector Requirement for Provinvial Permit to Take Water (PTTW) for extraction over 50,000 L/day	Additional Volumetric Water Extraction Charges / Water Rental Charges Applicable	Sector Priority as identified in Updated Water Quantity Management Framework (Priority 1: High, Priority 2: Moderate, Priority 3: Low, Priority 4: Very Low)
YES	YES	3

5.D.3.7. Public and Media Attention (Reputational) Risk: The tool populates the summary of the qualitative thematic analysis undertaken for reputational risk assessment in Ontario. The themes under public concern and media scrutiny are presented along with the results of the public opinion surveys conducted by Royal Bank of Canada and International Joint Commission. The user is instructed to review the qualitative assessment and then select a risk score. Since the results of the thematic analysis are detailed, they have been collapsed in the tool for the ease of navigation of the tool but can be expanded during user's review as instructed in the comment. The user is expected to read all of the results to make an informed judgement of the reputational risk score. A higher score reflects higher risk rating in this indicator as well. The baseline score for minimum risk is 1.

In our case, the user selects a risk score of 3 based on the reviewed information.

7 Reputational Risk: Public Opinion, Water Attitudes, Issues and Threats Identified in Media Analysis and Existing Public Attitudes and Opinions Polls (Qualitative Assessment/Themes)

2017 RBC Canadian Water Attitudes Survey (Ontario Specific Results)	Media Analysis - Generic water issues (public perception/ water + Ontario/ water governance issues) in addition to sector and sub-watershed specific issues	2021 IJC Public Opinion Survey on Great Lakes (BiNational)
Select Reputational Risk Score based on reveiwed Qualitative Assessment	3	

Click '+' sign on the left to expand results of this section and assign risk score based on qualitative assessment

Select from List: 3, 2.5, 2, 1.5, 1

5.D.4. WATR-DST Output 2: Water Risk Evaluation with Cumulative Water Risk Rating

In addition to the individual results of the seven water risk indicators i.e., the interdisciplinary water risk assessment/ estimation, the tool also provides a Water Risk Evaluation. In this section, the tool calculates a Cumulative Water Risk Score and Rating that integrates all the water risk indicator scores as well as engages priority risk multipliers elicited from the corporate and financial practitioner survey. The priority risk multipliers reflect the priority assigned to each of the seven water risk indicators based on the expert practitioner survey results.

5.D.4.1. Calculated Risk Score: In the first stage, the tool populates the risk scores for each indicator calculated in the estimation section described in Step 3. Since three indicators have more than one risk scores and to avoid double counting, specific formulas described in the main article were used to calculate each indicator's risk score.

5.D.4.2. **Priority Risk Multipliers:** In the second stage, the tool displays the multipliers for each water risk indicator based on the practitioner priorities elicited in the survey. The base priority is 1 and the highest is 3.5 for water quality risk indicator.

5.D.4.3. **Cumulative Water Risk Score and Rating:** Based on the multiplied product of the calculated risk scores and multipliers, i.e., (QUANTITY x QUALITY x SOURCE x REGULATORY x CONFLICT x SECTOR x REPUTATIONAL), the tool calculates the total risk score for each indicator and then the cumulative product score of all the indicators for the total/ cumulative water risk score for the user. The tool also calculates the maximum and minimum possible cumulative score based on the user selection such that a final rating can be calculated based on the relative score. The five point cumulative water risk rating scale based on the maximum and minimum value is also displayed in the tool at the end. For our hypothetical case, the Cumulative Water Risk Rating calculated for the user's facility is **Very High.**

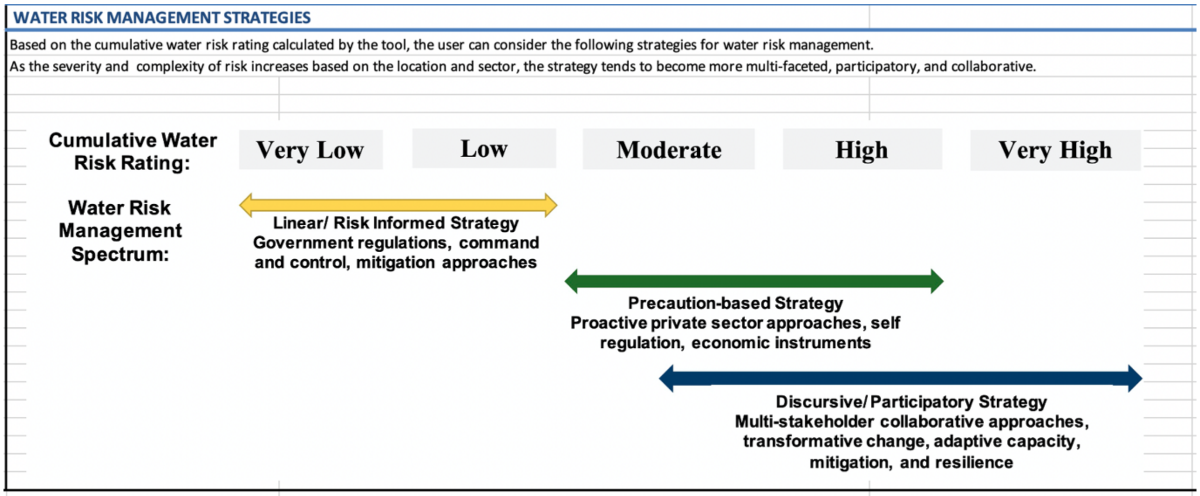
WATER RISK EVALUATION IN	Niagara	SUBWATERSHED FOR EXTRACTING	Groundwater	FOR THE PURPOSES OF	Beverage Manufacturing (Brewing, wine-making, soft drinks. etc.)

Overall Cumulative Risk Evaluation and Rating Matrix				
	Water Risk Indicator	Calculated Risk Score(maximum or multiplied, if applicable)	Priority Risk Multiplier (Water Risk Perception Survey), if applicable (default/ base priority set at 1)	Final Risk Score
1	Water Quantity Risk	2	2.5	5
2	Water Quality Risk	3	3.5	10.5
3	Source Specific Risk	2	1	2
4	Regulatory Risk	9	2	18
5	Water User Conflict Risk	3	2	6
6	Sector specific Risk	2.5	3	7.5
7	Reputational Risk (Public and Media Attention)	3	1.5	4.5
	CUMULATIVE WATER RISK SCORE (QUANTITY x QUALITY x SOURCE x REGULATORY x CONFLICT x SECTOR x REPUTATIONAL):			382725.0
	CUMULATIVE RISK RATING Based on 5 Point Scale			Very High
	Maximum Possible Risk Score/Rating	459270		
	Minimum Possible Risk Score/Rating	157.5		
	5 point Rating Scale Interval (based on maximum)	91854		

Cumulative 5 point Risk Rating Scale	Lower Limit Risk Score	Upper Limit Risk Score
Very High	367420	459270
High	275565	367419
Moderate	183710	275564
Low	91855	183709
Very Low	157.5	91854

5.D.5. Special Notes

5.D.5.1. **Water Risk Management Strategies:** Based on the reviewed literature and the insights from the interviews of multi-sector corporate and financial practitioners, the tool displays potential water risk management strategies as the final section. Based on the cumulative water risk rating calculated by the tool, the user can refer to the spectrum for the options for water risk management. The detailed explanation and background of the different strategies is provided in the main article.



5.D.5.2. **Risk Score Cards in WATR-DST:** As mentioned in the main article, the risk scores associated with the ratings of individual water risk indicators are pre-defined values that can be entered manually in the tool in the section labelled, "Risk Score Cards for Water Risk Indicators". Since there are additional risk indicators that do not have ratings and allow the user to self-select the scores, the tool also has the "Manually Entered Self-selected Risk Score", where the user can input their desired range or change the existing range. The light blue cells allow manual entry of values. The existing risk scores are entered for illustrative purposes to signal relative increase in severity as the rating increases proportionally on a 3 or 5 point scale. These values are not modelled or elicited but entered with a 0.5 increment. Values can be used as it is or elicited in multi-stakeholder consultations via roundtables or surveys similar to the priority risk multipliers.

Risk Score Cards for Water Risk Indicators

Water Quantity Risk Rating	Risk Score
High	2
Moderate	1.5
Low	1

Cumulative Regulatory Risk Rating	Risk Score
High	2
Moderate	1.5
Low	1

Manually Entered Self Selected Risk Score
3
2.5
2
1.5
1

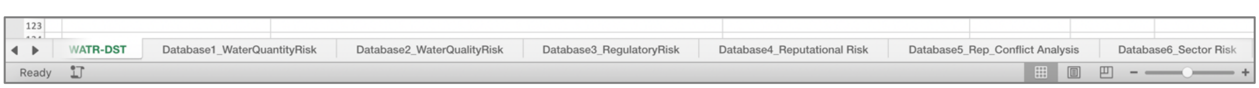
Source Type	Risk Score
Groundwater as Main Source	2
Both GW and SW as Main Source	1.5
Surface Water as Main Source	1

Water Quality Risk Rating	Risk Score
Very High	3
High	2.5
Moderate	2
Low	1.5
Very Low	1

Sub-watershed Specific Potential Conflict Risk Rating	Risk Score
Very High	3
High	2.5
Moderate	2
Low	1.5
Very Low	1

Sector specific Risk Rating	Risk Score
Very High	3
High	2.5
Moderate	2
Low	1.5
Very Low	1

5.D.5.3. **Underlying Databases/ Procedures:** If the user is interested in the underlying primary datasets and procedures used to arrive at the risk rating for the seven water risk indicators, they can refer to Sandhu et al., 2023a. This article has the detailed description of the procedures for the results that have been populated and integrated by the WATR-DST. The underlying databases for the indicators are also linked in the tool for the ease of reference and look up functions.



5.D.6. Summary of Inputs and Outputs for Hypothetical User

A. Inputs

(1) Main watershed: **Lake Ontario**
(2) Sub-watershed: **Niagara**
(3) Main Sector: **Industrial**
(4) Sub-sector: **Beverage Manufacturing**
(5) Source Type: **Groundwater**

B. Outputs

O1. Water Quantity Risk Type, Rating, and Score:

Groundwater	High	2

O2. Water Quality Risk Type, Rating, and Score:

Sub-watershed	Very High	3
Main-watershed	Qualitative, Self-select	2

O3. Source Type Risk Score:

Groundwater	2

O4. Regulatory Risk Rating Type and Score:

High Prevalence Risk Drivers	2
Moderate Risk Drivers	1.5
High Regulatory Focus Location	3

O5. Water user Conflict Rating and Score:

Very High	3

O6. Sector-specific Risk Rating and Score:

High	2.5

O7. Public and Media Attention (Reputational) Risk Rating and Score:

Qualitative, Self-select	3

O8. Integrated Water Risk Evaluation: Indicators, Calculated Risk Scores, Priority Multipliers and Total Scores based on product of score and priority multiplier:

Water Quantity Risk (maximum)	2	2.5	**5**
Water Quality Risk (maximum)	3	3.5	**10.5**
Source Specific Risk (as it is)	2	1	**2**
Regulatory Risk (product)	9	2	**18**
Water User Conflict Risk (as it is)	3	2	**6**
Sector specific Risk	2.5	3	**7.5**
Reputational Risk (Public and Media Attention) (as it is)	3	1.5	**4.5**

O9. Cumulative Water Risk Rating for User: **Very High**

O10. Recommended Water Risk Management Strategy: Participatory multi-stakeholder strategy, collaborative approaches

IV. Appendix D: Documentation for Research Ethics

D.1 Research Ethics Approval, REB # 44065

UNIVERSITY OF WATERLOO

Notification of Ethics Clearance to Conduct Research with Human Participants

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Principal Investigator: Olaf Weber (School of Environment, Enterprise and Development)

Student investigator: Guneet Sandhu (School of Environment, Enterprise and Development)

Co-Investigator: Michael Wood (School of Environment, Enterprise and Development)

Co-Investigator: Horatiu Rus (Economics)

Co-Investigator: Jason Thistlethwaite (School of Environment, Enterprise and Development)

File #: 44065

Title: Enabling the blue economy: Water risk management framework and tools

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The Human Research Ethics Board is pleased to inform you this study has been reviewed and given ethics clearance.

Initial Approval Date: 02/15/22 (m/d/y)

University of Waterloo Research Ethics Boards are composed in accordance with, and carry out their functions and operate in a manner consistent with, the institution's guidelines for research with human participants, the Tri-Council Policy Statement for the Ethical Conduct for Research Involving Humans (TCPS, 2nd edition), International Conference on Harmonization: Good Clinical Practice (ICH-GCP), the Ontario Personal Health Information Protection Act (PHIPA), the applicable laws and regulations of the province of Ontario. Both Boards are registered with the U.S. Department of Health and Human Services under the Federal Wide Assurance, FWA00021410, and IRB registration number IRB00002419 (HREB) and IRB00007409 (CREB).

This study is to be conducted in accordance with the submitted application and the most recently approved versions of all supporting materials.

Expiry Date: 02/16/23 (m/d/y)

Multi-year research must be renewed at least once every 12 months unless a more frequent review has otherwise been specified. Studies will only be renewed if the renewal report is received and approved before the expiry date. Failure to submit renewal reports will result in the investigators being notified ethics clearance has been suspended and Research Finance being notified the ethics clearance is no longer valid.

Level of review: Delegated Review

Signed on behalf of the Human Research Ethics Board

Karen Pieters, Manager, Research Ethics, karen.pieters@uwaterloo.ca, 519-888-4567, ext. 30495

This above named study is to be conducted in accordance with the submitted application and the most recently approved versions of all supporting materials.

Documents reviewed and received ethics clearance for use in the study and/or received for information:

D.2 Information letter and consent form for participant recruitment

Title of the study: Enabling the blue economy: Water risk management framework and tools

Principal Investigator/Faculty Supervisor: Dr. Olaf Weber, Professor and University Research Chair in Sustainable Finance, University of Waterloo, School of Environment, Enterprise, and Development, Faculty of Environment
Phone: 519-888-4567 ext. 48065
Email: oweber@uwaterloo.ca
Student Investigator: Guneet Sandhu, PhD Candidate, University of Waterloo, School of Environment, Enterprise, and Development, Faculty of Environment
Email: guneet.sandhu@uwaterloo.ca

To help you make an informed decision regarding your participation, this letter will explain what the study is about, the possible risks and benefits, and your rights as a research participant. If you do not understand something in the letter, please ask one of the investigators prior to consenting to the study. You will be provided with a copy of the information and consent form if you choose to participate in the study.

You are invited to participate in a mixed methods study on developing a novel, locally-attuned, and interdisciplinary water management framework and decision-support tools for Ontario, Canada, involving an online survey and online follow-up interview. As a full-time PhD candidate in the Sustainability Management program at the School of Environment, Enterprise and Development at the University of Waterloo, I am conducting research under the supervision of Professor and University Research Chair in Sustainable Finance, Dr. Olaf Weber, who is also leading this research project as the Principal Investigator.

What is the study about?

Canada including the economically diverse province of Ontario, is a compelling case for water risk assessment and management. Contrary to the perception of water abundance, critical water challenges including seasonal low flows, degraded water quality, drinking water advisories in indigenous communities, competing water user demands continue to persist. Sustainable use and management of a vital resource like water is necessary for a climate resilient and water secure future. Therefore, aligned with the Sustainable Development Goal 6, the risks posed by existing and emerging water issues need to be proactively assessed and managed. Moreover, in addition to assessment of interdisciplinary water risks, the literature highlights the need of examining risk perception or value and knowledge based judgement of practitioners for more comprehensive risk assessment and management.

Addressing these knowledge gaps, the objective of this study is to develop a theoretically robust, locally-attuned, and interdisciplinary water risk management framework and decision support tools by examining the perception of corporate and financial decision-makers and managers and then explain the relationship between water risk perception and risk assessment for the case of Ontario, Canada.

Rationale and importance of study

Past research has shown that in contrast to carbon emissions that can be assessed using global models, water issues and their impacts are locally defined and vary considerably at local and regional scales. Moreover, as major users of a socially, economically, and environmentally significant yet increasingly scarce resource like water, corporate and financial sector have a crucial role in water risk management. However, the systematic assessment of multi-dimensional water risks and integration of risk perception of decision makers for Ontario is largely under-explored. Consequently, the exploratory stage of this research project has examined different water issues for Ontario and identified seven water risk indicators. Therefore, by examining and integrating the perception, insights, and priorities of corporate and financial decision-makers for these indicators, this mixed methods study will inform the design of a novel and contextually attuned novel water risk management framework and decision support tool.

Overall, the study will enhance the understanding of complex water issues and the relationship between water risk perception, estimation and corporate and investment decision making. Given your role, experience and expertise in corporate sustainability management, your insights and inputs will be best suited for this study.

I. ***Your Involvement as a Participant***

What does participation in this study involve?

Participation in this study involves an online survey and an interview. While the relationship water risk perception and risk estimation will be examined using an online survey, the follow-up interviews, will help us explain the survey findings about the contextual factors shaping perceived risks and estimation.

Stage 1 Survey

For the first stage, you will be completing an online questionnaire-based survey consisting of approximately **30 questions** operated by Qualtrics. After receiving your signed consent form, I will send you the secure weblink to the survey. This survey will take about **35 minutes** of your time and can be filled out at your convenience between **1st July, 2022** and **10th August, 2022.**

In the survey you will be asked questions on ***your*** perception of water risks and how you would rate different water risks in corporate and financial decision making. Questions will focus on your **attitudes**, **knowledge, values and beliefs** regarding water issues, risks, impacts, and management as well as **trust** in institutions to allocate/ manage water resources. We will ask some **socio-cultural demographic** questions like your age group, gender, ethnicity, education, occupation, and location to help identify their relationship with water risk perception and estimation that are important to the study's objective. The municipal or sub-watershed location information will be used to develop a summary measure for home bias. Nonetheless, to ensure privacy, your location will not be individually identified in any publications. For **water risk estimation**, you will be asked to assign a priority to 7 water risk indicators for the case of Ontario, Canada.

Stage 2 Interviews

After the research team has concluded the survey stage as well as analyzed and aggregated key findings, follow up one on one semi-structured interviews will be conducted. The objective of the follow up interview is to obtain a deeper understanding and explanation of key findings of the survey. The interview will also be conducted over an online platform, MS Teams. The interview will take approximately **60 minutes** of your time. I will be scheduling the interviews from **1st October, 2022** and **15th December, 2022** that be arranged as per the convenience of your schedule. With your permission, I would also like to audio-record the interview to ensure accurate transcription and analysis. Your identity will be kept confidential.

The interview will contain open-ended questions, such as, your views on different water risks, impacts, and prioritization. Your insights on the aggregated survey findings, water risk management strategies and decision support tools. I will share a copy of all of the interview questions, with the reminder email. Shortly after the interview has been completed, I will send you a copy of the interview transcript to give you an opportunity to confirm the accuracy of our conversation and to add or clarify any points that you wish.

Qualtrics and MS Teams have implemented technical, administrative, and physical safeguards to protect the information provided via the Services from loss, misuse, and unauthorized access, disclosure, alteration, or destruction. However, no Internet transmission is ever fully secure or error free. Qualtrics temporarily collects your computer IP address to avoid duplicate responses in the dataset but will not collect information that could identify you personally.

Who will participate in this study?

We are inviting managers from corporate sector and financial sector in Ontario to participate in this study, who have had experience with assessing and integrating sustainability and environmental issues and risks in decision making. This will ensure diverse insights of decision-makers in sectors are considered.

II. Your Rights as a Participant

Is the participation in the study voluntary?

Your participation in the survey and interview is entirely voluntary. You may decline to answer any of the question(s) by skipping the question in the survey and/or by requesting to skip the question during the interview if you do not prefer to answer. Your survey response will be submitted for analysis only after you click the next/submission button on the "End of Survey" page. Therefore, you may withdraw from the survey stage at any time by not submitting your response. After the end of survey availability date i.e., 10th August, 2022, any unsubmitted survey responses will be automatically marked as withdrawn, and will be securely deleted by Qualtrics. However, if you have submitted the survey before this date, it is not possible to remove your data, because, to ensure your privacy, we are not collecting any identifying information and hence the researchers will not be able to identify your submitted response.

You may also withdraw from the interview stage at any time and request that your interview data removed until **1st March, 2023** simply by communicating us your decision via email. Your interview data will be removed from the dataset confidentially. However, it is not possible to remove your data from the study after this date since papers and publications would have been submitted to publishers.

What are the potential benefits of the study?

Participation in this study may not have direct personal benefits to you but it may benefit practitioners in corporate and financial sector companies, seeking to make water-related decisions. The study's water risk management framework and decision-support tool is expected to inform the assessment of interdisciplinary water risks and help gain an understanding of water risk perception and management that can help foster sustainable corporate and financial water policies and practices in Ontario. The research findings are expected to benefit the academic community by enhancing risk theory by applying it to water risk management. Therefore, advancing interdisciplinary knowledge development in corporate water management and sustainable finance. The results may benefit the broader society by supporting contextually attuned water policies and strategies envisioned to transition Ontario into a water secure and climate resilient economy and society.

After the data have been analyzed, you will receive a copy of a summary of the results and the decision-support tool will also be provided along with its instruction manual. If you would be interested in greater detail, an electronic PDF copy of the entire thesis can be made available to you, which will include the manuscripts submitted for publication.

Are there any anticipated risks associated with participation in the study?

There are no known or anticipated risks associated with the participation in this study. You will not be asked any sensitive questions and no sensitive information will be collected. The study's design is pre-determined and informed by existing studies on similar topics to ensure that there are no risks. The topic of water risk assessment and management is also a familiar topic based on your expertise and experience.

Will my identity be known?

Your identity in the survey and interviews will remain confidential. Your name or any information that can identify you will not appear in any thesis or any publication resulting from this study. The aggregated findings and any quotations appearing in the thesis and publications will be de-identified and anonymous.

Will my information be kept confidential and how?

Your identity will be kept confidential in both the survey and interview. The survey does not collect any direct identifying information. Any indirect identifying information collected in the survey like socio-demographics will be directly uploaded to an aggregated dataset for analysis. Moreover, to ensure there is no risk of indirect identification, the participant's location data will also not be identified/reported in any publications and instead a summary measure of "home bias" differentiated as high/moderate/low proximity to any water risk hotspots will be reported that is created by combining municipal locations and time spent variables during data analysis.

The interview data will be kept confidential by assigning an alphanumeric identification code, so that neither your name nor any identifying information is associated with the data collected. All information that could identify you will be removed from the data we have collected as soon as possible (within 2 days) and stored separately in a password protected and encrypted computer located in a restricted access area. The anonymous survey responses and de-identified and coded transcribed interview data will also be securely stored in a password-protected computer of the research team and any data that will be stored on a laptop will be encrypted. The team will follow University of Waterloo Information Systems & Technology (IST) data security standards, guidelines, and protocols. The research data will be retained for at least **seven years** and then confidentially erased according to University of Waterloo policy. Only the research team associated with this study, who are also under a non-disclosure and confidentiality agreement, will have access to the study data.

III. Questions, comments, or concerns

Who is sponsoring/funding this study?
This study is supported by funding from the Social Sciences and Humanities Research Council of Canada (SSHRC).

Has the study received ethics clearance?
This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Board (REB # 44065). If you have questions for the Board contact the Office of Research Ethics, at 1-519-888-4567 ext. 36005 or reb@uwaterloo.ca.

Who should I contact if I have questions regarding my participation in the study?
If you have any questions regarding this study, or would like additional information to assist you in reaching a decision about participation, please contact me, Guneet Sandhu, by email at guneet.sandhu@uwaterloo.ca. You may also contact my supervisor Dr. Olaf Weber at oweber@uwaterloo.ca.

Thank you in advance for your interest and consideration to participate in this research.

Yours sincerely,

Guneet Sandhu, PhD Candidate
University of Waterloo
School of Environment, Enterprise and Development
200 University Avenue West,
Waterloo, ON, Canada N2L 3G1

Email: guneet.sandhu@uwaterloo.ca

CONSENT FORM

By signing this consent form and providing your consent, you are not waiving your legal rights or releasing the investigator(s) or involved institution(s) from their legal and professional responsibilities.

Title of the study: Enabling the blue economy: Water risk management framework and tools.

I have read the information presented in the information letter about the study conducted by Dr. Olaf Weber (Principal Investigator/Supervisor) and Guneet Sandhu (Student Investigator) of the School of Environment, Enterprise and Development at the University of Waterloo. I have had the opportunity to ask questions related to the study and have received satisfactory answers to my questions and any additional details.

I was informed that participation in this study is voluntary. I am aware that I can withdraw consent to participate in the survey by not submitting the survey response. I am also aware that I can withdraw consent to participate in interview at any time by informing the researchers and can have my interview data removed until **1st March, 2023**.

As a participant in this study, I am aware that I may decline to answer any question that I prefer not to answer.

I am also aware of my interview being audio recorded to ensure accurate transcription and analysis. My identity will be confidential, and I will not be identified in the thesis or subsequent publications. I am also aware that excerpts from the survey and/or quotations from the interview may be included in the thesis and/or publications that come from the research, with the understanding that quotations will be anonymous.

This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Board (REB # 44065). If you have questions for the Board, please contact the Office of Research Ethics, at 1-519-888-4567 ext. 36005 or reb@uwaterloo.ca.

For all other questions contact Guneet Sandhu at guneet.sandhu@uwaterloo.ca

With full knowledge of all foregoing, I agree, of my own free will, to participate in this study involving an online survey and an online interview.

☐ Yes ☐ No

I agree to my interview being audio recorded to ensure accurate transcription and analysis.

☐ Yes ☐ No

I agree to the use of anonymous quotations in any thesis or publication that comes of this research.

☐ Yes ☐ No

Participant's Name: ___________________________________

Participant's Signature: ________________________________

Researcher's/Witness' Name: ____________________________________

Researcher's/Witness' Signature: __________________________________

Date: ____

D.3 Appreciation letter for participants

Study Title: Enabling the blue economy: Water risk management framework and tools.

Principal Investigator/Faculty Supervisor: Dr. Olaf Weber, Professor and University Research Chair in Sustainable Finance, University of Waterloo, School of Environment, Enterprise, and Development, Faculty of Environment

Phone: 519-888-4567 ext. 48065, Email: oweber@uwaterloo.ca

Student Investigator: Guneet Sandhu, PhD Candidate, University of Waterloo, School of Environment, Enterprise, and Development, Faculty of Environment

Email: guneet.sandhu@uwaterloo.ca

Dear [Participant's Name],

We appreciate your participation in our study and thank you for spending the time helping us with our research!

We would like to thank you for your participation in this study entitled "Enabling the blue economy: Water risk management framework and tools". In this study, you participated in an online survey that asked questions on your perception and rating of different water risks and follow up interviews, where you provided your insights on the key survey findings and explained how these risks have been integrated in corporate and/or financial decision making. The purpose of this study was to examine the value-based and sector-specific perception or priorities of decision-makers, managers, and analysts related to different water risks that will be integrated to develop a theoretically robust and interdisciplinary, water risk management framework and decision support tools for Ontario, Canada.

The tangible outputs of the study i.e., the water risk management framework and decision support tools are critically important for understanding complex interdisciplinary water issues and proactively integrating water risks in corporate and financial decision making especially for provinces like Ontario, perceived to be water abundant. Moreover, the survey and in-depth interviews helped understand and explain the relationship between water risk perception factors and water risk assessment and management that has been underexplored in academic literature. The results will further support designing contextually attuned and evidence based multi-sector policies and strategies for sustainable water management that are necessary for supporting a climate-resilient, water-secure, and sustainable society and economy of Ontario and Canada.

As a reminder, your identity for the survey and interview will remain confidential. Your name or any information that can identify you, will not appear in any thesis or any publication resulting from this study. The findings and any quotations appearing the thesis and publications will be de-identified and anonymous. Your survey data is anonymous and for interview stage your identity will be kept confidential by assigning an alphanumeric identification code, so that neither the individual name nor any identifying information is associated with the data collected. All information that could identify you will be removed from the interview data we have collected as soon as possible (within 2 days) and stored separately in a password protected computer in a restricted access area. The anonymous survey and de-identified interview data will also be securely stored in a password-protected computer of the research team and any data that will be stored on a laptop will be encrypted. The research data will be retained for at least **seven** years and then confidentially erased according to University of Waterloo policy. Only the research team associated with this study, who are also under a non-disclosure and confidentiality agreement, will have access to the study data.

This study was reviewed and received ethics clearance through a University of Waterloo Research Ethics Board (REB # 44065) If you have questions for the Board contact the Office of Research Ethics, at 1-519-888-4567 ext. 36005 or reb@uwaterloo.ca.

For all other questions contact Guneet Sandhu via email at guneet.sandhu@uwaterloo.ca or Dr. Olaf Weber via email at oweber@uwaterloo.ca

Once all the data are collected and analyzed for this study, I plan on sharing this information with the research community through seminars, conferences, presentations, and journal articles. You will receive summary of the results once the full study is completed, anticipated by April, 2023. If you would be interested in greater detail, an electronic copy (e.g., PDF) of the entire thesis can be made available to you tentatively by 1st May, 2024, which will include the manuscripts submitted for publication.

In the meantime, if you have any questions about the study, please do not hesitate to contact the research team by email.

We really appreciate your participation and your valuable contribution to this study, and hope that this has been an interesting experience for you.

Yours sincerely,

Guneet Sandhu,
PhD Candidate in Sustainability Management
University of Waterloo
School of Environment, Enterprise and Development
200 University Avenue West, Waterloo, ON, Canada N2L 3G1
Email: guneet.sandhu@uwaterloo.ca

V. Appendix E: Survey Questionnaire

Title of the study: Enabling the blue economy: Water risk management framework and tools

Principal Investigator/Faculty Supervisor: Dr. Olaf Weber, Professor and University Research Chair in Sustainable Finance, University of Waterloo, School of Environment, Enterprise, and Development, Faculty of Environment
Phone: 519-888-4567 ext. 48065
Email: oweber@uwaterloo.ca
Student Investigator: Guneet Sandhu, PhD Candidate, University of Waterloo, School of Environment, Enterprise, and Development, Faculty of Environment
Email: guneet.sandhu@uwaterloo.ca

Welcome to the survey!

The questionnaire will include 7 main categories of questions. The description or definition for each category and terms used in the questions/survey items is provided alongside for consistent understanding of all terms and items in the survey by all participants. You can choose to skip any question you do not feel comfortable to answer by selecting the "continue without answering" option. This is a not a timed survey and you can quit the survey at any time. You can fill out the survey in multiple sessions and your in-progress responses will be temporarily and securely saved. So, if you decide to complete the survey at later time, you can continue from where you left when using the same internet browser and computer. However, as a reminder please note that the survey will only be available till **10th August, 2022, 11:59 PM, ET,** so if you decide to complete your in-progress survey, please do so before then. After this date, all in-progress surveys will be marked as incomplete and withdrawn, and will be permanently and securely deleted by Qualtrics.

At the end of the questionnaire, there will be an "End of Survey" page, and for completion and submission of the survey, you have to click the next (submission) button on this page. Upon clicking this button and hence on successful completion and submission of the survey, you will see the ***"Thank you"*** page. If you have any questions regarding the survey, please contact Guneet Sandhu, by email at guneet.sandhu@uwaterloo.ca.

As a reminder, all details regarding this survey and the overall study are provided in the information and consent letter that was previously emailed to you.
This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Board (REB # 44065). If you have questions for the Board, please contact the Office of Research Ethics, at 1-519-888-4567 ext. 36005 or reb@uwaterloo.ca.

1. Introductory Questions

The following questions are some introductory or general questions pertaining to your personal view or perspectives on water issues, their drivers, and impacts along with the risks they pose.

Survey Item Q 1: Based on the context of Ontario, Canada please indicate your extent of agreement or disagreement with the following statements on water related issues:
Reference: (Mumbi & Watanabe, 2020)
Measuring Unit: 7-point Likert Scale

i. Watersheds and sub-watersheds across Ontario have been facing freshwater quantity issues including seasonal low flows/levels in streams, rivers, and lakes, potential drought conditions, over-extraction by users, and groundwater depletion.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

ii. Watersheds and sub-watersheds across Ontario have been facing degraded water quality issues in streams, rivers, lakes, and groundwater.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iii. The water-related allocation, taking (extraction), management and emission laws and regulations in Ontario are still evolving and changing in reaction to water issues.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iv. There is increasing competition over water taking (extraction) among different water user groups and sectors who depend on same local water resources in Ontario.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 2: Please indicate your rating of the overall likelihood of Ontario increasingly facing water related issues and risks across sub-watersheds.
Reference: (Krewski et al., 2008; McDaniels et al., 1997; Mumbi & Watanabe, 2020)
Measuring Unit: 7-point Likert Scale:

Very Low	Low	Somewhat Low	Moderate	Somewhat High	High	Very High
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 3: Please indicate based on your understanding and opinion, the degree to which the following are drivers or contributors to water issues in Ontario:
Reference: (Krewski et al., 2006, 2008; McDaniels et al., 1997; Mumbi & Watanabe, 2020)
Measuring Unit: 7-point Likert Scale

i. Climate change

Very Low contribution	Low	Somewhat Low	Moderate	Somewhat High	High	Very High contribution
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

ii. Industrial water use (water extraction, operational use, and effluent/run-off by all industrial sectors including agriculture, manufacturing, power utilities)

Very Low	Low	Somewhat Low	Moderate	Somewhat High	High	Very High
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iii. Mismanagement by Government or regulatory lapses

Very Low	Low	Somewhat Low	Moderate	Somewhat High	High	Very High
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iv. Inefficient water use by individuals

Very Low	Low	Somewhat Low	Moderate	Somewhat High	High	Very High
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

v. Population growth (hence increasing demand)

Very Low	Low	Somewhat Low	Moderate	Somewhat High	High	Very High
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

vi. If you think there are other drivers, Please specify and rate ________________________

Very Low	Low	Somewhat Low	Moderate	Somewhat High	High	Very High
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 4. i.: How confident are you that **Ontario**, **in general** has sufficient and abundant freshwater to meet the needs and demands for all current water users and in the future.

Very unconfident	Unconfident	Somewhat unconfident	Neither	Somewhat confident	Confident	Very confident
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

ii. How confident are you that **your sub-watershed/region of residence** has sufficient and abundant freshwater to meet the needs and demands for all current water users and in the future.

Very unconfident	Unconfident	Somewhat unconfident	Neither	Somewhat confident	Confident	Very confident
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

2. Water Attitudes

The following questions ask you to indicate your opinion regarding the statements on **attitudes** (awareness of impacts, perspectives of aspects of controllability, equity, previous experience with water scarcity, quality or other observed water access issues, overall concern regarding water issues)

Survey Item Q 5: Please indicate the extent of **negative impact** of different freshwater issues including water quantity like droughts, seasonal low flows, groundwater depletion, water quality issues (pollution, algal blooms, run-offs, municipal wastewater), conflicts among competing water users can have on the following in the context of Ontario, Canada:

Reference: (Dobbie & Brown, 2014; McDaniels et al., 1997; Mumbi & Watanabe, 2020)
Measuring Unit: 7-point Likert Scale

i. Country's economic growth

Very Low Negative impact	Low	Somewhat Low	Moderate	Somewhat High	High	Very High Negative impact
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

ii. Social well being of current and future generations

Very Low	Low	Somewhat Low	Moderate	Somewhat High	High	Very High
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iii. Human health

Very Low	Low	Somewhat Low	Moderate	Somewhat High	High	Very High
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iv. Environmental health, quality, and sustainability

Very Low	Low	Somewhat Low	Moderate	Somewhat High	High	Very High
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

v. From an organization's perspective, profitability

Very Low	Low	Somewhat Low	Moderate	Somewhat High	High	Very High
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

vi. From an organization's perspective, reputation and brand image

Very Low	Low	Somewhat Low	Moderate	Somewhat High	High	Very High
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

vii. From an organization's perspective, acceptability of local communities or social license to operate

Very Low	Low	Somewhat Low	Moderate	Somewhat High	High	Very High
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 6: Based on your understanding and perspective, please rate the scope i.e., the area and people affected/impacted by each of the following issues:
Reference: (McDaniels et al., 1997)
Measuring Unit: 7-point Likert Scale

i. Water quantity issues like droughts, seasonal low flows, groundwater depletion

Very small	Small	Somewhat Small	Average	Somewhat large	Large	Very Large
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

ii. Surface water (streams, rivers, lakes) quality issues (pollution, algal blooms, run-offs, municipal wastewater)

Very small	Small	Somewhat Small	Average	Somewhat large	Large	Very Large
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iii. Groundwater contamination

Very small	Small	Somewhat Small	Average	Somewhat large	Large	Very Large
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iv. Lack of access to clean and safe drinking water

Very few people	Few	Somewhat Few	Average	Somewhat large	Many	A lot of people
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

v. Conflicts (controversies, criticism) among competing water user groups over same water sources

Very small	Small	Somewhat Small	Average	Somewhat large	Large	Very Large
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 7: Please indicate your rating on the controllability each of the following issue i.e., the ability of experts/Governments/other entities to control and manage the risks and impacts posed by these issues on humans and the environment.
Reference: (Dobbie & Brown, 2014; McDaniels et al., 1997)
Measuring Unit: 7-point Likert Scale

i. Water quantity issues like droughts, seasonal low flows, groundwater depletion

Very Uncontrollable	Uncontrollable	Somewhat Uncontrollable	Neither	Somewhat Controllable	Controllable	Very Controllable
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

ii. Surface water (streams, rivers, lakes) quality issues (pollution, algal blooms, run-offs, municipal wastewater)

Very Uncontrollable	Uncontrollable	Somewhat Uncontrollable	Neither	Somewhat Controllable	Controllable	Very Controllable
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iii. Groundwater contamination

Very Uncontrollable	Uncontrollable	Somewhat Uncontrollable	Neither	Somewhat Controllable	Controllable	Very Controllable
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iv. Lack of access to clean and safe drinking water

Very Uncontrollable	Uncontrollable	Somewhat Uncontrollable	Neither	Somewhat Controllable	Controllable	Very Controllable
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

v. Conflicts (controversies, criticism) among competing water user groups over same water sources

Very Uncontrollable	Uncontrollable	Somewhat Uncontrollable	Neither	Somewhat Controllable	Controllable	Very Controllable
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 8: Please indicate your rating on the fairness and equity of all water related issues i.e., if water issues and risks posed affect all people equally and if people who are negatively impacts or incur the costs of impacts are the people who receive benefits from using water resources
Reference: (Dobbie & Brown, 2014; McDaniels et al., 1997)
Measuring Unit: 7-point Likert Scale:

Very Inequitable	Inequitable	Somewhat Inequitable	Neither	Somewhat Equitable	Equitable	Very Equitable
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 9: Please indicate your degree of agreement:
The economic benefits of activities causing water issues can offset the costs and risks
Reference: (Dobbie & Brown, 2014; McDaniels et al., 1997)
Measuring Unit: 7-point Likert Scale:

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 10 i.: Have you directly experienced any water issue (water shortage, use restrictions by regulatory authorities, quality issues, adverse drinking water quality, lack of access to drinking water, conflict with other water user) at any point in your life?
Reference: (Dupont et al., 2010; Eagly & Chaiken, 2007; Mumbi & Watanabe, 2020; Thistlethwaite et al., 2018)
Measuring Unit: 7-point Likert Scale:

Never	Rarely	Occasionally	Sometimes	Somewhat Frequently	Frequently	Very Frequently
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

ii. How recent has been this experience?

Less than 2 years	Last 5 years	Last 10 years	Last 15 years	Last 20 years	More than 20 years	Not applicable
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 11: Have any of your family or friends experienced any water issue (water shortage, use restrictions by regulatory authorities, quality issues, adverse drinking water quality, lack of access to drinking water, conflict with other water user) at any point?
Reference: (Thistlethwaite et al., 2018)
Measuring Unit: 7-point Likert Scale

Never	Rarely	Occasionally	Sometimes	Somewhat Frequently	Frequently	Very Frequently
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 12 i.: Please indicate your overall level of concern about water issues, their impacts, and risks posed in **Ontario in general**?
Reference: (Bouman et al., 2018; Dupont et al., 2010, 2014; Thistlethwaite et al., 2018)
Measuring Unit: 7-point Likert Scale:

Totally unconcerned	Unconcerned	Somewhat unconcerned	Neutral	Somewhat Concerned	Concerned	Very Concerned
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

ii. Please indicate your overall level of concern about water issues, their impacts, and risks posed in **your sub-watershed/region of residence**?

Totally unconcerned	Unconcerned	Somewhat unconcerned	Neutral	Somewhat Concerned	Concerned	Very Concerned
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 13: Please indicate your rating on how urgently you think water risks should be assessed and managed by private sector companies, investors, and government entities in Ontario.
Reference: (Dobbie & Brown, 2014; McDaniels et al., 1997; Mumbi & Watanabe, 2020; Slimak & Dietz, 2006)

Measuring Unit: 7-point Likert Scale:

Not at all urgent	Low Urgency	Somewhat Urgent	Neutral	Moderate Urgency	Urgent	Very Urgent
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 14: Please indicate your comparative rating on the priority assigned to assessing and managing water issues and risks in organizational decision making as compared to carbon/greenhouse gas emissions.
Reference: (Dobbie & Brown, 2014; McDaniels et al., 1997; Mumbi & Watanabe, 2020; Slimak & Dietz, 2006)

Measuring Unit: 7-point Likert Scale:

Very low Priority	Low Priority	Somewhat low Priority	Same Priority	Somewhat High Priority	High Priority	Very High Priority
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

3. Knowledge related to Water Issues and Risks

The following questions ask you to rate the statements on **knowledge** of water issues, risks as well as assessment and management i.e., understanding of water issues and risks based on your academic training and/or professional experience.

Survey Item Q 15 i. : Please rate your level of experience with sustainability assessment (e.g., environmental (carbon emissions, water related, waste etc.) social impact, governance) and management.
Reference: (Mumbi & Watanabe, 2020; Slimak & Dietz, 2006)
Measuring Unit: 7-point Likert Scale:

No experience	Novice	Somewhat Novice	Intermediate	Somewhat Experienced	Experienced	Very Experienced
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

ii. Please rate your level of experience specifically with water risk assessment and management.

No experience	Novice	Somewhat Novice	Intermediate	Somewhat Experienced	Experienced	Very Experienced
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 16: Based on your knowledge and professional experience in your organization, please indicate your degree of agreement with the following:
Reference: (Klinke & Renn, 2012; Krewski et al., 2008; Mumbi & Watanabe, 2020; Thistlethwaite et al., 2018)
Measuring Unit: 7-point Likert Scale

i. Water issues like scarcity, pollution, groundwater depletion, lack of drinking water access, competing water use demand continue to increase across the globe.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

ii. Water issues and subsequent risks are being assessed, managed, and integrated in decision making in my organization.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iii. Water risks can be best managed by additional and more stringent Government regulations on all water using sectors.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iv. Water risks can be best managed by more scientific research and expert based inputs on water risks for informed decision making.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

v. Water risks can be best managed using more proactive approaches to build water resilience in all water using sectors

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

vi. Water risks can be best managed using more participatory approaches by consulting and deliberating with all stakeholders i.e., different levels of Governments, companies in the same and different water using sectors, Indigenous communities, and local residents

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 17 i.: Please rate how much you feel is known by scientists and experts about different water issues, impacts, risks, and their likelihood in Ontario, Canada
Reference: (Krewski et al., 2008; McDaniels et al., 1997)
Measuring Unit: 7-point Likert Scale

Very Little Known	Little	Somewhat Little	Moderate	Somewhat High	High amount known	Very high amount
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

ii. : Please indicate based on your knowledge and experience, how much is known about water risks, their assessment and management in different organizational sectors in Ontario, Canada
Reference: (Dobbie & Brown, 2014; McDaniels et al., 1997; Mumbi & Watanabe, 2020; Slimak & Dietz, 2006)
Measuring Unit: 7-point Likert Scale:

Very Little Known	Little	Somewhat Little	Moderate	Somewhat High	High amount known	Very high amount
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 18: Please indicate your level of agreement with the following:
Reference: (Dobbie & Brown, 2014; McDaniels et al., 1997; Mumbi & Watanabe, 2020; Slimak & Dietz, 2006)
Measuring Unit: 7-point Likert Scale

I have sufficient knowledge through my educational training and/or professional experience about risks pertaining to:

i. Water scarcity (droughts, low water levels, groundwater depletion) and water quality issues.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

ii. Water related regulatory changes in Ontario, Canada

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iii. Public opinions, concerns, and local water user conflicts over shared water resources

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iv. Sector specific impacts of water taking and water emissions on local water resources

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 19: Where do you get your information on water issues, risks, and impacts in Ontario?
Reference: (Krewski et al., 2006)
Measuring Unit:

Internet	Newspapers	Social media	Government websites	Scientific/ University Research Journals or reports	Own company assessors	Environmental groups/Think Tank reports e.g., WWF
☐	☐	☐	☐	☐	☐	☐

Conferences	Other, Please Specify	
☐	☐	____________________

4. Values and Beliefs

The following questions ask you to rate the statements on **values and beliefs** (pertaining to water availability, quality, and equitable access as well as extent of integration of water risks in decision making). While general values are goals and guiding principles that guide an individual's action and behavior, in the context of this study, we aim to capture your water related values and beliefs specifically.

Survey Item Q 20: Please indicate your degree of agreement for the following statements:
Reference: (Bouman et al., 2018; Krewski et al., 2008; Sjöberg, 2000a, 2000b)
Measuring Unit: 7-point Likert Scale

i. It is important for me prevent environmental issues including water issues like scarcity, contamination, inequitable access, inefficient use etc.

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

ii. It is important for me to ensure the environmental health, quality, and sustainability of the environment and water resources is maintained for future generations

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iii. It is important for me that every person has fair and equitable access to water resources and its benefits

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iv. It is important for me to assess both the costs and benefits of water risks and management options

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

v. I believe that some level of risk is acceptable if economic benefits outweigh the costs

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

vi. I believe we can fully rely on technology and infrastructure solutions (e.g., dams, desalination, pollution control, waste recovery etc.) to address all water issues and risks

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

vii. I believe focus should be on proactive reduction of water risks by improving water use efficiency, conservation, and less waste production

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

viii. It is important for me to protect water resources for personal benefits and benefits to my organization

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

ix. It is important for me to protect water resources for benefits to all water users of water resources

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

x. It is important for me to protect water resources and the environment for ecological health and water dependent wildlife and all species in general

Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 21: Please indicate the extent to which water bodies have cultural importance to you. Culture is broadly defined as a system or set of shared or group beliefs, norms, meanings, customs and values of a group of people that is acquired by an individual (Weber & Hsee, 1998). Culture is not static but rather dynamic and evolving influenced by individual and group beliefs and the demands of their environment over time (López & Guarnaccia, 2000; Weber & Hsee, 1998). Therefore, cultural importance of water bodies refers to importance or value of water bodies to your shared set of group beliefs, norms, and values.
Reference: (Dobbie & Brown, 2014; Dupont et al., 2014)
Measuring Unit: 7-point Likert Scale:

Not at all Important	Low Importance	Slightly Important	Neutral	Moderate Importance	Important	Very Important
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

5. **Trust**

The following questions ask you to rate the statements on **trust** (in different institutions to allocate, manage, and protect water resources).

Survey Item Q 22: Please indicate your rating for the following questions.
Reference: (Dobbie & Brown, 2014; Krewski et al., 2008; Mumbi & Watanabe, 2020)
Measuring Unit: 7-point Likert Scale

i. Please indicate the degree or level of how much you trust the different levels of Government to proactively assess water issues and risks and manage them by apt regulations.

Not at all	Very Little	Little	Moderate	Somewhat High	High	Very high
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

ii. Please indicate the degree or level of how much you trust the private sector to self regulate and proactively manage water risks.

Not at all	Very Little	Little	Moderate	Somewhat High	High	Very high
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iii. Please indicate the degree or level of how much you trust the civil society organizations including environmental groups, citizen led groups, and individuals to aptly assess water risks and signal issues to authorities.

Not at all	Very Little	Little	Moderate	Somewhat High	High	Very high
1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

6. **Water Risk Ratings or Priorities**

The following question pertain to assigning a rating or weight to each the 7 water risk indicators (indicator description is given with each) based on your perception of their importance to business operations and/or investment decisions.
Survey Item Q 23: Please assign a risk rating or weight to each of the seven water risk indicators below, based on your knowledge, professional experience and perception, of their relative importance and impact

on your sector's business operations, policies, and decisions. Please note that a higher rating indicates a higher priority assigned to that type of water risk indicator as compared to others. 1: Lowest Rating or Weight or Priority and 7: Highest rating or Weight or Priority
Reference: (McDaniels et al., 1997; Mumbi & Watanabe, 2020; Slimak & Dietz, 2006; O. Weber, 2001)
Measuring Unit: 1-7 Continuous Rating Scale

i. **Biophysical water quantity risk,** i.e., risk of freshwater quantity issues with seasonal low flows/levels in streams, rivers, and lakes, potential drought conditions and water stress, over-extraction by users, and groundwater depletion

1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

ii. **Biophysical water quality risk**, i.e., risk of degraded surface water and grounded quality issues from different contaminants, high vulnerability of groundwater aquifer to contamination, quality threats from past and ongoing contaminated sites

1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iii. **Source type risk,** i.e., risk based on the type of source e.g., groundwater that is more susceptible to water quantity or quality issues

1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

iv. **Regulatory risk**, i.e., risk due to changing and more stringent water related laws, policies, and regulations for allocation, use, management, and water emissions by the Federal, Provincial or Municipal Governments

1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

v. **Sub watershed-specific water user conflict risk**, i.e., potential of conflicts i.e., controversies, criticism, public concerns, negative media attention, legacy issues, among different water user groups or sectors dependent on same water sources

1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

vi. **Sector specific risk**, i.e., assessed risks specific to the type of sector and sub-sector based on its impact, type of water use, regulatory focus, and public perception

1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

vii. **Qualitative themes of public concern and media attention**, i.e., aligned with reputational risk where risk is qualitatively assessed based on concerns of civil society and media coverage arising from actual or perceived adverse impact of corporate water use on equitable access and sustainability of water resource.

1	2	3	4	5	6	7
☐	☐	☐	☐	☐	☐	☐

7. Socio-cultural Demographic Questions
The following questions ask some socio-cultural demographic questions that you can select from the pre-coded drop down lists or self-report in the text box for “others” option.

We are collecting socio-cultural demographics like age, gender, ethnicity, education level and field, occupation, sector of occupation and upper tier municipal location of decision-makers, to identify their relationship with water risk perception and estimation. The location and time spent variables of sub-watershed or municipality as well as province/country lived outside Ontario/Canada are collected to develop a measure of “home bias” that captures the effect of geographical proximity to risk hotspots. The location variables will not be individually identified and reported in any findings. Therefore, given the theoretical importance and necessity of these socio-cultural demographic questions to the study’s objective on water risk perception and estimation, these questions are included in the survey.

Reference: (Dobbie & Brown, 2014; Dupont et al., 2014; Krewski et al., 2006; Mumbi & Watanabe, 2020; Money, 2014b; Siegrist & Árvai, 2020; Slimak & Dietz, 2006; Weber et al., 2002; Weber, 2001)

Survey Item Q 24: What is your age group?
Measuring Unit:

19-24 years	25-34 years	35-44 years	45-54 years	55-64 years	65-74 years	Over 75 years
☐	☐	☐	☐	☐	☐	☐

Survey Item Q 25: Which gender identity do you most identify with?
Measuring Unit :

Woman	Man	Gender non-conforming	Non-binary	Agender	Questioning	Trans
☐	☐	☐	☐	☐	☐	☐

Two-Spirit	Prefer not to answer	Another Gender, Please Specify	
☐	☐	☐	______________________

Survey Item Q 26: Which ethnicity do you most identify with?
Measuring Unit :

African	Black/ African American /Canadian African	East Asian (e.g., China, Japan, Vietnam etc.)	Hispanic	Indigenous (First Nations/ Métis/ Inuit)	Middle Eastern/North African	Mixed ethnicities
☐	☐	☐	☐	☐	☐	☐

South/Southeast Asian (India, Pakistan, etc.)	White/ Caucasian/ European origin	Prefer not to answer	Other, Please Specify	
☐	☐	☐	☐	____________________

Survey Item Q 27. i: What is the highest level of education attained?
Measuring Unit:

Apprenticeship or Trades Certificate/ Diploma	College or other non-University Certificate or Diploma, below Bachelor level	Secondary (High) School Diploma	University Degree or Certificate or Diploma, Bachelor level	University Degree or Certificate, Master or PhD level
☐	☐	☐	☐	☐

ii. What is the field of education or discipline of your highest level of education?
Measuring Unit:

Arts (including Economics, Business, Finance, Administration etc.)	Engineering and Technology (Applied Sciences)	Environment	Health Sciences	Mathematics	Natural and Physical Sciences
☐	☐	☐	☐	☐	☐

If other, please specify: __________________

iii: What is your current professional occupation?
Measuring Unit: Self-reported
Please specify: ______________________________

ii. Please select the sector of your occupation from the dropdown list.
Measuring Unit: Select from list

Agribusiness (including crops, aquaculture, livestock)	Food Processing	Textile and Textile Product mills	Plastics and Rubber Manufacturing	Mining (metal and non metallic minerals)
Commercial (Golf course, Snow making, Malls, Recreational facilities)	Fruit and Vegetable Canning or Pickling	Clothing Manufacturing	Fabricated Metal Product Manufacturing	Oil and Gas Extraction
Construction	Ready-mix Concrete Manufacturing and other Non-metallic Mineral Product Manufacturing	Leather and Allied Product Manufacturing	Machinery Manufacturing	Thermoelectric Power Production (including nuclear)
Conservation or Environmental Organization				
Governmental Organization				
Nongovernmental Organization				
Aggregate washing/ processing/pits and quarries	Pesticide, Fertilizer and other Agricultural Chemical Manufacturing	Pulp and Paper Manufacturing	Computer and Electronic Product Manufacturing	Hydroelectric Power Production
				Wind Power Production
Beverage Manufacturing (Brewing, wine-making, soft drinks. etc.) Water bottling	Inorganic Chemical Manufacturing	Wood Products Manufacturing	Transportation Equipment Manufacturing	Water utility – Municipal water treatment or wastewater treatment
Water bottling	Primary Metal Manufacturing	Petroleum and Coal Product Manufacturing	Furniture and related Product Manufacturing	Continued…..

If Other, Please specify ________________________________

Survey Item Q 28. i. Please specify the name of your municipality or city and Province/State of residence, and if known, the name of your sub-watershed/conservation authority:
Municipality/City: ______________________
Province/State: ______________________
Sub-watershed or conservation authority: _________________________

ii. Please specify the name of your municipality or city and Province/State of your work:
Municipality/City: ______________________
Province/State: ______________________
Sub-watershed or conservation authority: _________________________

Survey Item Q 29. Please specify for how many years have you lived or worked in Ontario:
____

Survey Item Q 30. Have you ever lived in other provinces and/or countries other than Ontario and/or Canada for more than a year?

YES **NO**

☐ ☐

If yes, please specify the province and/or country: ____________________________

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____
____

End of Survey Page:

This is the end of the survey.

Please click the next button to complete and submit the survey. You will see the "Thank you" page upon successful submission.

If you do not wish to submit your responses and you want to withdraw from the survey, please do not click the next button on this page.
