Climate Risk Management 35 (2022) 100393

Contents lists available at ScienceDirect

Climate Risk Management

journal homepage: www.elsevier.com/locate/crm

Infrastructure investments for resilience: Opportunities, barriers, and a future research agenda from the Orange-Senqu River Basin

Anita Lazurko [a,1,*], Laszlo Pinter [a,b]

[a] Department of Environmental Sciences and Policy, Central European University, Quellenstraße 51, 1100 Wien, Austria
[b] International Institute for Sustainable Development, 111 Lombard Avenue, Suite 325, Winnipeg, Manitoba R3B 0T4, Canada

ARTICLE INFO

Keywords:
Climate risk
Water infrastructure
Infrastructure finance
Deep uncertainty
Multifunctionality

ABSTRACT

Decision makers are under pressure to make strategic water infrastructure investments under climatic uncertainty. While governments are responding with investments in climate resilient infrastructure, the increasingly complex and unpredictable dynamics of the Anthropocene demand attention to the broader paradigm of resilience, which asks decision makers to situate investments in the dynamics of complex social-ecological systems. Doing so requires more explicit consideration of irreducible uncertainties beyond climate change and infrastructure functions and interdependencies beyond direct water supply. However, the path dependence of prevailing predict-and-control approaches limits transitions to resilience, and the established practices of different actors enable or constrain this transition in different ways. At the time of research, a large-scale climate resilient infrastructure project involving multiple countries in the Orange-Senqu River Basin was at pre-feasibility stage. Our research investigated this transboundary decision context to 1) understand how concepts indicative of a transition from a predict-and-control to resilience-oriented decision paradigm (i.e., uncertainty and multifunctionality) were conceptualized and integrated into a complex decision context and 2) explore how a group of actors with significant decision-making influence – project finance – could enable or constrain this transition. We showed that interviewees identified a wide range of uncertainties and efforts to explicitly consider them were underway. Still, the impact of these efforts was mediated by a continued reliance on established, predict-and-control decision approaches. Additionally, multifunctionality was primarily considered as direct economic benefits to various parties. Our exploratory analysis of the role of project finance actors uncovered several opportunities to enable transitions to resilience, such as expanding capacities to consider a more comprehensive scope of risk and leverage available risk mitigation measures. We conclude with a future research agenda, both to further investigate how multiple decision paradigms interact in real-world decision making and to leverage opportunities for finance actors to enable transitions to resilience.

1. Introduction

Climate change is expected to intensify climatic variability and regional water scarcity (IPCC, 2014; Jury, 2013; Kusangaya et al., 2014). Such increasing climate risk introduces significant uncertainties to water management (Bhave et al., 2016; Hallegatte et al.,

* Corresponding author.
E-mail addresses: anita.lazurko@uwaterloo.ca (A. Lazurko), pinterl@ceu.edu (L. Pinter).
[1] School of Environment, Resources and Sustainability, University of Waterloo, 200 University Avenue, Waterloo, Ontario N2L 3G1, Canada

https://doi.org/10.1016/j.crm.2021.100393
Received 9 March 2021; Received in revised form 24 November 2021; Accepted 31 December 2021
Available online 4 January 2022

2012a; Wardekker et al., 2010). In addition, the growing scope, scale, and speed of change in the Anthropocene impact water systems through accelerating human activities, growing technological and social uncertainties, and increasing interdependence of water systems with their surrounding environments (Chester et al., 2021; Falkenmark et al., 2019; Keys et al., 2019). Decision makers around the world are coming under increasing pressure to take efficient and effective action in narrowing time frames, including through strategic, climate resilient water infrastructure investments. However, the long lifetimes and the significant expense of water infrastructure (Hall et al., 2012; Lienert et al., 2013) introduce the risk that decisions made today configured around present-day climate patterns and assumptions of the stationarity of the broader operating environment may be maladaptive under increasingly likely future extremes (Gersonius et al., 2013; Marchau et al., 2019; Milly et al., 2008).

Decision making for water infrastructure is still frequently conducted under a predict-and-control paradigm, but the paradigm of resilience is emerging as more appropriate for complexity and uncertainty (Baird and Plummer, 2021; Chester et al., 2021; Falkenmark et al., 2019; Rockström et al., 2014). The predict-and-control paradigm optimizes plans and decisions for one most likely future and one or a few primary functions, focusing on human control of variability. In contrast, the resilience paradigm views linked human and natural systems as complex social-ecological systems (SESs) and disturbance as unavoidable, moving beyond engineering resilience or robustness to support water infrastructure systems that evolve and adapt *with* disturbance and change as a matter of standard operating procedures and business practices (Chester et al., 2021; Walker, 2020). This dynamic view of resilience is related to antifragility; a property of economic systems that are not only robust to change but become stronger by learning and reconfiguring following exposure to shocks (Babovic et al., 2018; Taleb, 2012). According to the resilience paradigm, climate resilient infrastructure investments are situated within co-evolutionary social, ecological, and technological systems, are subject to uncertainties beyond climate change, and produce externalities beyond water supply.

A resilience paradigm addresses previously ignored complexities, including cross-scale interconnectivity, tipping points associated with critical thresholds and regime shifts, irreducible uncertainty, market volatility, and dynamic changes in the surrounding social and ecological context (Falkenmark et al., 2019; Rockström et al., 2014). These complexities require new responses, including adaptive plans that monitor signals and anticipate tipping points (Haasnoot et al., 2013a), modular and flexible design (de Neufville and Scholtes, 2011), and methods for robustness assessment and multi-objective optimization (Lempert, 2003; Marchau et al., 2019). While research on this topic highlights new frameworks and tools, little research addresses how the paradigm of resilience interacts with the path dependence of predict-and-control approaches (Marshall and Alexandra, 2016; Mendez et al., 2012; Sendzimir et al., 2010). Yet, niche actors pushing forward the resilience paradigm face resistance from established regime structures and processes (Geels, 2002); for example, up-front cost implications of preparing resilient projects may be higher as proven investment risk calculation methods must be adapted. Moreover, substantial changes to water systems can be risky, warranting some resistance from prevailing water regimes (Jeffrey and Gearey, 2006). Still, persistent institutional inertia limits uptake of resilience, potentially constraining improved decision outcomes and increasing the likelihood that SESs will be pushed into undesirable future states.

New frameworks for transboundary water governance have surfaced in recent decades, enabling governance of multi-country river systems at the biophysical scale (Lautze and Giodrano, 2005; Zeitoun et al., 2013). These frameworks help parties negotiate upstream–downstream impacts and facilitate collaborative solutions for shared resources. Management at the biophysical scale also enables a more comprehensive view of SES feedbacks and interdependencies (Cumming et al., 2006; Epstein et al., 2015), offering an opportunity to address extreme regional discrepancies in water availability. However, transboundary resilience-building introduces new institutional, financial, and political complexities to project decision-making. For example, transboundary projects may involve multi-party diplomatic agreements, long lead times for project preparation, and unique financing considerations to balance risk and benefits across interested parties. Such unique characteristics of transboundary infrastructure decisions may also enable or constrain uptake of the resilience paradigm.

Our first research question attempts to identify and trace the implications of a complex, transboundary decision process that aims to build climate resilience when implemented in a decision context still strongly influenced by the predict-and-control paradigm. To do so, we isolate consideration of resilience to two key concepts: *uncertainty* and *multifunctionality*. We chose these concepts because the way these concepts are treated is markedly different under the predict-and-control versus resilience paradigm. Decisions made under the resilience paradigm consider *uncertainties* beyond traditional forms of risk to include irreducible, non-probabilistic uncertainties like deep climatic uncertainty. Similarly, the view of *multifunctionality* is broadened from assessing direct, quantifiable benefits to embedding water systems within complex SESs, drawing attention to ecosystems services and compounding risks during water infrastructure disruptions (e.g., to hydropower). Additionally, actors have some agency to choose how these concepts are considered in decision processes. Our first research question asks:

> How are uncertainty and multifunctionality conceptualized and considered in decisions for the resilience of water infrastructure in a transboundary project context? How could they be considered in future decision-making processes for more resilient outcomes?

Many actors in water systems play a role in resisting or enabling transitions to resilience, and a funding and finance gap is inhibiting investments in water infrastructure, particularly in sub-Saharan Africa (Briceño-G. et al., 2008; Tandi and Earle, 2015a). Additionally, transboundary institutions in southern Africa are seeking funding to pursue joint resilience-building plans and projects. Consequently, project finance actors hold a unique position of influence in bringing critical resources to climate resilient water infrastructure projects. Many financial actors are working to close the infrastructure financing gap by catering to unique risk contexts (Calitz and Fourie, 2010), blending finance to access new sources of revenue (Corfee-Morlot et al., 2012), and satisfying environmental, social and governance criteria for sustainability-oriented investors (Clapp et al., 2016). However, despite the sustainability lens of some financial actors, the fundamental decision criteria of project finance in water-related sectors continue to be project bankability and risk-adjusted

return (Morel and Bordier, 2012). Few researchers are examining the role of project finance as a gatekeeper to resilience, save a few isolated examples (Cremades et al., 2018; Galaz et al., 2018; Schmidt and Matthews, 2018). Moreover, few researchers are addressing the unique financing opportunities and constraints of transboundary infrastructure projects. This bias exists despite a rapidly changing financial risk environment due to more frequent cases of climate-induced water scarcity and abundance that demand more resilient infrastructure. Our second research question asks:

> How do project finance actors enable or constrain efforts to consider uncertainty and multifunctionality in transboundary water infrastructure investments? How could they adjust project investment rules and processes to enable more resilient outcomes?

2. Methods

2.1. Case study

We addressed these questions in the Orange-Senqu River Basin. The Orange-Senqu River Basin is a region with complex water infrastructure decisions. The basin originates in the highlands of Lesotho and travels through South Africa before draining into the Atlantic Ocean through Namibia and Botswana. The basin is characterized by extreme spatial differences in water availability, with the Lesotho Highlands providing about 50 percent of the total runoff in the entire catchment. Regional demands for water are expected to change, and climate projections reveal significant but uncertain impacts (ORASECOM, 2011a). The basin is regulated by 30 major dams, each with a capacity of over 12 million m^3 (Blumstein, 2017) and several large intra- and inter-basin transfer schemes (ORASECOM, 2014a). A joint river basin commission leads transboundary governance of water resources in the basin and is driving efforts to increase climate resilience. One such effort is a proposed bulk water transfer involving three member states (ORASECOM, 2017; World Bank, 2014). At the time of research, this project (herein referred to as "the Project") was at pre-feasibility stage. The

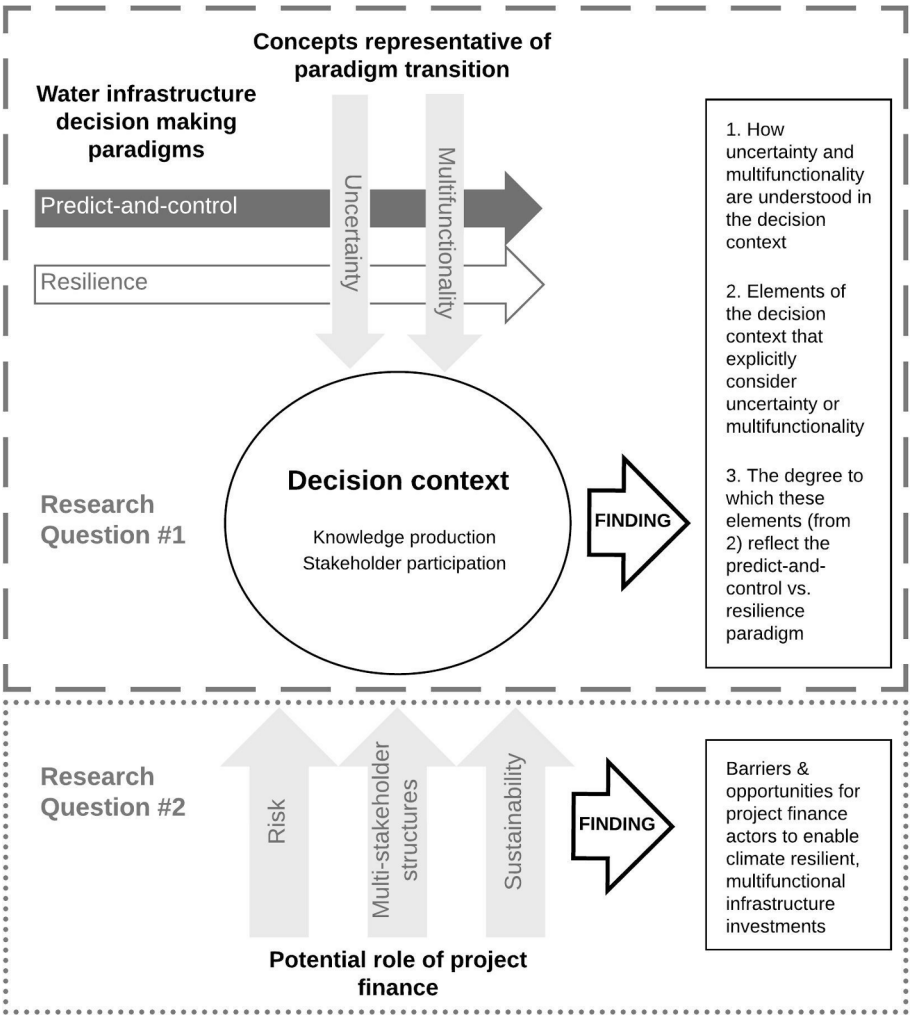

Fig. 1. Conceptual framework.

Project provided a timely opportunity to investigate these questions during a contemporary decision-making process.

2.2. Data collection and analysis

We collected primary data for research question 1 through document analysis and semi-structured expert interviews. Primary data for research question 2 was collected solely from the interviews. We generated a long list of documents from project stakeholders and interviewees, public documents in the river basin commission's online library, and online searches for project-specific documents. We chose a short list (see Table A1) by evaluating abstracts or executive summaries according to the relevance of content for application of the analytical framework and dates of publication, avoiding overlapping content. We first coded the documents to organize data according to the analytical framework, then conducted a thematic content analysis for each section of the framework to generate results.

We generated an initial list of interviewees through consultation with a consulting firm working on climate resilience in the region, which we expanded upon through snowball sampling. We sought 1) experts on decision making for large-scale water infrastructure projects in southern Africa and 2) experts on the water-related financial sector. We interviewed 16 people in total from 5 different institutions who fit at least one of these criteria. Part 1 of the interview asked directly about considerations of uncertainty and multifunctionality. Part 2 asked exploratory questions to link the interviewees' previous responses to opportunities for project finance actors to enable resilient infrastructure investments. We analyzed interview transcripts in two rounds: first, to organize data according to the analytical framework, and second, to generate results through inductive content analysis.

3. Theory

The analytical framework for our study is pictured in Fig. 1. First, we define concepts relevant to the first research question including *uncertainty, multifunctionality*, and a *decision context.* Our framework connects the elements of the *decision context* that address *uncertainty* or *multifunctionality*, differentiated by the *predict-and-control* versus *resilience* paradigms. The analytical framework for the second research question draws from concepts relevant to the first research question, in addition to aspects of *project finance* aligned with the resilience paradigm.

3.1. Uncertainty and multifunctionality

We define uncertainty according to the 4-part typology by Stirling (2006) depicted in Fig. 2. *Risk* defines a condition under which analysts can derive probabilities for a discrete range of outcomes. This definition of risk is broadened in our discussion of project finance (see section 3.4). *Uncertainty* defines a condition under which it is possible to identify a discrete range of outcomes, but there is no agreed-upon basis for assigning probability distributions to these outcomes. *Ambiguity* defines a condition in which there are broader challenges associated with agreeing upon how to choose, define, or prioritize the meaning of different decision outcomes. Finally, *ignorance* defines a condition under which there are challenges related to both selecting a discrete range of outcomes and defining the likelihood of those outcomes. The concept of deep uncertainty is gaining traction in the water sector and aligns with *uncertainty* and *ambiguity*, describing conditions in which parties to a decision cannot agree on "(1) the appropriate models to describe the interactions among a system's variables, (2) the probability distributions to represent uncertainty about key variables and parameters in the models, and/or (3) how to value the desirability of alternative outcomes" (Lempert, 2003).

We conceptualize *multifunctionality* as a principle and a planning paradigm in which multiple economic, social, and ecological functions are explicitly considered and leveraged, rather than simply occurring by chance (Kambites and Owen, 2006).

3.2. Decision context

Adaptive governance literature describes enabling structures and processes for resilience, such as polycentricity, experimentation, and learning (Folke et al., 2005; Herrfahrdt-Pähle, 2013; Lebel et al., 2006). While we did not evaluate these characteristics, we used

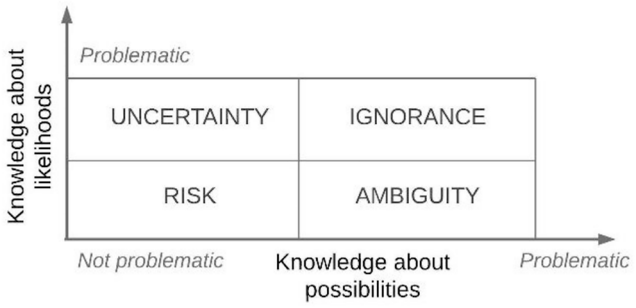

Fig. 2. Typology of uncertainty according to Stirling (2009).

this literature to define what we mean by a decision context, resulting in our focus on i) *knowledge production* (i.e. types and source of knowledge, mechanisms for acquiring knowledge) and ii) *participation* (i.e. participations mechanisms, types of stakeholders involved, use of the results of participation). Both elements feed into decision analysis and risk frameworks that directly inform decision making.

3.3. Predict-and-control versus resilience

The comparison of the *predict-and-control* and *resilience* paradigms is summarized in Table 1. While we treated these paradigms as distinct in our analysis, the line between them may not be as sharp as depicted in practice, and some of their elements may co-exist.

3.4. Project finance

We determined that three areas of project finance relate most directly to resilience: financial and non-financial risk assessment, structuring contracts and financial mechanisms, and green finance. For research question 1, we define risk according to the Stirling (2004) framework in Fig. 2. For research question 2, we define risk as the effect of uncertainty on water infrastructure investments, including project development risk, construction risk, operating risk, credit risk, etc. (Collier, 2014; Green Climate Fund, 2015). Thus, we focus on the way financial risk – i.e., the chance that the returns from an investment are different from expectations – is operationalized in ways that support transitions to resilience, such as by considering irreducible, non-quantifiable uncertainties. While not a focus of our analysis, we emphasize that the subjectivities and complexities of the term (Fischoff et al., 1984) demand a risk-informed rather than risk-based decision approach (Apostolakis, 2004), particularly under the resilience paradigm.

Financing water infrastructure involves both public and private financiers (Briscoe, 1999), and financial business cases are expected to improve if projects aim to serve multiple functions (Tandi and Earle, 2015b). However, multifunctionality also draws

Table 1
Predict-and-control versus resilience governance paradigms related to water.

Aspect	Predict-and-control	Resilience
General characteristics	• Deterministic system behavior • Static and efficient plans and decisions (i.e., predict-plan-act) • Probabilistic outcomes • Infrastructure optimized/calibrated to one stable future and a single (or few) primary objective(s) • Efficient, inflexible design	• Emergent/stochastic system behavior • Adaptive plans and decisions (i.e., experimentation, multiple pathways) • Non-probabilistic outcomes and surprise • Infrastructure evaluated for robustness to multiple futures and optimization to multiple objectives • Modularity and flexibility in design
Uncertainty	• Calculate and communicate uncertainty • Focus on risk; ignore uncertainty, ambiguity, ignorance (Fig. 2) • Assume changes to broader operating conditions are known; change as linear and predictable • Optimize decisions and plans to one most likely future • Predictable return on investment (ROI)	• Build decisions from uncertainty • Focus on a full range of risk, uncertainty, ambiguity, and ignorance (Fig. 2); consider deep uncertainty • Assume changes to broader operating conditions are unpredictable; change as potentially significant and disruptive • Evaluate decisions for robustness or resilience to multiple futures • Layered ROI across multiple functions; more uncertain
Multifunctionality	• Optimize a few primary functions in decision making • Externalize social, economic, or ecological benefits from decisions • Use a few primary functions to make the financial case • Stakeholder engagement as a means for project approval	• Optimize multiple functions in decision making • Endogenize social, economic, and ecological benefits in decisions (e.g., ecosystem services) • Use multifunctionality to layer financial case for investment • Stakeholder engagement as a means for improving knowledge, deliberating over multiple objectives, uncertainties
Examples of analytical and planning methods	• Cost-benefit analysis (CBA), multi-criteria decision analysis (MCDA), probability-based risk analyses • Risk and probability-based infrastructure planning • Minimal stakeholder engagement at later project stages	• Decision making under deep uncertainty methods (DMDU) for evaluating robustness (e.g., robust decision making, info-gap methods, climate-informed decision analysis, decision scaling, real options analysis) • DMDU methods for developing adaptive plans (e.g., regional infrastructure foresight, dynamic adaptive policy pathways • Resilience assessments to identify non-linear feedbacks • Deliberative stakeholder approaches at multiple stages
References	(Arkesteijn et al., 2015; Kalra et al., 2014; Lebel et al., 2005; Lienert et al., 2015; Ranger et al., 2013; Salet et al., 2013; Stakhiv, 2011; Stapelberg, 2010; Störmer and Truffer, 2009)	(Arkesteijn et al., 2015; Baird and Plummer, 2021; Haasnoot et al., 2013b; Hall et al., 2012; Hallegatte et al., 2012b; Kwakkel et al., 2016; Lempert and Groves, 2010; Marchau et al., 2019; McDaniels et al., 2008; Quinlan et al., 2016; Ray and Brown, 2015; Stapelberg, 2010)

attention to the complex transactional mechanisms required to facilitate projects involving multiple financiers and beneficiaries. For example, off-take agreements negotiated before the construction of water supply infrastructure allow water users to secure a portion of water for a set price over a defined time, thereby reducing overall financial risk. A resilient project that serves more functions and beneficiaries may involve increasingly complex financial risk distributions.

Efforts to close the water infrastructure gap are accompanied by a broader shift toward a financial system that better supports the 2030 Agenda for Sustainable Development and the Paris Agreement (Kerste et al., 2011; Wang et al., 2017; Zadek and Robins, 2016). This shift includes market-based initiatives, national-level climate adaptation or mitigation policies, and international initiatives under the Financial Stability Board and the United Nations (World Bank Group, 2017). Mechanisms involved in this financial shift may support the resilience paradigm, such as green or climate bonds that can help smaller, distributed resilience projects access project finance by packaging them together (Climate Bonds Initiative, 2017; Duru and Nyong, 2016).

4. Results

We present the results according to sections of the analytical framework (Fig. 1). The first section describes conceptualizations of

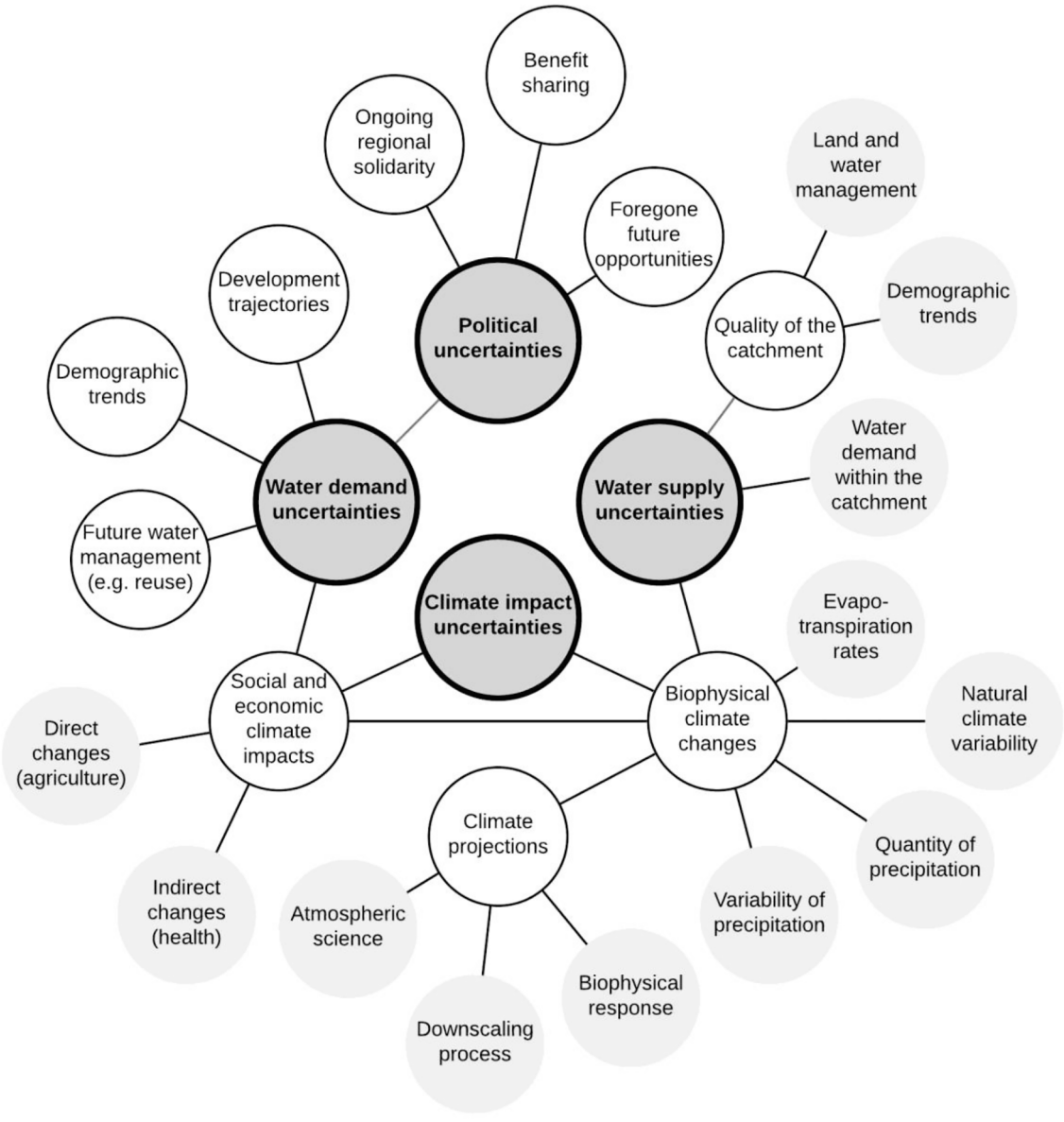

Fig. 3. Conceptualisations of uncertainty in the L-BWT project. Major themes are grey with bold outlines. White and light grey circles are 1st and 2nd degree connections to these major themes (Lazurko, 2018).

resilience, uncertainty, and multifunctionality evident in the decision context, including commentary on typologies of uncertainty. The second section identifies elements of the decision context that contribute to understanding and integrating uncertainty and multifunctionality in infrastructure decisions. This includes commentary on which findings reflect the paradigms of predict-and-control versus resilience. The final section draws out opportunities for project finance actors to enable resilience.

4.1. Conceptualizations of uncertainty and multifunctionality

Though *uncertainty* was not addressed widely in documentation, interviewees were aware of many uncertainties associated with the Project. Interview prompts focused on identifying critical uncertainties (i.e., high uncertainty, high importance). Interviewees described uncertain climate futures, complex water supply dynamics, ambiguous future development trajectories, and political risks covering all four quadrants of Stirling's framework (i.e., *risk, uncertainty, ambiguity,* and *ignorance*), as visualized in Fig. 3.

These uncertainties included a spectrum from project unknowns that would become clearer at later project stages to radical uncertainties described by interviewees as "possible foregone future opportunities" or "unknown unknowns". The depth and breadth of these descriptions of uncertainty indicate that challenges considering uncertainty in decision making may not stem from a lack of awareness, but other limiting factors.

Interviewees were asked to articulate the *multifunctionality* associated with the Project, and we scanned documents for additional evidence. Initial findings indicated that, as put by one interviewee, "the nature of regional projects is that they are probably very rarely the most important project for a country, but they are the most important project for a region". This finding underlines the importance of scale within a transboundary context in determining which functions are considered relevant, to whom, and to what extent. At a transboundary scale, the main project functions were to mitigate regional water scarcity and establish political trust and solidarity. At a domestic scale, upstream parties expected economic gains (e.g., revenue, hydropower) and an additional source of water supply. Downstream countries, whose issues of extreme water scarcity were motivating the Project, expected to secure a freshwater supply. All parties expected these functions to contribute to broader economic and social development.

As multiple economic, social, and ecological functions emerged, interviewees expressed a desire to understand which benefits could be leveraged in which contexts. Some interviewees described indirect project benefits, including economic development. Interviewees implied that multiple functions were critical to the Project because leveraging benefits for stakeholders in each country was important for transboundary cooperation. However, interviewees did not independently connect multifunctionality to the economic value of ecosystem services, which may be a crucial means to institutionalize the resilience paradigm.

4.2. Understanding and integrating uncertainty and multifunctionality in decision-making

We investigated how uncertainty and multifunctionality are considered in decision-making processes for the resilience of the Project (current), and how these concepts could be considered in decisions for the resilience of water infrastructure (future). Two broad themes emerged: the dual process of first *understanding* uncertainty and multifunctionality and then *integrating* them into broader decision processes. *Understanding* involves differentiating between various elements of each concept for a more detailed depiction of each element. *Integrating* involves bringing these differentiated concepts into broader decision-making processes alongside a host of other factors.

4.2.1. Understanding uncertainty in decisions

Our analysis showed that some planned efforts to understand water supply and demand uncertainty align with resilience, though most reaffirm the predict-and-control paradigm. Knowledge of multiple uncertainties (section 3.1) alongside the prevalence of the predict-and-control paradigm may represent a form of institutionalized cognitive dissonance, whereby decision makers must assume that infrastructure performance baselines will remain the same under the future climate regime (despite contrary evidence) in order to utilize established decision tools and planning frameworks. However, intentions to work with emerging concepts and methods may indicate that institutional learning is underway. Interviewees and the literature also described unplanned possibilities to better align decision making with resilience. This analysis is summarized in Table B1.

4.2.2. Understanding multifunctionality in decisions

Multifunctionality was understood through a combination of basin-wide and project-specific efforts. These efforts were solely focused on quantifying and allocating direct water use, likely due to the need to secure functions for parties in the transboundary context. Interviewees identified several stakeholder engagement mechanisms that may enable further understanding of multifunctionality. Future possibilities focus on the role of ecosystem services, such as how tools used to assess ecosystem services could highlight supply and demand for multiple functions and deal with trade-offs between functions over space and time (Hansen and Pauleit, 2014). This analysis is summarized in Table B2.

4.2.3. Integrating uncertainty and multifunctionality in decision-making

Our analysis of processes for integrating uncertainty and multifunctionality into the decision context led to further insights. Interviewees repeatedly referred to the use of scenarios as a favorable method for dealing with uncertainty, aligning with the resilience paradigm (Haasnoot et al., 2020; Peterson et al., 2003). They also discussed the potential for stakeholder engagement to further integrate uncertainty and multifunctionality in broader decision processes. Interviewees suggested several future possibilities, including using integrative systems analysis, embedding flexibility into infrastructure design, or expanding project boundaries. The

results show that real-world decision processes can reflect the co-existence of elements of both the predict-and-control and resilience decision paradigms.

The results also show that the potential benefits of resilience-based decision tools may be significantly affected by their use within well-established predict-and-control frameworks. For example, modeling multiple scenarios is important for understanding the implications of uncertain future hydrological flows. However, in the context of climate change, choosing a "most likely" core planning scenario for a basin-wide plan (ORASECOM, 2014b) may indicate a tendency toward optimization characteristic of the predict-and-control paradigm. While selecting a core scenario may be politically and institutionally expedient, designing for one core climate scenario may limit consideration of a precipitation regime or wildcard events far outside of the range of normal variability.

Taking these more extreme scenarios seriously would require novel technical and organizational responses. For example, the Project had not (at the time of research) utilized emerging frameworks like decision scaling (Brown, 2011), real options analysis (Gersonius et al., 2013; Manocha and Babovic, 2018a), or info-gap decision theory (Ben-Haim, 2018) that evaluate decisions against multiple scenarios and uncertainties, potentially revealing the value of more resilient or flexible infrastructure options (see section 4.3.1). Similarly, decision processes for the Project did not utilize the transformative potential of participatory scenario planning (e.g. Schneider and Rist, 2014; Amer et al.m 2013; Mahmoud et al., 2009), in favor of expert-led scenario approaches based on one dimension of uncertainty (World Bank Group, 2016; J. Hall et al. 2012). Decision processes also did not appear to consider the timing of scenario analysis with early-stage decision points, which may be required to improve their influence on later project stages.

The elements of multifunctionality that were most important for the transboundary decision process were integrated into decision making, but innovative methods for considering a broader set of benefits and ecosystem services were not prevalent at this early project stage. Delaying consideration of diverse benefits to multiple stakeholders and functions until later project stages may further reinforce the predict-and-control paradigm. Moreover, if multifunctionality is not broadened to include more beneficiaries and functions, the layered ROI that may improve project bankability will not be considered. This analysis is summarized in Table B3.

4.3. Project finance actors and resilience

Opportunities for project finance actors to enable transitions to the resilience paradigm are summarized according to four themes: 1) considering a more comprehensive scope of risk, 2) leveraging risk mitigation measures, 3) diffusing risk and benefits over space, time, and to different actors, and 4) defining roles to achieve multiple objectives. Quotations demonstrating these themes are summarized in Table C1.

4.3.1. Considering a more comprehensive scope of risk

Several interviewees suggested that project finance actors interested in enabling transitions to the resilience paradigm should consider a more comprehensive scope of risk factors. Though not directly articulated, the suggestion implies that doing so may lead financiers to support investments that are more resilient to a wider scope of risks, such as those associated with climatic or ecological change. As financiers shift their expectations for risk management, governments and project implementers may consider these risks more seriously in planning, generating a pipeline of more resilient projects.

Interviewees emphasized that these risks must have a quantifiable impact on cash flow and project bankability over a defined period to be included in contemporary risk assessments. For example, improved methods for quantifying climate uncertainties and the associated hydrological impacts may increase the willingness and capacity of the sector to translate those impacts to financial terms. Similarly, hydrological models and stakeholder engagement exercises may expose the impacts of changing water demands on future project revenue. Furthermore, integrating uncertainty and multifunctionality into basin-wide network models or integrated risk assessments may help financiers understand interrelated and compounding risks, and – while not directly articulated by interviewees - eventually offer dynamic analysis of the system as it absorbs and learns from shocks; an essential component of adaptive or antifragile systems.

Interviewees made it clear that the potential to quantify more diverse risks is inhibited by various factors. In addition to challenges quantifying and valuing risk, interviewees indicated that risks must also have a significant material impact within the payback period of the financier when discounted to present terms. One interviewee also mentioned that human volition – or the ad hoc risk mitigation measures adopted independently by communities or governments – create feedback effects on the risk landscape, complicating long-term risk assessments. Interviewees warned that properly understanding and managing a widening range of increasingly complex risks will likely increase transaction costs. Thus, a precondition to actualizing these changes is the need to quantitatively demonstrate their financial benefits (i.e., evidence of the financial impact of the increased long-term project resilience).

Even more challenging is that conventional project financial assessments are not equipped to assess the financial risks associated with often irreducible and non-probabilistic climatic and ecological uncertainties, nor do they adequately value the benefits of long-term flexibility or adaptivity (Kalra et al., 2014; Sayers et al., 2012). Consequently, project financiers may need to adopt new methods to evaluate project options against novel forms of risk or benefits. For example, real options analysis can be used to quantify the financial benefits of flexible and adaptive solutions, countering potential bias toward one-time, large-scale capital investments in net present value calculations (Dawson et al., 2018; Gersonius et al., 2013; Manocha and Babovic, 2018b). The cost of climatic uncertainty can be quantified by adapting standard financial sensitivity analyses, for example by estimating the financial impact of uncertain climatic variables on project income generation (e.g., due to changing water availability or people's ability to pay for water due to crop failures). Decision scaling operationalizes this idea by using climate "stress testing" to estimate risks associated with different levels or types of climate extremes, which may then inform financial analysis (Brown, 2011). Alternatively, robust decision making methods or info-gap decision theory can be used to parameterize climatic, ecological, or demographic uncertainty and narrow decision options

down to those that satisfy performance thresholds across a range of criteria and under the full range of plausible future scenarios (Ben-Haim, 2018; Kwakkel et al., 2016; Sayers et al., 2012). Only those options that satisfy those decision criteria – and thus are assumed to satisfy a tolerable level of climatic or ecological risk – would then be considered for financial analysis.

4.3.2. Leveraging risk mitigation measures

Considering a more comprehensive scope of risk may incentivize governments and financiers to support resilience-based risk mitigation. For example, catchment management efforts conventionally sit outside of the project boundaries but still impact project outcomes (e.g., the contribution of upstream afforestation on downstream flood buffering and sediment load reduction). Interviewees affirmed that catchment management initiatives should be integrated into a financial model, because the financial value of the associated risk reduction may be significant. Doing so may encourage investment in programs like catchment afforestation if the cost of afforestation is lower than the financial estimates of risk reduction, especially as technologies for quantifying these risks improve.

Despite this potential, interviewees cautioned that the average financier would not naturally link land management practices to the risk profile of hydraulic grey infrastructure. While this may be due to capacity, financiers may also lack the incentive to do so, though this may not always be the case (e.g., Postel and Thompson, 2005). For example, some interviewees assumed the impact of catchment management would likely be small when considered over the 10 to 15-year time horizon of a typical financier and further complicated by large uncertainties associated with long-term ecological responses and independent adaptations of governments and communities. Because of such mismatched time scales and causalities, interviewees emphasized that impacts must be clear in operational data used to manage infrastructure to be included in the financial model. This finding highlights the importance of monitoring and modeling for building evidence of functional linkages between risk mitigation measures and their system-wide impacts, such as the Sustainable Asset Valuation Model (SAVi) developed by the International Institute for Sustainable Development (IISD, 2021). Still, the higher transaction costs associated with implementing these efforts may create additional disincentives.

The link between the livelihoods of farmers in upstream regions of the Project and catchment degradation downstream prompted several interviewees to reflect on the importance of benefit sharing or payment for ecosystem service schemes. These appeared second priority to other efforts, as a financial model cannot only rely on their success. This is consistent with the broader recognition that until the natural resource use decisions of many diverse actors and related physical impacts can be systematically monitored, verified, and attributed to aggregate outcomes (e.g., on the landscape), incorporating the economic value of contribution to ecosystem services would work only in exceptional cases. Moreover, doing so may require financiers to adopt emerging methods for considering climatic or ecological risk in financial/options analysis (e.g., decision scaling, real options analysis, etc.), thereby helping monetize the potential value of catchment-scale risk mitigation.

4.3.3. Diffusing risk and benefits over space, time, and to different actors

Interviewees expressed that connecting uncertainty and multifunctionality to finance may inform project structures and agreements that consider a granular diffusion of risk and benefit. This may better enable a water system to recover from the impacts of uncertain risks. Interviewees also confirmed that up-front commitments to offtake water from a project reduce cash flow volatility, reducing risk and improving bankability.

An infrastructure project may supply water to diverse off-takers along the pipeline, which requires agreements among several entities with varied needs and characteristics. By adopting a broader view of multifunctionality earlier in the planning process, one could structure an offtake agreement to diffuse risk to multiple beneficiaries and distribute high-risk off-takers amongst low-risk off-takers. This process is standard financial practice and similar to securitization, but can also align with the role of higher functional and response diversity in building resilience (Norberg et al., 2008; Walker et al., 2004) as long as the role of higher-risk off-takers is transparent and limited. One interviewee hoped that a more rigorous risk assessment may improve government confidence in the project, thereby encouraging support toward social beneficiaries. Again, the potential for higher transaction costs may be a barrier to these more complex agreements.

In addition to diffusing risk to, and between, multiple users, several interviewees suggested that better knowledge of uncertainty might encourage solutions that spread financial risk into the future through design flexibility. The most common example was building a dam with foundations that allow for increasing the size of the dam later if required. Interviewees identified several potential financial implications: the initial capital burden would likely be lower, the cost of capital could be spread over time, and income gained from early phases may help pay for later enhancements. Though the overall costs may be greater if the need for later upgrades is required under the emerging climate regime, the project may achieve savings overall if the future costly upgrades are deemed unnecessary. Capturing the value of this temporal flexibility may require innovative financial models and novel assessment techniques like real options analysis (Buurman and Babovic, 2016; de Neufville and Scholtes, 2011; Manocha and Babovic, 2018a).

4.3.4. Defining roles to achieve multiple objectives

The final theme revealed the dissonant primary objectives of different stakeholders in a complex, transboundary decision context, which place boundaries around innovation. Interviewees articulated these objectives, including the emphasis on project bankability (implementing agency), risk-adjusted financial return (financier), end-cost of water (off-taker), and long-term water security and service delivery (governments). These competing objectives were accompanied by different time horizons; the 10 to 15-year time horizons of a typical financier do not align with the 3 to 5-year planning horizons of a mining operation and the multi-decade planning of governments.

These boundaries emphasize the need for government and transboundary organizations to take on the macro-scale, long-term perspective. For example, interviewees voiced concern that the process of translating non-financial risks to financial terms may cause

financial actors to deprioritize or ignore significant social impacts with small financial impacts. Similarly, the financial sector may not have an interest in protecting the government from risks that will manifest long after the financier's involvement.

Interviewees also emphasized the role of government in diffusing risk to different off-takers. For example, one interviewee emphasized that government must adopt the long-term view to plan water infrastructure for industrial users that operate on volatile, short-term planning cycles but are part of a long-term, stable sector in the region. Interviewees also emphasized the complex challenge of setting up off-take agreements with many entities, and that many governments prefer a "demand-responsible approach" by signing up off-takers before building the infrastructure. This was countered with the belief of other interviewees that government should take on some financial risk to plan for the longer-term perspective.

5. Discussion

5.1. Uncertainty and multifunctionality for resilience

Our findings revealed that interviewees conceptualized a wide range of uncertainties from risk to ambiguity, indicating that a lack of consideration of uncertainty in the decision context may be due to broader barriers. On the other hand, a broader view of multifunctionality beyond those functions needed for project buy-in was not yet considered, revealing a gap between resilience in theory and practice at the pre-feasibility stage of the project.

Our findings also showed that uncertainty and multifunctionality are understood and integrated into the decision context through diverse modes of knowledge production and participation from both the predict-and-control and resilience paradigms. This analysis of how different decision paradigms manifest in a real-world context offers a more integrated and comprehensive picture than currently exists in the literature. In addition, we revealed trade-offs between multiple decision paradigms, which may be typical of attempts to adopt niche methods from the resilience paradigm (e.g., scenarios to deal with uncertainty) in decision contexts still dominated by a predict-and-control regime (i.e., optimization to one most likely scenario).

We also revealed that multifunctionality focused on direct water use and associated economic benefits (e.g., hydropower), so emerging methods for capturing a broader range of social or ecological uses and benefits were not yet utilized. While actors may consider broader benefits or ecosystem services at later project stages, this gap may stem from a lack of established methods to quantify them and express them in financial terms. Our research generated practical possibilities that may be adopted to better understand and integrate uncertainty and multifunctionality into future large-scale water infrastructure decisions.

Our research also highlights the need for all stakeholders to pro-actively operationalize emerging methods to better understand and integrate uncertainty and multifunctionality in decision-making. We suggest that decision makers take time early in decision processes to do so, including by defining resilience, expanding the scope of uncertainties and functions they consider relevant, and seriously considering the consequences of a lack of resilience as an explicit and consequential part of their deliberations. In addition, decision makers using methods aligned with resilience must recognize that the unique value of these methods may not be realized if the outcomes are fed into decision processes reflecting the predict-and-control view. Practitioners may also find ways to align emerging methods with other factors in the decision context (e.g., political motivations related to the SDGs) and link them to key decision points. While these recommendations assume decision makers have agency over the choice of decision methods, external changes – such as changes to insurance premiums (Cremades et al., 2018) – may begin to force governments and investors to accelerate the uptake of emerging resilience-based decision methods. Altogether, these actions can lead to decisions that are more resilient to a range of uncertain context conditions and serve a wider range of interests. Moreover, they may also steer infrastructure systems toward adaptive – perhaps even antifragile systems - that have the capacity to evolve with and learn from change.

While the study was not explicitly framed to analyze the unique aspects of *transboundary* resilience projects, our results generated some interesting reflections. On one hand, the existence of a mature transboundary organization enabled a basin-wide approach to dealing with extreme downstream water scarcity through joint climate resilience projects. This is a promising development in future water resilience, particularly under more extreme climate change scenarios. However, the need to secure buy-in from all countries may have influenced actors to focus on only economic functions early in the project. Thus, the transboundary contexts limited consideration of broader interdependencies and ecosystem services until later project stages. The unique opportunities and challenges of transboundary contexts – and the associated implications for resilience – are a ripe avenue for future research.

Despite abundant research addressing resilience, there remain additional research gaps addressing how decision methods that align with resilience are integrated into real-world contexts. Examples of crucial future research areas include 1) a better understanding of trade-offs between resilience-based and predict-and-control methods and how to manage them, 2) how to leverage multifunctionality for large-scale grey infrastructure in the water sector, and 3) if trade-offs exist, which methods should be prioritized in complex decisions. In addition, because multifunctional infrastructure systems are multiscale and dynamic, where factors affecting the ability of a system to deliver benefits are constantly changing, further research should address 4) how multifunctionality can be used to leverage benefits across scales and 5) how the availability of multiple benefits and risks help negotiate and renegotiate the management of the system over time, particularly in cases where design flexibility is included as a resilient design alternative.

5.2. Project finance actors and resilience: Barriers, opportunities, and a future research agenda

We revealed opportunities for project finance actors to enable resilient infrastructure investments. These findings do not form a significant contribution in isolation; the financial sector routinely diffuses risk to decrease volatility, and financial actors habitually mitigate risk e.g., through the securitization of investment instruments and portfolios. However, under the framing of uncertainty and

multifunctionality, each of these findings could be taken one step further in service of a broader goal of resilience, reducing the risk of catastrophic failure, and anticipating future change to make systems more adaptive or antifragile. Moreover, synergies exist between these opportunities, and they may need to be applied together for improved outcomes.

Each theme can be extended beyond the findings of our study. For example, if financiers begin routinely considering more comprehensive risk factors, the landscape of forces that dictate or influence the priorities of governments, financiers, and project implementers may shift to prioritize more resilient investments. Additionally, more rigorous, early-stage financial risk assessments that incorporate irreducible and non-probabilistic uncertainties and/or value long-term flexibility and adaptive capacity (e.g., real options analysis, robust decision making, decision scaling) may incentivize actors to mitigate risk in project planning/design. Similarly, leveraging risk mitigation initiatives like catchment management draws more attention to multifunctionality, which may incentivize evidence-building of their financial costs and benefits over time. Such evidence could increase investment in risk mitigation that can be included in a financial model and inform increasingly rigorous consideration of these risks in novel financial analyses. These measures also require context-specific, integrated models that a) demonstrate linkages between the biophysical impacts of water infrastructure and catchment management, and b) relate those findings to the restricted boundary conditions (e.g., time scales) of financial models. Such models can inform cost-and-benefit sharing practices, so those who pursue watershed catchment efforts are not excluded from the financial benefits of the associated risk reduction.

Similarly, diffusing risks and benefits over space and time promotes resilience through opportunities to decrease the volatility of cash flow through the intentional allocation of diverse revenue streams. A diversified risk profile may also include a more diverse set of beneficiaries in infrastructure projects or highlight opportunities to design flexible infrastructure. Moreover, the disparate objectives, time horizons, and spatial scales guiding the decisions of different stakeholders indicate that complacency from any stakeholder group may tip the scales toward the priorities of others. While not inherently negative, a resilience perspective reveals government, transboundary organizations, or a supportive civil society, may be the primary advocate for resilience. It also indicates the importance of a negotiation framework, where the needs, interests, and capabilities of the affected beneficiaries can be exposed and brought to bear on the options and implementation pathways chosen.

Project finance actors should consider a more comprehensive scope of risk to support resilience and adjust norms to avoid the subpar rates of return we may expect under some future conditions. These efforts may prompt governments and financiers to support efforts like catchment preservation as risk mitigation. Governments, transboundary organizations, and a supportive civil society must recognize their role as advocates for a long-term perspective on resilience. However, external changes, such as climate-induced changes to insurance premiums, may also shift incentive structures so that investors begin to advocate for a resilience perspective.

These findings highlighted several topics for future research, including 1) an understanding of the systemic effect of integrating a more comprehensive scope of risk on the project finance landscape, 2) a characterization of enablers and inhibitors for leveraging risk mitigation measures upstream or downstream of a project, 3) an understanding of the opportunities, challenges, and potential mechanisms for diffusing risk over time, space and to different actors, including flexible engineering design, 4) a better understanding of the consequences of the interactions between competing time scales and objectives of actors in the project finance landscape, and 5) quantifying the long-term benefits of resilience to justify the potential increase in project transaction costs.

5.3. Limitations

Our study was exploratory, investigating a case study to identify barriers, opportunities, and a future research agenda. To do so, we had to make difficult choices in our analytical framework to make complexity tractable. For example, simplifying the paradigm of resilience to the concepts of *uncertainty* and *multifunctionality* was a necessary but limiting choice.

At the time of the study, the Project was at pre-feasibility stage, so all findings are only reflections of a snapshot in time and the Project has likely evolved significantly. While the contemporary nature of the Project was a benefit for investigating a complex, real-world decision context, it also limited our ability to obtain access to data and people. For example, some ongoing desktop studies were not public and were excluded from the document analysis. Due to the Project's ongoing political nature, we were not able to interview government experts. Our study makes no claims regarding the overall benefits or risks of the Project. Rather, we analyzed the decision context of the Project to reflect upon broader opportunities and challenges in the transition to a resilience-based decision paradigm in the water sector.

Finally, we expect that the challenges discussed in this study are common – and likely exacerbated – in many other transboundary contexts around the world. However, there may be limits to this generalizability. Further studies are required to gather a more holistic view of the challenge of transitions from the predict-and-control paradigm to resilience.

6. Conclusion

A new resilience paradigm is emerging, supporting water infrastructure systems that are flexible and adaptive to the uncertainties and complexities of the Anthropocene. As scientists and practitioners develop and implement new decision methods, studies that observe how elements of this emerging decision paradigm interact with the prevailing predict-and-control decision paradigm are crucial. Our research generated unique findings by doing so.

All actors play a role in enabling a transition to resilience. Growing efforts to address the powerful role of financial actors in enabling or inhibiting pathways to resilience demands an urgent look at the role of project finance in addressing challenges like those faced in the Orange-Senqu River Basin. While some of our suggestions for project finance actors to alter their practices may be routinely applied in the financial sector, our focus on uncertainty and multifunctionality pushed these practices further in service of

resilience.

Despite our attempts to apply a holistic analytical framework, some factors brought forward by interviewees were not adequately addressed. For example, challenges establishing a basic enabling financial environment in southern Africa (e.g. Berensmann et al., 2015) limit the ability of stakeholders to adopt our suggestions and to keep pace with ongoing financial transformation (Zadek and Robins, 2016). This reflection highlights the need to balance the costs of adopting our suggestions against the cost of not adopting them (e.g., cost of flexible and phased infrastructure design against an inflexible design; cost of ignorance to unquantified risks against the cost of improved monitoring programs). In addition, our analysis excluded politics, which may become increasingly important as water availability becomes more constrained.

As governments in low and middle-income countries work to institute a basic enabling environment for resilience, all actors should ask themselves how they can step outside of conventions to support the transition to resilience. In the case of project finance, this may require using competencies outside the financial sector more systematically, expanding boundaries to look at risks over new time horizons and scales, reconciling the incongruent objectives of stakeholders, and diffusing risk for the benefit of the financial sector and resilience. Though research that accepts and grapples with these challenges proved to be thought-provoking and challenging, there appears to be great potential in further exploring concepts like uncertainty and multifunctionality in complex, real-world decision contexts, and in further navigating the junction between resilience in theory and practice.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The research was conducted as part of the dissertation requirement for the Erasmus Mundus Master of Science in Environmental Sciences, Policy and Management under the supervision of Dr. Laszlo Pinter. The authors thank all interviewees for their assistance and time, which was critical for the success of the research.

Funding

Support for field research (interviews) was provided by the Department of Environmental Sciences and Policy at the Central European University.

Appendix A

Table A1. Documents analysed in the case study.

Institution	Document
ORASECOM	(2011) GCC Downscaling for the Orange-Senqu River Basin
	(2014) Integrated Water Resources Management Plan For The Orange-Senqu River Basin
	(2017) Terms of Reference: Selection of Consultants For Orange-Senqu River Basin Climate Resilient IWRM Investment Plan and Lesotho to Botswana Water Transfer Project
	(2014) Water Resources Modelling, Baseline Scenario, Yield Analysis, Stochastic Verification and Validation. Gabarone
	(2011) Projection of Impacts under Plausible Scenarios and Guidelines on Climate Change Adaptation Strategies. Pretoria
	(2013) Basin-wide Environmental Flow Regime in the Orange-Senqu River Basin. Pretoria
	(2009) A Fitness for Use assessment of the waters of the Orange-Senqu Basin. Gabarone
SADC	(2012) Regional Infrastructure Development Master Plan: Executive Summary
UNDP, GEF	(2014) Orange – Senqu River Basin Transboundary Diagnostic Analysis
World Bank Group	(2014) Project Paper for Small RETF Grant from the Multi-Donor Trust Fund for Cooperation in International Waters in Africa
	(2016) Lesotho Water Security and Climate Change Assessment
Other	Department of Water Affairs South Africa (2012) Development of Reconciliation Strategies for Bulk Water Supply Systems Orange River: Literature Review ReportGreen OO, Cosens BA, Garmestani AS (2013) Resilience in Transboundary Water Governance: the Okavango River Basin. Ecol Soc 18:. https://doi.org/10.5751/ES-05453–180223

Appendix B

Table B1. Knowledge systems and stakeholder participation mechanisms for understanding climate, water supply and demand, and political uncertainty in the Project.

Paradigm	*Decision timeline*		
	Current	**Future planned**	**Future possible**
Predict-and-control	*Water uncertainty* • Conducting supply–demand reconciliation studies (Department of Water Affairs South Africa, 2012) • Using basin-wide hydrological models (i.e. water yield, planning) (ORASECOM, 2014b) *Climate uncertainty* • Developing Integrated Water Resources Management (IWRM) plans based on one core scenario (interview)	*Water uncertainty* • Assessing groundwater and demand management potential (ORASECOM, 2017) • Updating basin-wide hydrological models (i.e. water yield, planning) (ORASECOM, 2017) *Climate uncertainty* • Updating core scenario of IWRM plans (ORASECOM, 2017)	
Resilience	*Climate uncertainty* • Using downscaled climate models (ORASECOM, 2011a, 2011b) • Using robust decision-making frameworks (World Bank Group, 2016) • Developing alternative climate scenarios (interview) *Political uncertainty* • Considering regional economic integration (interview)	*Water uncertainty* • Modeling climate impacts on water availability (ORASECOM, 2017) *Climate uncertainty* • Updating climate scenarios with emerging information (interview) • Updating downscaled climate models (ORASECOM, 2017) • Adopting a climate resilience lens (e.g., donors, implementers) (interview)	*Water uncertainty* • Expanding stakeholder engagement exercises (e.g. multiple water users) (interview) *Climate uncertainty* • Quantifying climate uncertainties (e.g., using self-organising maps) (interview) *Political uncertainty* • Using scenario planning, integrating wild cards (Kriegler et al., 2012; O'Neill et al., 2014)

Table B2. Knowledge systems and stakeholder participation mechanisms for understanding multifunctionality in the Project.

Decision scale	*Decision timeline*		
	Current	**Future planned**	**Future possible**
Basin-wide	• Assessments of basin-wide water security and trade-offs (World Bank Group, 2016) • Basin-wide and national water allocation policies and plans (ORASECOM, 2014a) • Basin-wide environmental flow studies (ORASECOM, 2013) • Basin-wide assessment of water quality and fitness-for-use (ORASECOM, 2009) • Transboundary Diagnostic Analysis of basin-wide ecological and social functions (UNDP and GEF, 2014) • Basin-wide economic analysis of water users (UNDP and GEF, 2014)	• Assessment of potential for water demand management and benefits to sectors (ORASECOM, 2017) • Updates to basin-wide water requirements and allocations by sector (ORASECOM, 2017) • Benefits of environmental flows to be considered in economic assessments (ORASECOM, 2017) • Core scenario of IWRM plan to include direct and indirect costs and benefits (ORASECOM, 2017)	
Project	• Broad benefits estimated by country (e.g. Hansen and Pauleit 2014)	• Assessments of hydropower potential (ORASECOM, 2017) • Hydraulic studies for potential links to offtaker networks (ORASECOM, 2017) • Assessment of water demands for Lesotho, South Africa and Botswana for multiple sectors (ORASECOM, 2017)	• Mass stakeholder engagement exercise to reconcile multiple potential users and water availability (interview) • Borrowing technical tools to leverage multifunctionality from other sectors (e.g. green infrastructure) (Pauleit et al., 2011; Schindler et al., 2014) • Community-level benefit sharing exercise (interview)

Table B3. Knowledge systems and stakeholder participation that integrate uncertainty and multifunctionality in decisions in the Project.

Decision paradigm	*Decision timeline*		
	Current	**Future planned**	**Future possible**
Predict-and-control	• Defining core scenario for IWRM plan and socio-economic/ biophysical elements (ORASECOM, 2014a)	• Updating core scenario with information about the Project and water conservation measures (ORASECOM, 2017)	

(*continued on next page*)

(*continued*)

Decision paradigm	*Decision timeline*		
	Current	**Future planned**	**Future possible**
	• Concentrating stakeholder participation at national level (interview)	• Economic optimisation of water management actions based on "value for money" (ORASECOM, 2017) • Using multi-criteria analysis for decisions (ORASECOM, 2017)	
Resilience	• Testing regional infrastructure development plans against climate scenarios (SADC, 2012) • Assessing impacts of future climate variability on key sectors as "costs of losses of revenues" (World Bank, 2014) • Integrating knowledge and input from diverse stakeholders	• Testing core scenario for IWRM plan against multiple climate futures (ORASECOM, 2017) • Considering the Project alongside climate risk and adaptation measures (interview)	• Use more rigorous participatory scenario planning tools (interview) • Test emerging scenario tools (e.g. climate risk informed decision analysis) (Haasnoot et al., 2013b; Störmer and Truffer, 2009) • Perform integrated models using basin networks methods (interview) • Using flexibility and sequencing in infrastructure design; use real options to measure flexibility (Kalra et al., 2014; Manocha and Babovic, 2018a) • Expand project boundaries to multiple sectors, regions and the catchment; implement monitoring system (interview)

Appendix C

Table C1. Select quotations for themes understanding and integrating uncertainty and multifunctionality to water infrastructure finance.

Theme	**Select Quotations**
Considering a more comprehensive scope of risk	"what is the probability of [the event] happening, and if there is a financial cost to the event can the project manage it or handle it" "financiers look at pretty much all of the risks, not that they tend to understand them" "trying to get the financiers to extend the boundary of their thinking and [on] risk"
Leveraging risk mitigation measures	"…[catchment management consideration] needs to be integrated into the project because of the likelihood of greater intensity of rainfall and greater sediment erosion" "Any environmental risk of potential siltation that would affect the capacity of the dam would definitely have to be considered… If actions around catchment conservation are going to keep those risks at bay then you would definitely consider them" "[mismatched time scales and difficult-to-measure impacts means that the positive impact of catchment preservation must] come through very strongly on the operational side of things… in the data that we use to understand what's happening on an operational level"
Diffusing risk and benefits over space, time, and to different actors	"the analysis of different beneficiaries along the way, which is essentially distributing beneficiaries, is a make-or-break in this project" "the larger your user-base the larger your risk spread" "in extremely broad terms you have a revenue driver and a cost driver, and if you are beefing up your revenue drivers you are automatically reducing the risk and making the project more resilient"
Defining roles to achieve multiple objectives	"… [even if the financial sector does not consider them] from a government perspective that impact [of catchment degradation] is real – it will happen in the future and it will be big" "the financiers are looking at financial impacts, but the impacts [may be] on individual communities… The impacts may be well understood, but if it's only impacting one thousand people we might actually ignore it" "a lot of financiers do not think about climate change too much yet… they may decide that if they are getting their money back in 5, 10, or 15 years' time it may not make a huge difference… as long as they can get their money back within 10–15 years…"

References

Apostolakis, G.E., 2004. How Useful Is Quantitative Risk Assessment? Risk Anal. 24, 515–520. https://doi.org/10.1111/j.0272-4332.2004.00455.x.
Arkesteijn, M., van Mierlo, B., Leeuwis, C., 2015. The need for reflexive evaluation approaches in development cooperation. Evaluation 21 (1), 99–115. https://doi.org/10.1177/1356389014564719.
Babovic, F., Babovic, V., Mijic, A., 2018. Antifragility and the development of urban water infrastructure. Int. J. Water Resour. Dev. 34 (4), 499–509. https://doi.org/10.1080/07900627.2017.1369866.
Baird, K., Plummer, R., 2021. Water Resilience: Management and Governance in Times of Change, Water Resilience. Springer. https://doi.org/10.1007/978-3-030-48110-0.

Ben-Haim, Y., 2018. Info-Gap Decision Theory, in: Vincent A. W. J. Marchau Warren E. Walker Pieter J. T. M. Bloemen Steven W. Popper Editors (Ed.), Decision Making Under Deep Uncertainty: From Theory to Practice. Springer, p. 93. https://doi.org/https://link.springer.com/chapter/10.1007/978-3-030-05252-2_5.
Bhave, A.G., Conway, D., Dessai, S., Stainforth, D.A., 2016. Barriers and opportunities for robust decision making approaches to support climate change adaptation in the developing world. Clim. Risk Manag. 14, 1–10. https://doi.org/10.1016/j.crm.2016.09.004.
Blumstein, S., 2017. Integrating Water and Climate Diplomacy in the Orange-Senqu River. Berlin, Germany. https://doi.org/https://www.adelphi.de/en/publication/integrating-water-and-climate-diplomacy-orange-senqu-river.
Briceño, G.C., Smits, K., Foster, V., 2008. Financing Public Infrastructure in Sub-Saharan Africa: Patterns, Issues, and Options. Africa Infrastructure Country Diagnostic, Washington, D.C. https://doi.org/https://openknowledge.worldbank.org/handle/10986/28238.
Briscoe, John, 1999. The Changing Face of Water Infrastructure Financing in Developing Countries. Int. J. Water Resour. Dev. 15 (3), 301–308. https://doi.org/10.1080/07900629948826.
Brown, C., 2011. Decision-Scaling for Robust Planning and Policy under Climate Uncertainty. World Resources Report Uncertainty Series, Washington, D.C. https://doi.org/http://www.worldresourcesreport.org/files/wrr/papers/wrr_brown_uncertainty.pdf.
Buurman, Joost, Babovic, Vladan, 2016. Adaptation Pathways and Real Options Analysis: An approach to deep uncertainty in climate change adaptation policies. Policy Soc. 35 (2), 137–150. https://doi.org/10.1016/j.polsoc.2016.05.002.
Calitz, Estian, Fourie, Johan, 2010. Infrastructure in South Africa: Who is to finance and who is to pay? Dev. South. Afr. 27 (2), 177–191. https://doi.org/10.1080/03768351003740449.
Chester, M., Underwood, B.S., Allenby, B., Garcia, M., Sanders, K., Preston, B., Miller, T.R., Samaras, C., Markolf, S., 2021. Infrastructure resilience to navigate increasingly uncertain and complex conditions in the Anthropocene. npj Urban Sustain. 1 https://doi.org/10.1038/s42949-021-00016-y.
Clapp, C., Alfsen, K., Lund, H., Pillay, K., 2016. Policy Note 2016 : Green Bonds and Environmental Integrity : Insight from CICERO Second Opinions. Oslo. https://doi.org/http://www.cicero.uio.no.
Climate Bonds Initiative, 2017. Climate Bonds Standard, Climate Bonds Standard, Version 2.1. https://doi.org/https://www.climatebonds.net/climate-bonds-standard-v21.
Collier, P., 2014. Attracting international private finance for African infrastructure. J. African Trade 1, 37–44. https://doi.org/10.1016/j.joat.2014.09.002.
Corfee-Morlot, Marchal, V., Kauffmann, C., Kennedy, C., Stewart, F., Kaminker, C., Ang, G., 2012. Towards a Green Investment Policy Framework: The Case of Low-Carbon, Climate-Resiliant Infrastructure (No. 48), OECD Environment Working Papers. Paris. https://doi.org/http://files/26040/5k8zth7s6s6d-en.pdf.
Cremades, R., Surminski, S., Máñez Costa, M., Hudson, P., Shrivastava, P., Gascoigne, J., 2018. Using the adaptive cycle in climate-risk insurance to design resilient futures. Nat. Clim. Chang. 8 (1), 4–7. https://doi.org/10.1038/s41558-017-0044-2.
Cumming, G.S., Cumming, D.H.M., Redman, C.L., 2006. Scale Mismatches in Social-Ecological Systems: Causes, Consequences, and Solutions. Ecol. Soc. 11, art14. https://doi.org/10.5751/ES-01569-110114.
Dawson, D.A., Hunt, A., Shaw, J., Gehrels, W.R., 2018. The Economic Value of Climate Information in Adaptation Decisions: Learning in the Sea-level Rise and Coastal Infrastructure Context. Ecol. Econ. 150, 1–10. https://doi.org/10.1016/j.ecolecon.2018.03.027.
de Neufville, R., Scholtes, S., 2011. Flexibility in Engineering Design. MIT Press. https://doi.org/https://mitpress.mit.edu/books/flexibility-engineering-design.
Department of Water Affairs South Africa, 2012. Development of Reconciliation Strategies for Bulk Water Supply Systems Orange River: Literature Review Report. https://doi.org/https://www.dws.gov.za/iwrp/Orange%20Recon/Docs/Background%20Information%20Document.pdf.
Duru, U., Nyong, A., 2016. Why Africa Needs Green Bonds. https://doi.org/https://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/AEB_Vol_7_Issue_2_Why_Africa_Needs_Green_Bonds.pdf.
Epstein, G., Pittman, J., Alexander, S.M., Berdej, S., Dyck, T., Kreitmair, U., Rathwell, K.J., Villamayor-tomas, S., Vogt, J., Armitage, D., 2015. Institutional fit and the sustainability of social – ecological systems. Curr. Opin. Environ. Sustain. 14, 34–40. https://doi.org/10.1016/j.cosust.2015.03.005.
Falkenmark, Malin, Wang-Erlandsson, Lan, Rockström, Johan, 2019. Understanding of water resilience in the Anthropocene. J. Hydrol. X 2, 100009. https://doi.org/10.1016/j.hydroa.2018.100009.
Fischoff, B., Watson, S.R., Hope, C., 1984. Defining Risk. Policy Sci. 17, 123–129. https://doi.org/https://www.cmu.edu/epp/people/faculty/research/Defining-Risk1984.pdf.
Folke, Carl, Hahn, Thomas, Olsson, Per, Norberg, Jon, 2005. Adaptive governance of social-ecological systems. Annu. Rev. Environ. Resour. 30 (1), 441–473. https://doi.org/10.1146/energy.2005.30.issue-110.1146/annurev.energy.30.050504.144511.
Galaz, V., Crona, B., Dauriach, A., Scholtens, B., Steffen, W., 2018. Finance and the Earth system – Exploring the links between financial actors and non-linear changes in the climate system. Glob. Environ. Chang. 53, 296–302. https://doi.org/10.1016/j.gloenvcha.2018.09.008.
Geels, Frank W., 2002. Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. Res. Policy 31 (8-9), 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8.
Gersonius, Berry, Ashley, Richard, Pathirana, Assela, Zevenbergen, Chris, 2013. Climate change uncertainty: Building flexibility into water and flood risk infrastructure. Clim. Change 116 (2), 411–423. https://doi.org/10.1007/s10584-012-0494-5.
Green Climate Fund, 2015. Consideration of funding proposals – Addendum Funding Proposal Summary for FP004 14, 57. https://doi.org/http://www.greenclimate.fund/documents/20182/87610/GCF_B.11_04_ADD.05_REV.01_-_Funding_proposal_package_for_FP005.pdf/c38034c9-f86f-41b7-bc3a-11f052aba5e0?version=1.0.
Haasnoot, M., Biesbroek, R., Lawrence, J., Muccione, V., Lempert, R., Glavovic, B., 2020. Defining the solution space to accelerate climate change adaptation. Reg. Environ. Chang. 20, 37. https://doi.org/10.1007/s10113-020-01623-8.
Haasnoot, Marjolijn, Kwakkel, Jan H., Walker, Warren E., ter Maat, Judith, 2013a. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Glob. Environ. Chang. 23 (2), 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006.
Haasnoot, M., Kwakkel, J.H., Walker, W.E., ter Maat, J., 2013b. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Glob. Environ. Chang. 23, 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006.
Hall, J.W., Lempert, R.J., Keller, K., Hackbarth, A., Mijere, C., Mcinerney, D.J., 2012. Robust Climate Policies Under Uncertainty: A Comparison of Robust Decision Making and Info-Gap Methods. Risk Anal. 32, 1657–1672. https://doi.org/10.1111/j.1539-6924.2012.01802.x.
Hallegatte, Stéphane, Shah, A., Lempert, R., Brown, C., Gill, S., 2012a. Investment Decision Making Under Deep Uncertainty. Application to Climate Change, Policy Research Working Paper. https://doi.org/10.1596/1813-9450-6193.
Hallegatte, Stephane, Shah, A., Lempert, R., Brown, C., Gill, S., 2012b. Investment decision-making under deep uncertainty—Application to climate change WPS 6193, 41 pp. https://doi.org/10.1596/1813-9450-6193.
Hansen, Rieke, Pauleit, Stephan, 2014. From Multifunctionality to Multiple Ecosystem Services? A Conceptual Framework for Multifunctionality in Green Infrastructure Planning for Urban Areas. Ambio 43 (4), 516–529. https://doi.org/10.1007/s13280-014-0510-2.
Herrfahrdt-Pähle, Elke, 2013. Integrated and adaptive governance of water resources: The case of South Africa. Reg. Environ. Chang. 13 (3), 551–561. https://doi.org/10.1007/s10113-012-0322-5.
IISD, 2021. The Sustainable Asset Valuation (SAVi) [WWW Document]. URL https://www.iisd.org/savi/ (accessed 7.27.21).
IPCC, 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability: Summary for policy makers. Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/cbo9780511976988.002.
Jeffrey, P., Gearey, M., 2006. Integrated water resources management: Lost on the road from ambition to realisation? Water Sci. Technol. 53, 1–8. https://doi.org/10.2166/wst.2006.001.
Jury, Mark R., 2013. Climate trends in southern Africa. S. Afr. J. Sci. 109 (1/2), 1–11. https://doi.org/10.1590/sajs.2013/980.
Kalra, N., Hallegatte, S., Lempert, R., Brown, C., Fozzard, A., Gill, S., Shah, A., 2014. Agreeing on Robust Decisions New Processes for Decision Making Under Deep Uncertainty. World Bank Policy Res. Work. Pap. No. 6906 https://doi.org/10.1596/1813-9450-6906.
Kambites, C., Owen, S., 2006. Renewed prospects for green infrastructure planning in the UK. Plan. Pract. Res. 21, 483–496. https://doi.org/10.1080/02697450601173413.

Kerste, M., Rosenboom, N., Sikken, B.J., Weda, J., 2011. Financing Sustainability: Triggering Investments for the Clean Econ (No. 25), EPSC Strategic Notes.
Keys, P.W., Galaz, V., Dyer, M., Matthews, N., Folke, C., Nyström, M., Cornell, S.E., 2019. Anthropocene risk. Nat. Sustain. 2, 667–673. https://doi.org/10.1038/s41893-019-0327-x.
Kriegler, E., O'Neill, B.C., Hallegatte, S., Kram, T., Lempert, R.J., Moss, R.H., Wilbanks, T., 2012. The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. Glob. Environ. Chang. 22, 807–822. https://doi.org/10.1016/j.gloenvcha.2012.05.005.
Kusangaya, S., Warburton, M.L., Archer van Garderen, E., Jewitt, G.P.W., 2014. Impacts of climate change on water resources in southern Africa: A review. Phys. Chem. Earth 67–69, 47–54. https://doi.org/10.1016/j.pce.2013.09.014.
Kwakkel, Jan H., Walker, Warren E., Haasnoot, Marjolijn, 2016. Coping with the Wickedness of Public Policy Problems: Approaches for Decision Making under Deep Uncertainty. J. Water Resour. Plan. Manag. 142 (3), 01816001. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000626.
Lautze, J., Giodrano, M., 2005. Transboundary Water Law in Africa: Development, Nature, and Geography. Nat. Resour. J. 45, 1053–1087.
Lazurko, A., 2018. Navigating uncertainty and multifunctionality for resilience: Bridging decision making and finance for water structure in the Orange-Senqu River Basin. Master of Science thesis. Central European University, Budapest.
Lebel, Louis, Anderies, John M., Campbell, Bruce, Folke, Carl, Hatfield-Dodds, Steve, Hughes, Terry P., Wilson, James, 2006. Governance and the Capacity to Manage Resilience in Regional Social-Ecological Systems. Ecol. Soc. 11 (1) https://doi.org/10.5751/ES-01606-110119.
Lebel, L., Garden, P., Imamura, M., 2005. The politics of scale, position and place in the governance of water. Ecol. Soc. 10, 18. https://doi.org/18.
Lempert, R.J., 2003. Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis. Santa Monica, CA. https://doi.org/10.1016/j.techfore.2003.09.006.
Lempert, Robert J., Groves, David G., 2010. Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west. Technol. Forecast. Soc. Change 77 (6), 960–974. https://doi.org/10.1016/j.techfore.2010.04.007.
Lienert, J., Schnetzer, F., Ingold, K., 2013. Stakeholder analysis combined with social network analysis provides fine-grained insights into water infrastructure planning processes. J. Environ. Manage. 125, 134–148. https://doi.org/10.1016/j.jenvman.2013.03.052.
Lienert, Judit, Scholten, Lisa, Egger, Christoph, Maurer, Max, 2015. Structured decision-making for sustainable water infrastructure planning and four future scenarios. EURO J. Decis. Process. 3 (1-2), 107–140. https://doi.org/10.1007/s40070-014-0030-0.
Manocha, Nishtha, Babovic, Vladan, 2018a. Sequencing Infrastructure Investments under Deep Uncertainty Using Real Options Analysis. Water 10 (2), 229. https://doi.org/10.3390/w10020229.
Manocha, N., Babovic, V., 2018b. Sequencing Infrastructure Investments under Deep Uncertainty Using Real Options Analysis. Water 10, 229. https://doi.org/10.3390/w10020229.
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 Nature.
Marshall, G.R., Alexandra, J., 2016. Institutional path dependence and environmental water recovery in Australia's Murray-Darling Basin. Water Altern. 9, 679–703.
McDaniels, Timothy, Chang, Stephanie, Cole, Darren, Mikawoz, Joseph, Longstaff, Holly, 2008. Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation. Glob. Environ. Chang. 18 (2), 310–318. https://doi.org/10.1016/j.gloenvcha.2008.03.001.
Mendez, P.F., Isendahl, N., Amezaga, J.M., Santamarea, L., 2012. Facilitating Transitional Processes in Rigid Institutional Regimes for Water Management and Wetland Conservation: Experience from the Guadalquivir Estuary. Ecol. Soc. 17 https://doi.org/10.5751/ES-04494-170126.
Milly, P.C.D., Betancourt, Julio, Falkenmark, Malin, Hirsch, Robert M., Kundzewicz, Zbigniew W., Lettenmaier, Dennis P., Stouffer, Ronald J., 2008. Stationarity is dead: Whither water management? Science (80-.) 319 (5863), 573–574. https://doi.org/10.1126/science:1151915.
Morel, R., Bordier, C., 2012. Financing the transition to a green economy: their word is their (green) bond? (No. 14), CDC Climat Research, Climate Brief: Focus on the economics of climate change.
Norberg, J., Wilson, J., Walker, B., Ostrom, E., 2008. Diversity and Resilience of Social-Ecological Systems. In: Norberg, J., Cumming, G. (Eds.), Complexity Theory for a Sustainable Future. Columbia University Press, pp. 46–80.
O'Neill, Brian C., Kriegler, Elmar, Riahi, Keywan, Ebi, Kristie L., Hallegatte, Stephane, Carter, Timothy R., Mathur, Ritu, van Vuuren, Detlef P., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim. Change 122 (3), 387–400. https://doi.org/10.1007/s10584-013-0905-2.
ORASECOM, 2017. Terms of Reference: Selection of Consultants For Orange-Senqu River Basin Climate Resilient IWRM Investment Plan and Lesotho to Botswana Water Transfer Project.
ORASECOM, 2014a. Integrated Water Resources Management Plan For The Orange-Senqu River Basin.
ORASECOM, 2014b. Water Resources Modelling, Baseline Scenario, Yield Analysis. Stochastic Verification and Validation, Gabarone.
ORASECOM, 2013. Basin-wide Environmental Flow Regime in the Orange-Senqu River Basin. Pretoria.
ORASECOM, 2011a. GCC Downscaling for the Orange-Senqu River Basin. Pretoria.
ORASECOM, 2011b. Projection of Impacts under Plausible Scenarios and Guidelines on Climate Change Adaptation Strategies. Pretoria.
ORASECOM, 2009. A Fitness for Use assessment of the waters of the Orange-Senqu Basin. Gabarone.
Pauleit, S., Liu, L., Ahern, J., Kazmierczak, A., 2011. Multifunctional Green Infrastructure Planning to Promote Ecological Services in the City, in: Urban Ecology: Processes, Patterns and Applications. Oxford University Press, Oxford. https://doi.org/10.1093/acprof:oso/9780199563562.003.0033.
Peterson, Garry D., Cumming, Graeme S., Carpenter, Stephen R., 2003. Scenario planning: A tool for conservation in an uncertain world. Conserv. Biol. 17 (2), 358–366. https://doi.org/10.1046/j.1523-1739.2003.01491.x.
Postel, S.L., Thompson Jr., B.H., 2005. Watershed protection: Capturing the benefits of nature's water supply services. Nat. Resour. Forum 29, 98–108. https://doi.org/10.1111/j.1477-8947.2005.00119.x.
Quinlan, Allyson E., Berbés-Blázquez, Marta, Haider, L. Jamila, Peterson, Garry D., Allen, Craig, 2016. Measuring and assessing resilience: broadening understanding through multiple disciplinary perspectives. J. Appl. Ecol. 53 (3), 677–687. https://doi.org/10.1111/1365-2664.12550.
Ranger, Nicola, Reeder, Tim, Lowe, Jason, 2013. Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project. EURO J. Decis. Process. 1 (3-4), 233–262. https://doi.org/10.1007/s40070-013-0014-5.
Ray, P.A., Brown, C.M., 2015. In: Confronting climate uncertainty in water resources planning and project design: The decision tree framework. https://doi.org/10.1596/978-1-4648-0477-9.
Rockström, J., Falkenmark, M., Allan, T., Folke, C., Gordon, L., Jägerskog, A., Kummu, M., Lannerstad, M., Meybeck, M., Molden, D., Postel, S., Savenije, H.H.G., Svedin, U., Turton, A., Varis, O., 2014. The unfolding water drama in the Anthropocene: Towards a resilience-based perspective on water for global sustainability. Ecohydrology 7 (5), 1249–1261. https://doi.org/10.1002/eco.v7.510.1002/eco.1562.
SADC, 2012. Regional Infrastructure Development Master Plan: Executive Summ.
Salet, Willem, Bertolini, Luca, Giezen, Mendel, 2013. Complexity and uncertainty: Problem or asset in decision making of mega infrastructure projects? Int. J. Urban Reg. Res. 37 (6), 1984–2000. https://doi.org/10.1111/j.1468-2427.2012.01133.x.
Sayers, P.B., Galloway, G.E., Hall, J.W., 2012. Robust decision-making under uncertainty – towards adaptive and resilient flood risk management infrastructure. Flood Risk 281–302. https://doi.org/10.1680/fr.41561.281.
Schindler, Stefan, Sebesvari, Zita, Damm, Christian, Euller, Katrin, Mauerhofer, Volker, Schneidergruber, Anna, Biró, Marianna, Essl, Franz, Kanka, Róbert, Lauwaars, Sophie G., Schulz-Zunkel, Christiane, van der Sluis, Theo, Kropik, Michaela, Gasso, Viktor, Krug, Andreas, T. Pusch, Martin, Zulka, Klaus Peter, Lazowski, Werner, Hainz-Renetzeder, Christa, Henle, Klaus, Wrbka, Thomas, 2014. Multifunctionality of floodplain landscapes: relating management options to ecosystem services. Landsc. Ecol. 29 (2), 229–244. https://doi.org/10.1007/s10980-014-9989-y.
Schmidt, J.J., Matthews, N., 2018. From state to system: Financialization and the water-energy-food-climate nexus. Geoforum 91, 151–159. https://doi.org/10.1016/j.geoforum.2018.03.001.
Sendzimir, Jan, Flachner, Zsuzsana, Pahl-Wostl, Claudia, Knieper, Christian, 2010. Stalled regime transition in the upper Tisza River Basin: the dynamics of linked action situations. Environ. Sci. Policy 13 (7), 604–619. https://doi.org/10.1016/j.envsci.2010.09.005.

Stakhiv, E.Z., 2011. Pragmatic approaches for water management under climate change uncertainty. J. Am. Water Resour. Assoc. 47, 1183–1196. https://doi.org/10.1111/j.1752-1688.2011.00589.x.
Stapelberg, R., 2010. Infrastructure systems interdependencies and risk informed decision making (RIDM): impact scenario analysis of infrastructure risks induced by natural , technological and intentional hazards. Analysis 6, 21–27. https://doi.org/https://doi: 10.1016/j.jup.2016.04.015.
Stirling, A., 2006. Precaution, Foresight and Sustainability: reflection and reflexivity in the governance of technology, in: Vob, J.P., Kemp, R. (Eds.), Sustainability and Reflexive Governance.
Störmer, E., Truffer, B., 2009. Strategic decision making in infrastructure sectors : participatory foresight and strategic planning for sustainable sanitation. Geogr. Helv. 64, 73–80. https://doi.org/10.5194/gh-64-73-2009.
Taleb, N., 2012. Antifragile: Things that gain from disorder. Random House, New York.
Tandi, N., Earle, A., 2015. Financing water infrastructure in Africa: Financing water-related infrastructure development in Africa - what's stopping us? No. 24.
Tandi, N., Earle, A., 2015b. Financing water infrastructure in Africa: Financing water-related infrastructure development in Africa - what's stopping us? (No. Working Paper 24). Stockholm.
UNDP, GEF, 2014. Orange – Senqu River Basin Transboundary Diagnostic Analysis.
Walker, B., Holling, C.S., Carpenter, S.R., Kinzig, A., 2004. Resilience, Adaptability and Transformability in Social – ecological Systems. Ecol. Soc. 9, 5. https://doi.org/10.1103/PhysRevLett.95.258101.
Walker, B.H., 2020. Resilience: what it is and is not. Ecol. Soc. 25, 1–3. https://doi.org/10.5751/ES-11647-250211.
Wang, Y., Zadek, S., Liu, Q., Luo, T., Cong, H., Xu, Y., Xia, H., Chen, C., Pan, D., Zhang, D., 2017. 2017. Progress Report, Establishing China's Green Financial System.
Wardekker, J. Arjan, de Jong, Arie, Knoop, Joost M., van der Sluijs, Jeroen P., 2010. Operationalising a resilience approach to adapting an urban delta to uncertain climate changes. Technol. Forecast. Soc. Change 77 (6), 987–998. https://doi.org/10.1016/j.techfore.2009.11.005.
World Bank, 2014. Project Paper for Small RETF Grant from the Multi-Donor Trust Fund for Cooperation in International Waters in Africa.
World Bank Group, 2017. A UN Environment – World Bank Group Initiative Roadmap for a Sustainable Financial System. World Bank.
World Bank Group, 2016. Lesotho Water Security and Climate Change Assessment.
Zadek, S., Robins, N., 2016. Financing Sustainable Development. Moving From Momentum To Transformation in a Time of Turmoil, Nairobi.
Zeitoun, M., Goulden, M., Tickner, D., 2013. Current and future challenges facing transboundary river basin management. WIREs Clim. Chang. 4, 331–349. https://doi.org/10.1002/wcc.228.