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Water, climate change and uncertainty in the Great Lakes and Rio Grande/Bravo Regions

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ABSTRACT

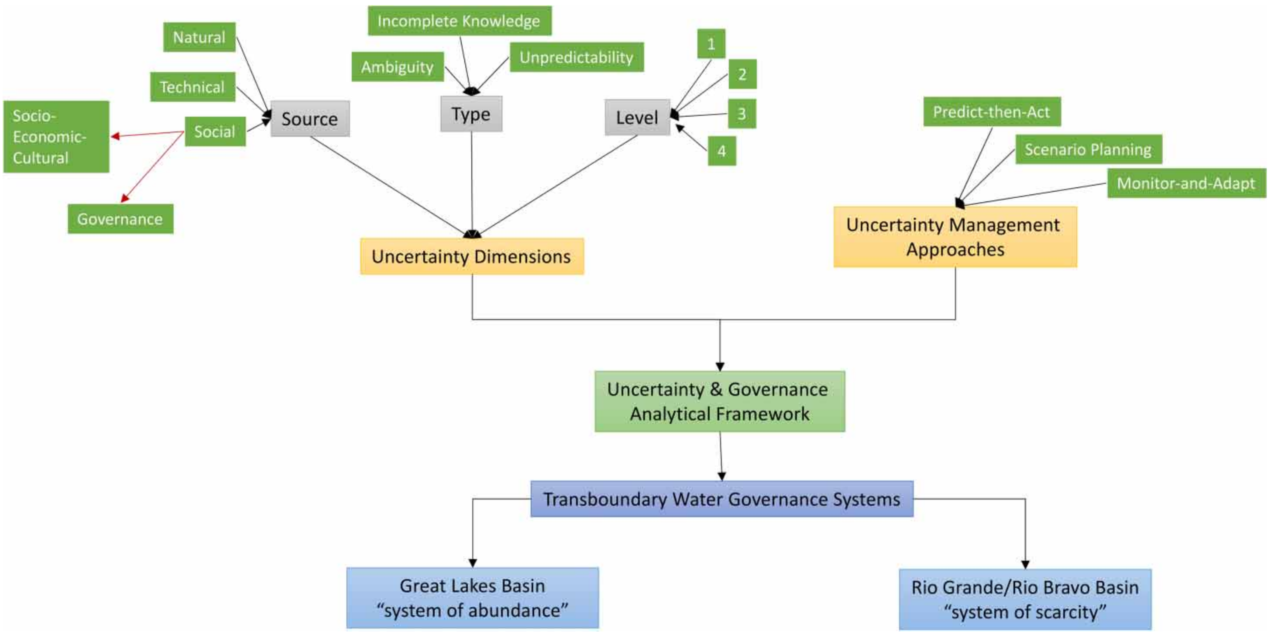
Uncertainty is inherent in transboundary water governance, yet climate change is deepening the uncertainties faced by those who manage shared water resources. This paper identifies and assesses uncertainties in the transboundary water governance context by applying an analytical framework which integrates insights from the uncertainty, adaptive governance, and public policy literatures to analyze policy documents in two complex transboundary cases: the Great Lakes and Rio Grande/Bravo basins. Findings from the analysis indicate that: first, deep uncertainties exist in both cases but the two basins face different combinations of, and interactions between, uncertainties; second, the system of scarcity assessed in this analysis (the Rio Grande/Bravo Basin) indicates more conflict-based uncertainties which aggravate natural and technical system uncertainties; and third, the governance system itself is a significant source of uncertainty, or exacerbates existing uncertainties, in both basins. The case studies reveal that governance systems need to focus on different sources, types and levels of uncertainty, and that policy responses need to be designed to move to a 'monitor-and-adapt' governance approach to reflect different uncertainties across systems of abundance and scarcity. An analysis of the preparedness of governance systems to respond and adapt to uncertainties is also needed and highly recommended.

Key words: climate change, deep uncertainty, transboundary water management, water governance

HIGHLIGHTS

- Develops and applies a framework for characterizing uncertainties in climate-impacted water basins.
- Demonstrates the ways in which different water basins face unique combinations of uncertainties.
- Discusses the utility of moving to a 'monitor-and-adapt' water management approach.
- Sets out a research agenda for linking uncertainties with concrete governance mechanisms.

GRAPHICAL ABSTRACT



INTRODUCTION

Uncertainty – or, rather, many types of uncertainty – is inherent in water governance and management. Unpredictable precipitation levels and annual run-off, hydrological fluctuations and changing levels of water demand from different sectors of society, along with the lack of appropriate infrastructure, have long made the water manager's task challenging. Further, over the past few decades, the demand for freshwater has been double that of population growth in many regions, taxing the ability of managers to predict future needs (Cosgrove & Loucks 2015). Not surprisingly, conflicts and protests over access to water are also on the increase as supplies become more strained (Espinoza & Meriam 2020). In transboundary water basins, the water management task is even more complex, given the need to manage shared surface and groundwater resources across differing political and legal frameworks, social and cultural traditions and levels of economic development, using institutions that in most cases were not designed for these complex conditions (VanNijnatten & Johns 2020).

To make matters worse, climate change is further deepening the uncertainties faced by those who must manage shared water resources. Globally, climate change is predicted to lower upstream water availability and increase the unpredictability of water resource demand in all 886 subbasin areas where water drains across a country boundary (Munia *et al.* 2020). Future scenarios for almost all water bodies in North America, for example, suggest a progressive decline in the quantity of water sources due to decreased snowpack and runoff, as well as changes in seasonal and inter-annual precipitation (US Global Climate Research Program 2019). While surface water use has decreased in the US, groundwater withdrawals for urban, agricultural and industrial uses is increasing (Warziniack *et al.* 2021). Climate change also threatens water quality due to altered ecosystem conditions which may favour invasive species, excess algal growth and higher levels of salinity, for example (Michalak 2016; Murdoch & Baron 2022).

How can governments prepare for these uncertainties? The Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Working Group II (IPCC WGII 2014, p. 9) included some of the first substantive discussion regarding how decision-making processes must adopt risk-based frameworks to cope with 'complex situations characterized by large potential consequences, persistent uncertainties, long timeframes, potential for learning, and multiple climatic and non-climatic influences changing over time.' At the same time, research on how complex transboundary water governance systems are coping with increasing climate change impacts (e.g., Timmerman *et al.* 2011; Sanchez & Roberts 2014; Earle *et al.* 2015) has been garnering the attention of scholars from several different disciplines including public policy, international relations and natural resource management. These literatures tend to raise more questions than they answer, however, and we argue that there is a need to examine in more detail the uncertainties that are embedded within transboundary water systems experiencing climate change impacts, in order to better understand what kinds of governance processes, policies and practices are needed in response.

While researchers in the uncertainty sphere have focused on identifying and modelling 'natural' and 'technical' uncertainties (Ehteram *et al.* 2018; Sharafati & Pezeshki 2020; Gaur *et al.* 2021), there has been much less focus on the 'social' and 'governance' sources of uncertainty. This paper makes three contributions to the uncertainty literature related to water governance in an era of escalating climate impacts. First, the paper introduces the concept of 'governance uncertainty', as distinct from broader 'socio-economic and cultural' uncertainties encompassed under the 'Social' category of uncertainty in the uncertainty literature; to this point, they have been not been differentiated. Second, we consciously integrate insights from the uncertainty literature into water governance and policy literature and practice; despite the fact that uncertainties are widely considered in the water infrastructure planning fields, this has not yet been done. Third, this paper also introduces an analytical framework that can be used to identify the different types, levels and sources of uncertainty present in a water basin, as a first step to introducing uncertainty concepts and approaches to decision-makers, policy-makers and water governance practitioners.

This study is guided by three central research questions:

(1) Can we identify the full range of uncertainties arising from climate change in transboundary water governance systems, using an analytical framework which is applicable across different systems facing unique challenges?
(2) How can we determine the degree to which uncertainties, including deep uncertainty, are conceptualized and recognized in transboundary water governance systems by policy-makers?
(3) What does the analysis of uncertainties in the context of climate change tell us about the challenges facing different complex transboundary water systems, particularly systems characterized by water scarcity versus systems that have abundant water resources?

These central questions direct the research towards characterizing the range of uncertainties that may be present in a transboundary water system, and then analyzing the awareness and conceptualization of these uncertainties within particular basins. Bringing together insights from various analyses found in the interdisciplinary literature which addresses uncertainty, our analytical framework is applied to two complex transboundary water systems in North America both facing uncertainties related to climate change. The cases compared are: (i) the Canada-United States Great Lakes basin, a system of water abundance, and (ii) the United-States-Mexico Rio-Grande-Bravo basin, a system of scarcity. We theorize that policy makers in systems of scarcity will conceptualize and articulate different sources, types and levels of uncertainty in policy documents due to heightened insecurity and water stress related to climate change. Indeed, the existing literature posits that systems of scarcity face deepening and compounding uncertainties (Greve *et al.* 2018) as they reach tipping points for ecological decline, surface and groundwater degradation and shrinking water availability (Guilfoos 2020).

This analysis aims to illuminate how different transboundary water governance systems that face uncertainties related to climate change are conceptualizing uncertainty in policy documents. More generally, this work is intended to provide tools for scholars and practitioners to analyze uncertainties, and system readiness for coping with these uncertainties, that can be applied across basins.

THEORETICAL FOUNDATIONS: FRAMEWORKS OF UNCERTAINTY

There has been a long history of considering uncertainty in problem-solving and decision-making, with roots as far back as Frank Knight's distinctions between risk and uncertainty in economics (Knight 1921). More recently, managing and coping with uncertainty has emerged as an increasingly important focus in long-term quantitative policy analysis and water infrastructure planning, finding its roots in the work of Lempert *et al.* (2003), Walker *et al.* (2013), Haasnoot *et al.* (2013), Brugnach *et al.* (2008) and others. In contrast, traditional policy studies have been slow to integrate uncertainty and complexity into their methods (Morçöl 2013), relying instead on the rational policy process and methods to reduce, eliminate or simplify uncertainties. In an era in which climate change is creating more uncertainties for environmental managers, this paper aims to contribute to the uncertainty, adaptive governance and policy studies literatures by integrating and exploring the potential implications of uncertainty analysis for the governance of complex transboundary water systems.

To begin, it is necessary to define the concept of uncertainty**.** Multiple definitions exist in the uncertainty and related literatures, the simplest of which is uncertainty as 'limited knowledge' about events in the past, present or future (Walker *et al.* 2013; Marchau *et al.* 2019). For the purposes of this analysis, we use a definition by Brugnach *et al.* (2008), who view uncertainty as '*a situation in which there is not a unique and complete understanding of the system to be managed*', and particularly in the context of public policy, '*as viewed by the decision-maker [s] affected by uncertainty*' (Brugnach *et al.* 2008).

In addition, it is important to highlight the difference between uncertainty and risk. Knight (1921) defined risk as the '*calculable and controllable part of all that is knowable*', whereas uncertainty is defined as the '*incalculable and uncontrollable*' part (Knight 1921 cited in Marchau *et al.* 2019, p. 6). Further, it must be acknowledged that uncertainty is unavoidable and cannot be completely eliminated (Walker *et al.* 2013; Marchau *et al.* 2019). This has important implications for managing uncertainty and underlies the recent literature on new and effective approaches for dealing with uncertainty. Within this literature, it is noted that the strategies chosen by decision-makers to manage uncertainties are very dependent on the *type* of uncertainty and whether it is considered inherent and unsolvable, or solvable by the acquisition of additional information and knowledge (Brugnach *et al.* 2008; Haasnoot *et al.* 2013; Walker *et al.* 2013; van den Hoek *et al.* 2014). This approach complements and contributes to the significant amount of literature on decision-making strategies in public policy that already exists, such as Room (2011), Cairney (2012) and Morçöl (2013).

The literature also provides different means for categorizing uncertainties. These typologies include some conceptual overlap yet approach the concept of uncertainty from slightly different angles. Most pertinent to this paper are discussions of the *sources*, *types* and *levels of uncertainty* which are summarized in the work of Brugnach *et al.* (2008), van den Hoek *et al.* (2014) and Marchau *et al.* (2019).

The literature identifies three main **sources of uncertainty**: natural, technical and social (van Asselt & Rotmans 2002; van den Hoek *et al.* 2014; Cado van der Lely *et al.* 2021). Natural systems uncertainty is related to the dynamics of natural processes and encompasses uncertainty due to external drivers of environmental change (such as the climate) and the ecosystem response to these external drivers (Cado van der Lely *et al.* 2021). Technical system uncertainty is related to '*the performance of interventions in the natural system*' and encompasses both infrastructure and technological interventions (Cado van der Lely *et al.* 2021, p. 13). Social system uncertainty is due to economic, cultural, legal, political, administrative and organizational factors that influence or contribute to a problem of interest and its potential solutions.

The literature also identifies three **types of uncertainty**: unpredictability, ambiguity and incomplete knowledge (Brugnach *et al.* 2008; van den Hoek *et al.* 2014). Unpredictability, also known as 'ontological uncertainty', refers to the inherent variability of a system. Ambiguity, which is also described as 'multiple knowledge frames,' exists when there are 'too many possible [and valid] interpretations of a situation' (Weick 1995 cited in Brugnach *et al.* 2008). Incomplete knowledge, also known as 'epistemic uncertainty', refers to imperfect knowledge about a system.

Complementary to work identifying the types and sources of uncertainty is the literature which characterizes **levels of uncertainty** ranging from Level 1 to Level 4 (Marchau *et al.* 2019). Each level of uncertainty is defined based on whether the future is known or unknown; how well the system of interest can be modelled; whether the system outcomes can be estimated with any level of certainty; and whether the relative importance of outcomes is known or can be agreed upon (Marchau *et al.* 2019; Cado van der Lely *et al.* 2021). Lower levels of uncertainty (i.e., Levels 1–3) range from a clearly known future with a single possible outcome to a few plausible futures with a limited range of outcomes. In contrast, Level 4 uncertainty, also known as 'deep uncertainty', is characterized by the unknowability/unknowable nature of each element (i.e., the future, the system model, system outcomes and importance of outcomes). It is defined as situations in which '*the parties to a decision do not know or cannot agree upon how a system works, how likely various future states of the world are and how important the various outcomes are*' (Marchau *et al.* 2019, p.2).

It should be noted that based on the definition of 'unpredictability' in the literature, it is expected that uncertainties that are classified as 'unpredictable' would most likely fall under a 'Level 4' or deep uncertainty classification (due to the impossibility of knowing/predicting something that is inherently variable). Similarly, the definition of ambiguity lends itself to classification as Level 3 or Level 4 uncertainties due to the possibility of many different system models, outcomes and weights caused by a variety of 'equally valid' interpretations. Uncertainty sources are, however, independent of levels and therefore can be classified as any of the levels ranging from 1 to 4.

The characterization of the levels of uncertainty in the literature (especially 'deep uncertainty) combined with the source of uncertainty, highlights the layered nature of uncertainty by bringing into focus how different levels can exist within the same type and source. With this framework, it is therefore possible to distinguish between a Level 2 uncertainty stemming from the natural system that is due to incomplete knowledge which can be addressed, and a Level 4 uncertainty (deep uncertainty) stemming from the natural system that is also due to incomplete knowledge yet can never fully be eliminated. These distinctions are important because the types of governance processes, practices and rules that are appropriate for managing lower levels of uncertainty are generally not suitable or sufficient for managing situations of deep uncertainty (Lempert *et al.* 2003; Room 2011; Cairney 2012; Morçöl 2013).

In fact, specific tools and approaches have been developed for addressing and managing situations of deep uncertainty and are encompassed under the broad theoretical umbrella of the 'decision-making under deep uncertainty' (DMDU) literature. This literature posits that the most suitable approaches for dealing with deep uncertainty are those based on plans, policies or strategies that are robust and adaptive. In the consulting and practitioner literature, **robustness** is defined as the ability of a strategy, plan or policy to '*perform reasonably well, compared to the alternatives, across a wide range of plausible scenarios, evaluated using the many value systems held by different parties to the decision*' (Lempert *et al.* 2003, p. xiv). **Adaptiveness,** on the other hand, is defined as '*strategies [or plans or policies] that evolve over time in response to new information*' (Lempert *et al.* 2003, p. xiv).

DMDU tools and approaches are generally more resource-intensive than traditional decision-making methods. They are recommended in cases where they are absolutely necessary, such as when the level of problem complexity is high, policy options are few, and the uncertainties are difficult to characterize (Dewar 2006 cited in Marchau *et al.* 2019). This makes DMDU tools and approaches well-suited to complex policy problems such as transboundary water management, and for managing and dealing with 'deep uncertainties' such as those that occur as a result of climate change.

A key factor in determining the appropriateness of a policy or decision-making approach is whether or not the uncertainty is reducible by the acquisition of additional information. For situations in which additional knowledge or information is able to reduce the level of uncertainty, the typical 'predict-then-act' approach (where water use, allocation and management actions rest on assumptions and predictions based on historical observations of climate and hydrological data and consumption trends, statistical analysis and then probability analysis) is sufficient (Marchau *et al.* 2019). However, for situations of deep uncertainty, DMDU tools and approaches emphasize the need to move to a 'monitor and adapt' approach (Stanton & Roelich 2021). This shifts the focus to more dynamic policy and decision-making based on constant monitoring and data collection. This shift, while challenging, is increasingly feasible with data-centred policy approaches.

DMDU tools have been developed by both scholars and practitioners to address uncertainties in long-term policy analysis and planning. These tools, both quantitative and qualitative, have predominantly focused on long-term infrastructure planning. An example here is the use of the Multi-Objective Robust Decision-Making (MORDM) approach that helped four North Carolina cities to coordinate and link their short-term operational water plans and long-term water investment plans while taking into account their different objectives and deep uncertainties (Herman *et al.* 2014). Other examples that utilize computational/numeric modelling approaches and decision matrices to assess and account for uncertainty include works by Ehteram *et al.* (2018), Sharafati & Pezeshki (2020) and Gaur *et al.* (2021).

In contrast, an example of work that relies on long-term adaptive planning and management methods includes the application of Dynamic Adaptive Policy Pathways (DAPP) for flood risk management of the Hutt River catchment which contributed to the uptake of DAPP and uncertainty-based planning in climate change policy and practice in New Zealand (Lawrence & Haasnoot 2017). The aim of these tools is to allow decision-makers to assess and choose between available near-term actions while ensuring that these actions contribute to achieving long-term future goals (Haasnoot *et al.* 2013). In this respect, there is an important distinction to be made between adaptive and robust *plans* that are focused on specific infrastructure problems, and broader adaptive and robust *policies and strategies* that are vision-oriented and act as broader guidelines for those specific actions. Further, we must differentiate between these components, and adaptive and robust governance *systems*, which provide the authoritative decision-making institutions, processes and rules which provide the authoritative decision-making architecture for enabling adaptive policies, plans and strategies.

While there are numerous definitions of governance in the scholarly and practitioner literatures (Colebatch 2014), for this analysis we adopt the OECD's definition of water governance, as 'the set of rules, practices and processes (formal and informal) through which decisions are taken and implemented, stakeholders can articulate their interests and have their concerns considered, and decision-makers are held accountable for water management' (OECD 2015). This definition captures the way in which we conceptualize water governance as a source of uncertainty (rather than as an explanatory variable) in our methodology.

METHODS: IDENTIFYING AND ASSESSING UNCERTAINTY

The primary aim of this paper is to identify the different sources, types and levels of uncertainty that are present in the transboundary water governance and policy context using analysis of two complex cases by applying an analytical framework which builds on insights from the uncertainty literature. The methodology uses document analysis to discover how uncertainty, and specifically 'deep uncertainty', is conceptualized in two different complex water governance systems: a system of scarcity and a system of abundance. The focus of the analysis in this paper is not on explanation through isolation and manipulation of variables but rather testing the utility of the uncertainty framework developed here from the literature using two illustrative case studies with different water basin conditions.

Case studies

In North America, rising awareness of the need to address the impacts of climate change, due either to international climate commitments or on-the-ground experience of prolonged droughts and increasingly damaging floods, for example, has increased the importance of considering current and future uncertainties. Understanding when and how these uncertainties manifest within particular systems and ensuring that policy-makers have the means to manage these uncertainties, are of increasing concern to decision-makers, particularly those managing water resources that are at critical thresholds of stress.

Policy-makers in the Great Lakes Basin (GLB) and the Rio Grande/Bravo (RGB) basin, similar to many water systems across the globe, face the challenge of managing water resources in the context of climate change; increased population growth and more intense water uses; and uncertain water quantity and quality impacts. Both systems are thus grappling with uncertainties related to climate change. Both are governed by transboundary, binational agreements that have been in place for at least a century, with water policy goals formalized 50 or more years ago. Both have multiple water users and stakeholders, including Indigenous communities and peoples and a wide range of economic users.

Despite these systems facing common challenges related to climate change uncertainty, there is a key difference between the two basins that is notable and important in this analysis. The Great Lakes region is a complex lake system; a system of abundance with sufficient water available to meet all needs, most of the time. (Sproule-Jones 2002; deBoer & Krantzberg 2013; Norman *et al.* 2013; Johns & Thorn 2015; Norman 2015; Johns 2017).

The Rio Grande/Bravo, by contrast, is a complex river system and is a system of scarcity (where there is not enough fresh water to meet current demands, most of the time), with 'extremely high' levels of water stress (World Resources Institute 2014; VanNijnatten 2020). This case represents a system of scarcity where theoretically a focus on various sources, types and levels of uncertainty should be central in policy documents, given that climate change is likely to exacerbate already difficult water basin conditions.

While all transboundary water systems are different and there are limitations related to comparing these complex cases, comparing these particular transboundary systems allows us to generate 'thick knowledge' (Collier & Elman 2008) about the context and dynamics of two very different cases facing uncertainties related to accelerating climate change impacts, which allows us to gain new insights into the full range of differences in types, levels and sources of uncertainty across basins. These insights can then be used in future research to understand and explore governance approaches and responses to uncertainties in each basin, that are appropriate for their specific governance systems.

Analytical framework

The approach in this analysis is based on the premise that assessing the sources, types and levels of uncertainty related to climate change and transboundary water governance requires a new analytical perspective that brings together the literatures on water governance and uncertainty. The uncertainty literature contains three broad categories of sources of uncertainties (Natural, Technical, Social). The literature also delineates types and levels of uncertainty as other important dimensions. The definitions of each uncertainty dimension are described in Table 1.

For the purposes of this study, the 'Social' category was further divided into a 'governance' sub-category, and a 'societal-economic-cultural' sub-category in the analytical framework. This is a new distinction/contribution we are adding to the uncertainty literature that enables analysis to capture uncertainties stemming specifically from the governance system in each transboundary basin, as opposed to the broader, vague and loosely defined 'social' uncertainties. Differentiating between these uncertainties also allows us to clearly capture those uncertainties that might more easily be addressed (uncertainties stemming from the governance system) versus those that are exogenous and more likely to be unpredictable and thus a source of deep uncertainty.

In addition, a separate and specific category ('uncertainty management approach') was developed to capture the different approaches to managing uncertainty that are discussed in the literature, such as the 'predict-then-act' or 'monitor-and-adapt' approaches, and that are currently discussed and reflected in the policy and planning documents. A list of questions was

Table 1 | Uncertainty dimensions: sources, types, levels and approaches

Uncertainty Dimension	Description
Uncertainty Source	
Natural (Nat)	Uncertainty stemming from the dynamics of natural processes, including both exogenous environmental drivers of change and ecosystem responses and ecological processes
Governance (Gov)	Uncertainty stemming from legal, political, administrative and organizational factors that influence problems or solutions of interest
Societal-Economic-Cultural (SEC)	Uncertainty stemming from wider societal, economic, cultural trends that influence problems or solutions of interest.
Technical (Tech)	Uncertainty stemming from performance of interventions in the natural system: including both infrastructural and technological interventions
Uncertainty Type	
Ambiguity	Uncertainty stemming from the simultaneous presence of multiple frames of reference (or multiple valid interpretations) about a phenomenon or system
Incomplete Knowledge	Uncertainty stemming from imperfect knowledge about a system
Unpredictability	Uncertainty stemming from inherent variability or unpredictability about a system
Uncertainty Level	
Level 1	Uncertainties for which there is a clear enough, knowable future; a single deterministic system model; a single point estimate for each outcome; and a single set of weights/relative importance for each outcome
Level 2	Uncertainties for which there are alternate futures with associated probabilities; a single stochastic system model; a confidence interval for each outcome; and several sets of weights/relative importance for each outcome
Level 3	Uncertainties for which there are a few or many plausible futures without probabilities; a few or many alternative system models; a range of possible outcomes; and a limited range of weights/relative importance for each outcome
Level 4	Uncertainties for which there is an unknown or unagreed upon future; unknown or unagreed upon system model; unknown or unagreed upon system outcomes; and unknown or unagreed upon weights/relative importance of outcomes
Uncertainty Management Approach	
Adaptation-based	Approaches that reflect an evolution of plans, policies and strategies over time in response to new information
Prediction-based	Approaches that emphasize development of static plans, policy and strategies that are based on a prediction of outcomes, or system behaviour
Scenario-based	Approaches that emphasize the development of plans, policies and strategies based on a range of plausible scenarios

Sources: adapted from van Asselt & Rotmans (2002); Brugnach *et al.* (2008); Marchau *et al.* (2019) and Cado van der Lely *et al.* (2021).

developed based on the definitions in the literature and used to characterize the uncertainties in both basins through the analysis of policy documents that focus on climate change and water governance.

Document analysis

In assessing the sources, types and levels of uncertainty in the two transboundary water basins, we undertake an analysis of key policy and planning documents. In order to select documents for analysis, a list of selection criteria was developed. The five criteria are summarized below, along with the rationale for each selection criteria.

(1) Documents must have been published within the last ten years (i.e. 2012–2022). This time period was selected to align with the increased global focus on the impacts of climate change and how these impacts can be managed, in addition to the uncertainties that may affect the approaches used.
(2) Documents must be focused on watershed/transboundary policy and planning, which are likely to contain governance and/or policy uncertainties in addition to natural and technical uncertainties.

(3) Documents must include or consider climate change/climate hazards, climate change impacts, and/or climate adaptation methods/approaches since each of these categories is a significant source of uncertainty for planning and policy.
(4) Documents must focus on water quantity and/or water quality, as these are important dimensions in the two cases representing a system of abundance vs. a system of scarcity.
(5) Documents must discuss at least one of two countries in the transboundary watershed, or ideally both countries. This criterion would allow comparisons between uncertainties in the two transboundary regions.

Based on the document selection criteria, six climate and policy and planning documents were reviewed for each of the Great Lakes Basin (GLB) and Rio Grande-Rio Bravo basin (RGB). A detailed list of the documents that meet the criteria can be found in the Supplementary material.

Uncertainties in each of the six documents were categorized using the analytical framework described above and results were reviewed to generate insights on the different sources, types and levels of uncertainty present in the policy and planning documents for each basin. In order to complete a comparative assessment, the uncertainties in each basin were reviewed alongside one another to identify similarities and differences, to generate insights about the sources, types and levels of uncertainty in complex transboundary systems of abundance and scarcity, especially the presence of deep uncertainty. Insights into the types of 'uncertainty management approaches' reflected in the policy documents were also generated based on the categorization of uncertainties. The uncertainty assessment was completed by generating frequency tables for each code dimension in each basin, in addition to comparative tables of code dimensions and sub-categories for both basins. The tables were reviewed to generate more nuanced understandings of the relationships between the different codes in each basin, particularly the presence of combined and cascading uncertainties (i.e., one uncertainty causing or resulting in another uncertainty). The tables were also reviewed to determine whether the results confirmed or contradicted the existence of distinct governance-related social uncertainties and demonstrated the presence of deep uncertainty within each or both basins. Based on an understanding of the contextual background of each basin, it was expected that there would be more instances of ambiguity-type uncertainty related to conflict over the limited resources in a system of scarcity than in a system of water abundance. In addition, this paper posits that, even if documents do not explicitly refer to uncertainties, or specifically deep uncertainties, these uncertainties do already exist in both basins and therefore need to be clearly identified in order to allow/put in place suitable governance mechanisms that are able to handle/cope with these deeper, more complex uncertainties.

RESULTS AND ANALYSIS

The Great Lakes case

An overview of the documents reviewed in the Great Lakes Basin (GLB) case is provided in the Supplementary material. As shown in Table 2, the most frequently coded **uncertainty source** in the GLB is that of natural system uncertainty. These uncertainties generally take two forms: they either referred to uncertainties regarding specific climate phenomenon (e.g., the amount of future precipitation, or future temperatures in the region), or they referred to uncertainties regarding the response of natural ecosystems or the impacts of climate change on these ecosystems and/or on human systems.

For example: the IJC Climate Change Guidance Framework Highlights report (IJC CCGF) notes that '*climate change is expected to increase temperature and precipitation, but whether that drives lake levels up or down depends on how much the higher temperatures offset the higher precipitation.*' (IJC 2021a, p. 11). These combined/complex uncertainties were noted throughout the coding process.

The governance system was the second most frequently coded source of uncertainty, followed by societal-cultural and economic (SEC) uncertainties. Most of the governance uncertainties that were identified were related to possible changes in current or future 'policies, processes and practices' that could hinder effective climate action. For example, the Great

Table 2 | GLB uncertainty sources

Document classification	Uncertainty Source & Coding Frequency			
Great Lakes Basin (GLB) – All Documents	Nat 18	Gov 7	SEC 5	Tech 4

Lakes Horizons report notes: '*the threat of inadequate governance structures and policies…was recognized…as a real concern for the biology, ecology and chemistry of the lakes. The threat [that] was characterized [was] concern that policies and programs that had been created in the past may be more vulnerable to alteration or rescission due to political forces than appreciated.*' (IJC 2021b, p. 6).

In contrast, most of the socio-economic uncertainties coded were related to current and future geopolitical dynamics and demographic changes such as the potential for climate refugees in/to the Great Lakes and how this might affect the local population and economics. The higher frequency of governance uncertainties in comparison to SEC uncertainties demonstrates that there is merit in distinguishing between the two types of 'social' system uncertainty.

Technical uncertainties were the least frequently coded source of uncertainty and were mostly associated with finding ways to address existing problems while minimizing undesired side-effects. For example, the Great Lakes Horizons document specifically notes uncertainty regarding ways to reduce '*non-point nutrient loads without crippling agricultural production*' or to retrofit '*cities to handle runoff more effectively*' (IJC 2021b, p. 8).

The most frequently coded **uncertainty type** in the GLB was 'Incomplete Knowledge' (Table 3). Most of the uncertainties coded under incomplete knowledge were related to a lack of knowledge about some of the mechanisms of climate change, as well as its direct and indirect impacts within the basin. For example, the draft Progress Report of the Parties (PRP) notes that further research and monitoring are necessary to '*improve understanding of how future climate conditions may affect nutrient conditions in the Lake Erie basin*' (Government of Canada & Government of the United States 2022, p. 7). Many of these uncertainties were also coded under the 'natural system', reflecting that most of the incomplete knowledge within the basin was related to the natural systems.

In contrast, all of the references coded under ambiguity were co-coded under the social (governance or socio-economic) system, and almost all the references coded under 'unpredictability' were co-coded under social systems. For example, regarding ambiguity (i.e. differences in opinions, values or conflicts among decision-makers and stakeholders), the Great Lakes Horizons report notes that, '*as with many areas of governance, some of the largest gaps and limitations are related to overlapping jurisdictions and tensions between individual rights and the public good, which often manifest as debates between voluntary versus mandatory measures to improve environmental conditions and preferences for public versus private funding of these measures*.' (IJC 2021b, p. 8). Similarly, regarding unpredictability, the Science Advisory Board's (SAB) report on a possible Early Warning System for the Great Lakes explicitly recognizes unpredictability and notes that '*there are 'unknown unknowns' and … vigilance is required to recognize these once they emerge.*' (Johnson & Twiss 2020, p. 11).

As noted in the earlier discussion of the uncertainty literature, the presence of both unpredictability and ambiguity typically reflects higher levels of uncertainty and can be considered indicative of deep uncertainty within the basin.

Indeed, the most frequently coded **uncertainty level** in the GLB was Level 4, followed closely by Level 3 (Table 4), indicating a definite presence of deep uncertainty within the basin. Of note, the Level 4 uncertainties were predominantly associated with the socio-economic or governance systems, and not the natural system. For example, the Great Lakes Horizons report notes: '*The context surrounding…potential future power conflicts, especially over water security, is contingent on two sets of ambiguous drivers. First, whether the region experiences a dramatic shift in population stock, or even grows substantially, because of climate refugees…Participants felt this uncertainty merited its own second order ambiguity – what*

Table 3 | GLB uncertainty types

Document classification	**Uncertainty Type & Coding Frequency**		
Great Lakes Basin (GLB) – All Documents	Ambiguity 5	Incomplete Knowledge 19	Unpredictability 17

Table 4 | GLB uncertainty levels

Document classification	**Uncertainty Level & Coding Frequency**			
Great Lakes Basin (GLB) – All Documents	Level 1 0	Level 2 8	Level 3 15	Level 4 16

decision-makers might do in the face of these tensions about local, regional, and global rights and responsibilities.' (IJC 2021b, p.2).

In contrast, the Level 2 and Level 3 uncertainties were related to uncertainties in the natural system and reflect instances where there was a well-established understanding of system dynamics but significant uncertainty on the magnitude of outcomes or the probabilities of specific outcomes. For example, an assessment report of the impacts of climate change on the Great Lakes (ELPC Report) notes, '*climate change will likely threaten drinking water quality and place great stress on water infrastructure. For example, in southern Wisconsin, extreme precipitation could rise by 10% to 40%, overloading water treatment infrastructure, increasing sewer overflows, and increasing the quantity of water-borne pathogens flowing into streams, rivers, and Lake Michigan*' (Wuebbles *et al.* 2019, p.2). There were no Level 1 uncertainties which was expected based on the complexity of climate change, and the definition and characteristics of Level 1 uncertainties (e.g. a single, near-certain future).

The Rio Grande/Bravo case

An overview of the documents reviewed for the Rio Grande/Rio Bravo Basin (RGB) is provided in the Appendix. Tables 5–7 summarize the frequency of occurrence of each code category, followed by a discussion of the results.

In the RGB, the most frequently coded **uncertainty source** was the natural system, followed by the governance, technical and socio-economic systems (Table 5). Some of the natural system uncertainties identified were related to existing issues that are expected to be aggravated by climate change, though the extent to which this would occur was unknown. For example, the 'Science and Engineering to Comprehensively Understand and Responsibly Enhance (SECURE) Water Act' report notes that, '*in the Rio Grande Basin, the water management challenges posed by a highly variable and extremely limited water supply have been exacerbated in recent decades by prolonged drought, combined with increasing basin temperatures*' (Bureau of Reclamation 2021, p. 1). Other natural system uncertainties were predominantly due to the changing climate and noted to have impacts on the human and technical systems. For example, the Fourth US National Climate Assessment (4th NCA SE) report notes that '*The combined effects of changing extreme rainfall events and sea level rise are already increasing flood frequencies, which impacts property values and infrastructure viability, particularly in coastal cities. Without significant adaptation measures, these regions are projected to experience daily high tide flooding by the end of the century (likely, high confidence)*' (Carter *et al.* 2018, p. 784).

The governance uncertainties identified were mostly due to different governance approaches between the two countries (i.e. Mexico and the US) and significant legal conflict between US states. However, they also resulted in and generated further

Table 5 | RGB uncertainty sources

Document classification	Uncertainty Source & Coding Frequency			
Rio Grande-Rio Bravo Basin (RGB) - All	Nat 20	Gov 7	SEC 4	Tech 8

Table 6 | RGB uncertainty types

Document classification	Uncertainty Type & Coding Frequency		
Rio Grande-Rio Bravo Basin (RGB) - All	Ambiguity 3	Incomplete Knowledge 19	Unpredictability 14

Table 7 | RGB uncertainty levels

Document classification	Uncertainty Level & Coding Frequency			
Rio Grande-Rio Bravo Basin (RGB) - All	Level 1 2	Level 2 13	Level 3 12	Level 4 6

uncertainties within the natural/technical systems, demonstrating very clearly the presence of cascading uncertainties. For example, the SECURE Water Act report notes that '*overlapping jurisdictions, the impact of groundwater pumping, and other complexities of this apportionment have resulted in an ongoing Supreme Court lawsuit over the terms of and compliance within the compact. This lawsuit could alter water distribution between the States, creating even greater water supply uncertainty*.' (Bureau of Reclamation 2021, p. 5). In contrast, the broader SEC uncertainties are US-specific and are mainly related to changes in population demographics. The US 4th NCA SE notes that, '*Population projections are inherently uncertain over long time periods and shifts in immigration or migration rates and shifting demographics will influence urban vulnerabilities to climate change*.' (Carter *et al.* 2018, p. 784).

The technical uncertainties identified in the RGB mainly focused on the risk posed by deteriorating infrastructure, although most of these uncertainties are specific to infrastructure in the US.

The most frequently identified **uncertainty type** in the RGB was that of 'incomplete knowledge' followed by 'unpredictability' (Table 6). The uncertainties characterized under 'incomplete knowledge' were mostly from the natural and technical systems, and usually referenced both simultaneously. For example, the SECURE Water Act report highlights how the anticipated effects of reductions in water supply and an increase in temperature are expected to '*make environmental flows in the [Rio Grande] river more difficult to maintain and to reduce the shallow groundwater available to riparian vegetation*' (Bureau of Reclamation 2021, p. 18). The extent of these reduced flows is unknown, though not 'unknowable'. In contrast, the uncertainties categorized under 'unpredictability' in the natural system were related to difficulties in predicting future flooding events or the availability of future water supplies.

In the RGB, uncertainties categorized under 'ambiguity' were mainly related to the governance systems, particularly the existence of ongoing lawsuits and water conflicts, both within and between the US States, but also between the border communities of Mexico and the US. The outcomes of these 'ambiguity'-type uncertainties are dependent on a range of factors that vary widely and are therefore extremely difficult to predict, though not impossible. The high frequency of unpredictability and presence of complex ambiguity-based uncertainties indicates the likely occurrence of deep uncertainties in the RGB.

The **uncertainty levels** most frequently coded in the RGB are Levels 2 and 3. The Level 2 uncertainties are related to very specific phenomena where there is a much clearer understanding of the likelihood of occurrence of specific climate impacts. For example, the Secure Water Act report notes, '*climate projections suggest that annual precipitation in the Rio Grande Basin will remain variable over the next century. Precipitation in both the Rio Grande and the Pecos River Basins will likely change in total volume, spatial distribution, and timing. Changes in winter precipitation, from snow to rain, are already occurring and are nearly certain to continue*' (Bureau of Reclamation 2021, p. 13). In contrast, the Level 3 uncertainties identified in the basin are related to the interaction between the wide-reaching impacts of climate change and human, natural and technical systems. For example, the Water chapter in the US 4th NCA (US 4th NCA Water) report notes that, '*studies show that compound extreme events will likely have a multiplier effect on the risk to society, the environment, and built infrastructure. Sea level rise is expected to increase in a warming climate. Sea level rise adds to the height of future storm tides, reduces pressure gradients that are important for transporting fluvial water to the ocean, and enables greater upstream tide/wave propagation and coastal flooding.*' (Lall *et al.* 2018, p. 162).

Most of the Level 4 uncertainties identified in the RGB were related to the natural system. For example, the US 4th NCA SE chapter report notes that, '*although it is possible to make general predictions of climate change effects, specific future ecological transformations can be difficult to predict, especially given the number of interacting and changing biotic and abiotic factors in any specific location. Uncertainties in the range of potential future changes in multiple and concurrent facets of climate and land-use change also affect our ability to predict changes to natural systems*' (Carter *et al.* 2018, p. 787). Consequently, deep uncertainties in this basin encompass the unpredictability and ambiguity in the natural system, and in the social-governance system as identified previously.

Comparative analysis

The research design developed in this project sought to focus the analysis on two different complex transboundary water systems – a system of scarcity and a system of abundance – in order to generate insights into the uncertainties they face. It was anticipated that the analysis would provide quite different pictures of uncertainty, given the varying levels of water stress in the two cases. Our analysis overall yields more similarities than differences in numbers of sources, types and levels of uncertainty being reflected in policy documents in the two basins; however, there were some nuanced differences between the two systems which we explore below.

First, the **uncertainty source** in both cases follows a similar trend, with natural system uncertainties being the most frequently identified source, followed by 'social-governance'. The similarities and differences in uncertainties between the two cases are summarized in Table 8.

This analysis highlights a pattern in policy documents on climate change in both basins, whereby there is more emphasis on uncertainties within the natural system as compared to those within the social or governance system. Yet, in both cases, the second most-frequently identified uncertainty source was that of 'social-governance.' Although there were different types and levels of social-governance uncertainty in each basin, the GLB had SEC/governance uncertainty related to unpredictability, whereas RGB had more instances of ambiguity. This implies that the current focus of policy and planning within both basins is predominantly to manage or address natural uncertainties – without substantial emphasis on considering or addressing the presence or impact of social uncertainties, particularly governance uncertainties.

In both basins, the most frequently identified and acknowledged **uncertainty type** was that of incomplete knowledge, followed by 'unpredictability' (Table 9). Most instances of incomplete knowledge were related to natural system uncertainty whereas there were differences between basins on the source of unpredictability. In the RGB, most of the unpredictability-based uncertainties identified were related to natural systems, whereas most of the unpredictability-based uncertainties identified in the GLB were related to governance/SEC systems.

Despite the low instances of ambiguity, the scale and type of ambiguity varied between basins. In the GLB, most of the ambiguity identified was related to smaller-scale decision-maker or stakeholder-specific perspectives on external factors such as the impact of population growth on water resources (availability). However, in the RGB, the instances of ambiguity were related to higher-level conflicts between jurisdictions over the use of limited water resources, resulting in multiple lawsuits across territorial borders.

Regarding **uncertainty level**, even though there are similar frequencies of Level 3 uncertainty in both basins, most of the RGB uncertainties fall under Levels 2 and 3; whereas most of the GLB's uncertainties fall under Levels 3 and 4 (Table 10). There were substantially more Level 4 uncertainties identified in GLB than in RGB, however the instances of Level 4 uncertainties in the documents reviewed indicate a clear presence of deep uncertainty in both basins.

Interestingly, most of the Level 4 uncertainties in the RGB were related to natural system uncertainty, whereas there were more instances of social-governance system uncertainty and socio-economic system uncertainty identified in the GLB. This

Table 8 | Comparison between GLB & RGB uncertainty sources

	Uncertainty Source & Coding Frequency			
Document classification	**Nat**	**Gov**	**SEC**	**Tech**
Great Lakes Basin (GLB)	18	7	5	4
Rio Grande-Rio Bravo Basin (RGB)	20	7	4	8

Table 9 | Comparison between GLB & RGB uncertainty types

	Uncertainty Type & Coding Frequency		
Document classification	**Ambiguity**	**Incomplete Knowledge**	**Unpredictability**
Great Lakes Basin (GLB)	5	19	17
Rio Grande-Rio Bravo Basin (RGB)	3	19	14

Table 10 | Comparison of GLR & RGB uncertainty levels

	Uncertainty Level & Coding Frequency			
Document classification	**Level 1**	**Level 2**	**Level 3**	**Level 4**
Great Lakes Basin (GLB)	0	8	15	16
Rio Grande-Rio Bravo Basin (RGB)	2	13	13	6

Table 11 | Comparison of uncertainty management approaches in GLB & RGB

	Uncertainty Management Approach & Coding Frequency		
Document classification	**Adapt**	**Predict**	**Scenario**
Great Lakes Basin (GLB)	8	10	6
Rio Grande-Rio Bravo Basin (RGB)	6	4	3

may reflect more awareness, reflection and capacity in the GLB system of abundance to focus on governance related deep uncertainties, in contrast to the RGB system of scarcity which may be focused more on managing the deep, unpredictable and inherent natural uncertainty associated with a system under water stress.

When considering the findings on the type and level of uncertainties in the two basins across the policy documents, it is clear that the uncertainties identified are generally interrelated and influence one another. The presence of deep uncertainties (either categorized as Level 4 uncertainty, or uncertainty due to unpredictability and ambiguity) identified in both basins highlights the fact that climate change and its impacts are changing the types of uncertainties that need to be incorporated into governance and policy and managed in each basin.

Turning to the uncertainty management approach utilized in both basins (Table 11), the most frequently identified approach in the GLB was the prediction-based approach, followed by adaptation-based approaches and finally scenario-based approaches. In contrast, the most-frequently identified approach in the RGB was an adaptation-based approach, followed by almost equal instances of prediction and scenario-based approaches. In general, most of the prediction-based approaches identified in both basins refer to specific examples where a predictive strategy has been used to better understand the functioning of a (predominantly) natural system (i.e., to acquire additional knowledge). In contrast, the adaptation-based approaches included specific examples of adaptive strategies used in technical systems, and general mentions of the need for adaptive management approaches and strategies.

The assessment that was undertaken to categorize and compare the uncertainty management approaches also allowed for a high-level comparison and discussion of whether or not the approaches being used were suitable for the sources, types and levels of uncertainty identified in the basins. Based on the results of this assessment, it is noted that the prediction-based approaches identified in the uncertainty management approach assessment are useful for addressing lower-level uncertainties yet unsuitable for the Level 3 and Level 4 uncertainties identified in the analysis. The relatively high frequency of prediction-based approaches in the GLB indicates that there is a possible mismatch between the types of uncertainty level and type identified in the basin, and the current management approaches. Indeed, in the Great Lakes Basin, the strong emphasis on incomplete knowledge about the natural system and the focus on the use of predictive approaches highlights a strategy based on acquiring additional knowledge to reduce or eliminate uncertainties, not on applying more adaptive and robust strategies which recognize the unpredictable and ambiguous nature of some uncertainties and the existence of more complex and higher-level uncertainties (i.e. Levels 3 and 4) associated with climate change. In contrast, the comparatively low frequency of 'prediction' based approaches in the RGB may be a reflection of the difficulties associated with utilizing this approach in a system facing unpredictability and water scarcity.

The findings do highlight some awareness in both basins of the need for adaptive approaches to water governance in a context of considerable and complex uncertainties, although the RGB documents in particular clearly state the need for more adaptive and robust governance responses to uncertainties.

DISCUSSION AND IMPLICATIONS FOR THE ADAPTIVE GOVERNANCE OF TRANSBOUNDARY WATER SYSTEMS

The uncertainty assessment conducted above provides several key insights into how uncertainty is conceptualized and reflected in policy documents in both cases and into the governance and institutional responses that are required for complex transboundary water systems to embrace uncertainty as they face a climate change-impacted future.

First, as noted in the analysis, there is a difference between the nature and intensity of 'ambiguity'-type uncertainties found in the GLB 'system of abundance' versus in the RGB 'system of scarcity'. In the GLB, the 'ambiguity'-type uncertainties are related to smaller stakeholder disagreements/difference in perspectives, whereas in our system of scarcity, the RGB, 'ambiguous'-type uncertainties are related to conflict between countries, which also further aggravate natural and technical uncertainties. This difference in the uncertainty types means that governance responses may need to differ across basins (and across systems of abundance vs. systems of scarcity), and that an analysis of adaptive governance in complex transboundary water basins will need to take such nuances into account.

Second, despite differences in water resource abundance between both systems, one of the most important findings of the uncertainty analysis is that the governance system itself is a significant source of uncertainty and contributes further to existing uncertainties in both the GLB and RGB basins. The governance uncertainties identified speak to the limitations of existing governance structures, processes and instruments, and validates the approach taken to distinguish between governance and broader socio-economic uncertainty. In fact, in addition to identifying the governance system as a source of uncertainty, the identification of some adaptation-based uncertainty management approaches speaks to a growing recognition in both basins of the need for developing more adaptative and robust systems, both governance and technical, to manage the complex and deep uncertainties associated with climate change.

Third, the lower level (levels 1–3, i.e. not deep) uncertainties that were identified and evident in the documents point to the fact that there is some recognition of uncertainty within the basin, although these are mostly limited to natural and technical uncertainties. The analysis findings also confirm that, even though they are not explicitly recognized as such in the policy documents reviewed, deep uncertainty is present within both basins. This is an important finding because the type of uncertainty that is most recognized or acknowledged is crucial in determining the policy actions taken, and where resources will be directed. Both systems display a strong emphasis/focus on the acquisition of additional knowledge to resolve (the lower level) uncertainties and less focus on the practicalities involved in implementing adaptive management and governance systems which would be instrumental in addressing deep uncertainties. Therefore both basins may in actuality be unprepared to grapple with their unique set of deep uncertainties and the requirements of truly adaptive approaches to governing and managing water.

Fourth, although the analysis noted similarities in sources, types and levels of uncertainty across the two complex transboundary water basins (e.g., the prevalence of uncertainties related to natural systems), the two basins also face different combinations of, and interactions between, uncertainties. These findings highlight that the sources, types and levels of uncertainty need to be identified and unravelled in *each specific case*, in order to understand potential governance and policy challenges for each basin. It is therefore important in future research to analyze governance system capacity along with uncertainties in order to more fully assess adaptiveness in complex transboundary water systems (VanNijnatten & Johns 2020). These unique and interrelated or cascading uncertainties may, in reality, be a greater source of deep uncertainty than each distinct category of uncertainty, and thus must be taken into account when considering the governance response.

The deep uncertainties, and 'cascading' and/or combined uncertainties identified in this analysis, point toward the potential need for a combination of predictive and adaptive management approaches. As discussed previously, the uncertainty literature suggests that water governance and management systems must shift from the dominant 'predict-then-act' approach (Stanton & Roelich 2021) to a 'monitor-and-adapt' approach which recognizes the non-stationarity of water resources and ecosystems (Cosgrove & Loucks 2015) and thus the need for more adaptive and responsive water governance mechanisms, in situations of deep uncertainty. This analysis shows that uncertainties differ across source, type and level, and that they interact and cascade in complex ways, indicating that decision-makers may need to be able to pivot between these approaches.

LIMITATIONS & RECOMMENDATIONS FOR FURTHER RESEARCH

There are hundreds of transboundary water basins across the globe. This analysis focuses on two cases: one a system of abundance and one a system of scarcity. Certainly, there are limitations related to comparing these two cases. For example, while both face uncertainties related to climate change, they have many complex features that may determine the sources, types and levels of uncertainties being articulated in policy documents. This analysis, however, does allow for the application of an uncertainty framework from the literature to see if there are any notable differences in how uncertainties are conceptualized by policy-makers in one system of abundance and one system of scarcity. Furthermore, despite the limitations to using these two cases as illustrative cases, this analysis allows for some important insights which can generate hypotheses for future research in these cases or in other complex transboundary water governance systems.

Given that this analysis focused on how uncertainty is reflected in policy documents, a deeper, more complex analysis of the relationships between different uncertainties was not carried out due to limitations of the qualitative analysis software utilized, as it only enabled pairwise comparison of codes. Further work is recommended to expand and develop the analytical framework to account for cascading uncertainties, as well as to test different software tools that can complete a more complex analysis.

Some judgement and interpretation of wording in the policy documents was also necessary during application of analytical frameworks which may influence the number of uncertainties identified in each basin. It is recommended that future studies undertake a secondary level of validation with policy practitioners working at the interface of climate change and water governance within specific basins to validate the range of uncertainties identified.

Although frequency of occurrence is used as the metric for assessing uncertainty, it should not be interpreted as being reflective of relative importance. For example, it should be noted that the GLB policy documents reviewed explicitly mentioned complexity and uncertainty, which likely contributed to the higher numbers/instances of uncertainties coded in some categories. Furthermore, the lower number of SEC uncertainties coded in the RGB may be a reflection of, or influenced by the authoring jurisdiction (i.e., the US *vs*. Mexico). Similarly, the relative frequencies of occurrence for the different uncertainty management approaches in each basin may be influenced by the policy documents reviewed.

CONCLUSIONS

The application of the uncertainty analytical framework developed in this paper to two complex transboundary water governance systems indicates that, overall, systems of scarcity are not conceptualizing and articulating various sources, types and levels of uncertainty to any greater extent than systems of abundance. Detailed analysis of the results reveal that both basins are facing similar uncertainty challenges: first and foremost, that deep uncertainties are present in both basins, in addition to the 'lower level' uncertainties that decision-makers face (and already know how to address). The analysis indicates that policy practitioners may already be identifying and addressing many of the 'lower level' uncertainties yet using those same policy approaches and tactics for deep uncertainties, which is likely to be insufficient. Deep uncertainties require different governance mechanisms which policy practitioners may not be fully aware of or know how to implement. Consequently, transboundary water governance systems may be *differently* (in addition to *insufficiently*) prepared to respond adaptively to climate change threats using 'monitor-and-adapt' or 'predictive-and-adaptive' management approaches – a finding that needs to be explored in future research.

There are limitations related to analyzing and comparing these two cases using the uncertainty analytical framework, including the differences in policy documents selected for analysis and the unique governance features in each case. Nevertheless, the analytical framework could be applied to other transboundary cases and more in-depth analysis could focus on primary data sources related to how policy makers themselves in these transboundary systems are conceptualizing and addressing uncertainty at various scales.

A key question for future research is whether the governance systems in these basins have appropriate adaptive processes, rules and practices in place that can facilitate the necessary governance response, since we know from existing research that the institutional context strongly influences the feasibility, success or adoption of adaptive water governance (VanNijnatten & Johns 2020) and DMDU tools, especially those concerned with adaptive planning (Malekpour & Newig 2020; Stanton & Roelich 2021). But how are we to determine this? In terms of our two cases, previous comparative research indicates the Great Lakes Basin appears to have more appropriate institutional mechanisms in place to support adaptive governance, whereas in the RGB case, the transboundary governance regime appears to face some challenges in terms of readiness for adaptive approaches (Johns & VanNijnatten 2021). Yet, a more fulsome assessment of the preparedness of these water governance systems to respond to the differing, cascading and deep uncertainties they face is needed, particularly related to climate change uncertainties.

The starting point for such an assessment is to reflect on how the concepts of 'robustness' and 'adaptivity', which are central to understanding how water governance systems can respond to the deep uncertainties wrought by climate impacts, can be linked to concrete governance processes, practices and rules. An evaluative instrument – perhaps along the lines of an 'adaptive governance barometer' – could then be developed which would allow for assessment within and across basins. The adaptive governance and DMDU literatures provide some touchstones in this regard, advocating for tools and approaches that focus on strategic planning processes which set out adaptation actions (Malekpour & Newig 2020) that can then be incorporated into short-, medium- and long-term policy and planning documents on climate change and water governance. Such actions are intended to be planned and anticipatory, not made on an ad-hoc or reactive basis (Haasnoot *et al.* 2013;

Walker *et al.* 2013). For this type of adaptive strategic planning, a monitoring scheme is key and pre-determined 'triggers' or specific performance thresholds where action or decisions are needed. However, discussion in the uncertainty literature has been largely abstract to this point, and insights from the adaptive governance and public policy literatures could be brought to bear on how, exactly, governance systems can respond to the range of uncertainties they face.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Brugnach, M., Dewulf, A., Pahl-Wostl, C. & Taillieu, T. 2008 Toward a relational concept of uncertainty: about knowing too little, knowing too differently, and accepting not to know. *Ecology and Society* **13** (2), 30. https://doi.org/10.5751/ES-02616-130230.

Bureau of Reclamation 2021 *Rio Grande Basin SECURE Water Act Section 9503(c) Report to Congress*. Available from: https://www.usbr.gov/climate/secure/docs/2021secure/basinreports/RioGrandeBasin.pdf (accessed 25 April 2022).

Cado van der Lely, A., van Eekelen, E., Honingh, D., Leenders, J., McEvoy, S., Penning, E., Sterk, M., Voskamp, I., Warren, A. & van Zelst, V. 2021 *Building with Nature: A Future Proof Strategy for Coping with A Changing and Uncertain World*. Ecoshape White Paper. Available from: https://www.ecoshape.org/app/uploads/sites/2/2021/05/Whitepaper-a-future-proof-strategy-for-coping-with-a-changing-and-uncertain-world.pdf (accessed 11 November 2021).

Cairney, P. 2012 Complexity theory in political science and public policy. *Political Studies Review* **10** (3), 346–358. Available from: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1478-9302.2012.00270.x

Carter, L., Terando, A., Dow, K., Hiers, K., Kunkel, K. E., Lascurain, A., Marcy, D., Osland, M., Schramm, P., 2018 Southeast. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* (Reidmiller, D. R., Avery, C. W., Easterling, D. R., Kunkel, K. E., Lewis, K. L. M., Maycock, T. K. & Stewart, B. C., eds). U.S. Global Change Research Program, Washington, DC, USA, pp. 743–808. https://doi.org/10.7930/NCA4.2018.CH19.

Colebatch, H. K. 2014 Making sense of governance. *Policy and Society* **33** (4), 307–316. https://doi.org/10.1016/j.polsoc.2014.10.001.

Collier, D. & Elman, C. 2008 Qualitative and multi-method research: Organizations, publication, and reflections on integration. In. *Oxford Handbook of Political Methodology* (J. M. Box-Steffensmeier, H. E. Brady & D. Collier, eds.). Oxford, University Press, Oxford, UK, pp. 780–795.

Cosgrove, W. J. & Loucks, D. P. 2015 Water management: current and future challenges and research directions. *Water Resources Research* **51**, 4823–4839. https://doi.org/10.1002/2014WR016869.

deBoer, C., Krantzberg, G., 2013 Great Lakes water governance: a transboundary inter- regime analysis. In: *Water Governance as Connective Capacity* (Edelenbos, J., Bressers, N. & Scholten, P., eds). Ashgate Publishing, Farnham, UK, pp. 313–332.

Dewar, J. A. 2006 New practices in long-term planning: Building plans for deep uncertainty. In: *Presentation Given at the Next Generations of Infrastructure (NGI) Workshop*, November 16, 2006. Delft University of Technology.

Earle, A., Cascao, A. E., Hansson, S., Jägerskog, A., Swain, A. & Öjendal, J. 2015 *Transboundary Water Management and the Climate Change Debate*. Routledge, London, UK.

Ehteram, M., Mousavi, S. F., Karami, H., Farzin, S., Singh, V. P., Chau, K. W. & El-Shafie, A. 2018 Reservoir operation based on evolutionary algorithms and multi-criteria decision-making under climate change and uncertainty. *Journal of Hydroinformatics* **20** (2), 332–355. https://doi.org/10.2166/hydro.2018.094.

Espinoza, G. & Meriam, E. 2020 *Water Conflicts in International Rivers*. GIS Blog. Available from: https://www.esri.com/arcgis-blog/products/arcgis-living-atlas/water/water-conflicts-in-international-rivers/ (accessed 21 August 2022).

Gaur, S., Bandyopadhyay, A. & Singh, R. 2021 Modelling potential impact of climate change and uncertainty on streamflow projections: a case study. *Journal of Water and Climate Change* **12** (2), 384–400. https://doi.org/10.2166/wcc.2020.254.

Government of Canada and Government of the United States 2022 *2022 Progress Report of the Parties*. Available from: https://binational.net/2022/07/29/2022-prp-rep/ (accessed 21 August 2022).

Greve, P., Kahil, T., Mochizuki, J., Schinko, T., Satoh, Y., Burek, P., Fischer, G., Tramberend, S., Burtscher, R., Langan, S. & Wada, Y. 2018 Global assessment of water challenges under uncertainty in water scarcity projections. *Nature Sustainability* **1** (9), 486–494. https://doi.org/10.1038/s41893-018-0134-9.

Guilfoos, T. 2020 *Water Governance and Climate Change Uncertainty: How are Institutions for Water Management Affected by Climate Change? And how Should Rules be Adjusted to Incorporate the Future Changes From Climate Change?* Available from: https://sustainabilitycommunity.springernature.com/posts/62447-water-governance-and-climate-change-uncertainty (accessed 12 December 2022).

Haasnoot, M., Kwakkel, J. H., Walker, W. E. & ter Maat, J. 2013 Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change* **23** (2), 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006.

Herman, J., Zeff, H., Reed, P. & Characklis, G. 2014 Beyond optimality: multistakeholder robustness tradeoffs for regional water portfolio planning under deep uncertainty. *Water Resources Research* **50** (10), 7692–7713. https://doi.org/10.1002/2014WR015338.

Intergovernmental Panel on Climate Change – Working Group II 2014 *Climate Change 2014: Impacts, Adaptation and Vulnerability. Summary for Policy-Makers*. Available from: https://www.ipcc.ch/site/assets/uploads/2018/02/ar5_wgII_spm_en.pdf (accessed 21 August 2022).

International Joint Commission [IJC] 2021a *Climate Change Guidance Framework: 2021 Highlights Report*. Available from: https://www.ijc.org/sites/default/files/2021_IJC_CCGF_Highlights.pdf (accessed 23 March 2022).

International Joint Commission [IJC] 2021b *Great Lakes Horizons Task 1 Report*.

Johns, C., 2017 The Great Lakes, water quality and water policy in Canada. In: *Water Policy and Governance in Canada* (Renzetti, S. & Dupont, D., eds). Springer Publications, New York, NY, pp. 159–178.

Johns, C. & Thorn, A. 2015 Subnational diplomacy in the Great Lakes Region: towards explaining variation between water quality and quantity regimes. *Canadian Foreign Policy Journal* **21** (3), 195–211. https://doi.org/10.1080/11926422.2015.1035296.

Johns, C. & VanNijnatten, D. 2021 Using indicators to assess transboundary water governance in the great lakes and Rio Grande-Bravo regions. *Environmental and Sustainability Indicators* **10**. https://doi.org/10.1016/j.indic.2021.100102.

Johnson, J. & Twiss, M. 2020 *Toward a Great Lakes Early Warning System FINAL REPORT*. Available from: https://ijc.org/sites/default/files/2020-06/SAB_GLEWSReport_April2020.pdf (accessed 23 March 2022).

Knight, F. H. 1921 *Risk, Uncertainty and Profit*. Houghton Mifflin Company, New York. (republished in 2006 by Dover Publications, Inc., Mineola, N.Y.).

Lall, U., Johnson, T., Colohan, P., Aghakouchak, A., Brown, C., McCabe, G., Pulwarty, R., Sankarasubramanian, A., 2018 Water. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* (Reidmiller, D. R., Avery, C. W., Easterling, D. R., Kunkel, K. E., Lewis, K. L. M., Maycock, T. K. & Stewart, B. C., eds). U.S. Global Change Research Program, Washington, DC, USA, pp. 145–173. https://doi.org/10.7930/NCA4.2018.CH3 (accessed 25 April 2022).

Lawrence, J. & Haasnoot, M. 2017 What it took to catalyse uptake of dynamic adaptive pathways planning to address climate change uncertainty. *Environmental Science & Policy* **68**, 47–57. https://doi.org/10.1016/j.envsci.2016.12.003.

Lempert, R. J., Popper, S. W. & Bankes, S. C. 2003 *Shaping the Next one Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis*. MR-1626-RPC, RAND, Santa Monica, CA.

Malekpour, S. & Newig, J. 2020 Putting adaptive planning into practice: a meta-analysis of current practices. *Cities* **106**, 102866. Available from: https://sustainability-governance.net/2020/10/21/what-it-takes-to-exercise-adaptive-planning/.

Marchau, V. A. W. J., Walker, W. E., Bloemen, P. J. T. M. & Popper, S. W. 2019 *Decision Making Under Deep Uncertainty: From Theory to Practice*. Springer International Publishing. https://doi.org/10.1007/978-3-030-05252-2.

Michalak, A. M. 2016 Study role of climate change in extreme threats to water quality. *Nature* **535**, 349–350. Available from: https://www.nature.com/articles/535349a.

Morçöl, G. 2013 *A Complexity Theory for Public Policy*. Routledge, New York, NY.

Munia, A. M., Guillaume, J. H. A., Yoshihide, W., Veldkamp, T., Virkki, V. & Kummi, M. 2020 Future transboundary water stress and its drivers under climate change: a global study. *Earth's Future*. https://doi.org/10.1029/2019EF001321.

Murdoch, P. S. & Baron, J. S. 2022 Potential effects of climate change on surface-water in North America. *Journal of the American Water Resources Association* **36** (2), 347–366. https://doi.org/10.1111/j.1752-1688.2000.tb04273.x.

Norman, E. S. 2015 *Governing Transboundary Waters: Canada, the United States, and Indigenous Communities*. Routledge Press, Earthscan Series in Water Resource Management, London.

Norman, E., Cohen, A. & Bakker, K. 2013 *Water Without Borders? The Future of Canada-US Transboundary Water Governance*. University of Toronto Press, Toronto.

Organization for Economic Cooperation and Development (OECD) 2015 *OECD Principles on Water Governance, Paris*. Available from: https://www.oecd.org/governance/oecd-principles-on-water-governance.htm (accessed 11 October 2021).

Room, G. 2011 *Complexity, Institutions and Public Policy: Agile Decision-Making in A Turbulent World*. Edward Elgar Publishing, Cheltenham, UK.

Sanchez, J. C. & Roberts, J. 2014 *Transboundary Water Governance: Adaptation to Climate Change*. IUCN. Available from: https://www.iucn.org/resources/publication/transboundary-water-governance-adaptation-climate-change (accessed 21 August 2022).

Sharafati, A. & Pezeshki, E. 2020 A strategy to assess the uncertainty of a climate change impact on extreme hydrological events in the semi-arid Dehbar catchment in Iran. *Theoretical and Applied Climatology* **139** (1), 389–402.

Sproule-Jones, M. H. 2002 *Restoration of the Great Lakes: Promises, Practices, Performance*. University of British Columbia Press, Vancouver.

Stanton, M. C. B. & Roelich, K. 2021 Decision making under deep uncertainties: a review of the applicability of methods in practice. *Technological Forecasting and Social Change* **171**, 120939. https://doi.org/10.1016/j.techfore.2021.120939.

Timmerman, J. G., Koeppel, S., Bernardini, F. & Buntsma, J., 2011 Adaptation to climate change: challenges for transboundary water management. In: *The Economic, Social and Political Elements of Climate Change* (Leal Filho, W., ed.). Springer.

U.S. Global Change Research Program 2019 *Climate Change Impacts in the United States: The Fourth National Climate Assessment*. Available from: https://nca2018.globalchange.gov/chapter/front-matter-about/ (accessed 25 April 2022).

Van Asselt, M. & Rotmans, J. 2002 Uncertainty in integrated assessment modeling. from positivism to pluralism. *Climatic Change* **54** (1), 75–105.

Van den Hoek, R. E., Brugnach, M., Mulder, J. P. M. & Hoekstra, A. Y. 2014 Uncovering the origin of ambiguity in nature-inclusive flood infrastructure projects. *Ecology and Society* **19** (2), 51. https://doi.org/10.5751/ES-06416-190251.

VanNijnatten, D. 2020 The potential for adaptive water governance on the US-Mexico border: application of the OECD's water governance indicators to the Rio Grande/Bravo Basin. *Water Policy* **22** (6), 1047–1066. https://doi.org/10.2166/wp.2020.120.

VanNijnatten, D. & Johns, C. 2020 Proximity to the desired end state in complex water systems: adaptive governance in the Great Lakes and Rio Grande Transboundary Basins. *Environmental Science and Policy* **114**, 194–203. https://doi.org/10.1016/j.envsci.2020.07.026.

Walker, W., Haasnoot, M. & Kwakkel, J. 2013 Adapt or perish: a review of planning approaches for adaptation under deep uncertainty. *Sustainability* **5** (3), 955–979. https://doi.org/10.3390/su5030955.

Warziniack, T., Arabi, M., Brown, T. C., Froemke, P., Ghosh, R., Rasmussen, S. & Swartzentruber, R. 2021 Projections of freshwater use in the United States under climate change. *Earth's Future* **10**, e2021EF002222. https://doi.org/10.1029/2021EF002222.

Weick, K. 1995 *Sensemaking in Organizations*. Sage Publications, Thousand Oaks, California, USA.

World Resources Institute 2014 *Water Stress by Most Populous River Basins*. Map Available from: https://www.wri.org/data/water-stress-most-populous-river-basins (accessed 21 august 2022).

Wuebbles, D., Cardinale, B., Cherkauer, K., Davidson-Arnott, R., Hellmann, J., Infante, D., Johnson, L., de Loë, R., Lofgren, B., Packman, A., Seglenieks, F., Sharma, A., Sohngen, B., Tiboris, M., Vimont, D., Wilson, M. R., Kunkel, K. & Ballinger, A. 2019 *An Assessment of the Impacts of Climate Change on the Great Lakes*. Environmental Law & Policy Center. Available from: https://elpc.org/resources/the-impacts-of-climate-change-on-the-great-lakes/ (accessed 23 March 2022).

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