Socio-hydrology from Local to Large Scales: An Agent-based Modeling Approach

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Abstract

For decades, the interaction between water and people has attracted hydrologists' attention. However, the coevolution of social and natural processes, which occurs across a range of time scales, has not yet been adequately characterized. This research gap has motivated more research in recent years under the umbrella of "socio-hydrology". The purpose of socio-hydrology is to posit the endogeneity of humans in a hydrological system and then to investigate feedback mechanisms between hydrological and human systems that might lead to emergent phenomena.

The current state-of-the-art in socio-hydrology faces several challenges that include (1) a tenuous connection of socio-hydrology to broader research on social, economic, and policy aspects of water resources, (2) the (in)capability of socio-hydrological models to capture human behavior by generic feedback mechanisms that can be extrapolated to other places, and (3) unsatisfying calibration or validation processes in modeling. To address the first gap, a socio-hydrology study needs to connect proper social theories on water-related human decision making with a water resource model based on a given context and scale. Addressing the second gap calls for socio-hydrology research with case studies in different and contrasting regions and at different scales. In fact, such study can shed light on the similarities and differences in socio-hydrological systems in different contexts and scales as initial steps for future research. The third research gap calls for a socio-hydrology study that improves calibration and validation processes. Thus, to address all these gaps in one thesis, two case studies with completely different environments are chosen to investigate various phenomena at different scales.

The research presented here contributes to socio-hydrological understanding at two spatial scales. To account for the heterogeneity of human decision making and its interactions with the hydrologic system, an agent-based modeling (ABM) approach is used in this research. The first objective is to explore human adaptation to drought as well as the subsequent expected or unexpected effects on the agricultural sector and to develop a socio-hydrological model to predict agricultural water demand. To do so, an agent-based agricultural water demand model (ABAD) is developed. This model is applied to the Bow River Basin in Alberta, Canada, as a study region, which has recently experienced drought periods. The second objective is to explore conflict-and-cooperation processes in transboundary rivers as socio-hydrological phenomena at a large scale. The Eastern Nile Basin Socio-hydrological (ENSH) model is developed and applied to the Eastern Nile Basin (ENB) in Africa in which conflict-and-cooperation dynamics can be seen among Egypt, Sudan, and Ethiopia. The ENSH model aims to quantify and simulate these countries' willingness to cooperate in the ENB.

ABAD demonstrates (1) how farmers' attitudes toward profits, risk aversion, environmental protection, social interaction, and irrigation expansion explain the dynamics of the water demand and (2) how the conservation program may paradoxically lead to the rebound phenomenon whereby the water demand may increase after decreasing through modernized irrigation systems. Through the ABAD model analysis, economic factors are found to dominantly control possible

rebounds. Based on the insights gained via the model analysis, it is discussed that several strategies, including community participation and water restrictions, can be adopted to avoid the rebound phenomenon in irrigation systems. Fostering farmers’ awareness about the average water use in their community could be a means to avoid the rebound phenomenon through community participation. Also, another strategy to avoid the rebound phenomenon could be to reassign water allocations to reduce farmers’ water rights.

The ENSH model showed that (1) socio-political factors (i.e., relative political stability and foreign direct investment) can explain two historical trends (i.e., (a) fluctuations in Ethiopia’s willingness to cooperate between 1983 and 2009 and (b) a decreasing Ethiopia’s willingness to cooperate between 2009 and 2016); (2) the 2008 food crisis (i.e., Sudan’s food gap) may account for Sudan recovering its willingness to cooperate; and (3) Egypt’s political (in)stability plays a role in its willingness to cooperate.

The outcomes of this research can provide valuable insights to support policymakers for the long-term sustainability of water planning. This research investigates two main socio-hydrological phenomena at different spatial scales: the agricultural rebound phenomenon at a small geographical scale and the conflict and cooperation phenomena at a large geographical scale. The emergence of these phenomena can be a complex resultant of interaction and feedback mechanisms between the social system at the individual, institutional, and society levels and the hydrological system. Through developing quantitative socio-hydrological models, this research investigates the feedback mechanisms that may lead to the rebound phenomenon at a small scale and the conflict and cooperation phenomenon at a large scale. Finally, the research shows how these socio-hydrological models can be used for sustainable water management to avoid negative long-term consequences.

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"Allah is sufficient for me. There is no god except Him. In him, I have put my trust."[1]

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[1] The Qur'an Taubah 9

Dedication

I dedicate this thesis to my family.

In Memory of My Insightful Father…

Table of Contents

List of Figures

List of Tables

List of Abbreviations

Abbreviation	**Explanation**
ABAD	Agent-Based Agricultural Water Demand
ABM	Agent-Based Model
AHD	Aswan High Dam
BC	Basin-wide Cooperation
BRB	Bow River Basin
C&C	Conflict and Cooperation
CFA	Cooperative Framework Agreement
CHANS	Coupled Human and Natural Systems
ENB	Eastern Nile Basin
ENSH	Eastern Nile Basin Socio-hydrological
FDI	Foreign direct investment
GERD	Grand Ethiopian Renaissance Dam
GSA	Global Sensitivity Analysis
HRU	Hydrological Response Unit
IWRM	Integrated Water Resource Management
JMP	Joint Multipurpose Project
NBI	Nile Basin Initiative
NSE	Nash–Sutcliffe efficiency
NSGA	Nondominated Sorting Genetic Algorithm
PDF	Probability Distribution Function
PLHS	Progressive Latin Hypercube Sampling
R	Rebound
SA	sensitivity analysis
SWAT	Soil Water Assessment Tool
TECCONILE	Technical Cooperation Commission for the Promotion and Development of the Nile
VARS	Variogram Analysis of Response Surfaces
WC	Willingness to Cooperate

“We cannot solve our problems with the same thinking we used when we created them.’’

Albert Einstein

Chapter 1

Introduction

1.1 Research Background and Motivation

Hydrology was described by Chow (1964) as the science dealing *“... with the waters of the earth: their distribution and circulation, their physical and chemical properties, and their interaction with the environment, including interaction with living things, and, in particular, human beings.”* Early attempts focused on quantifying hydrological variables (e.g., rainfall, surface runoff, and infiltration) to accurately represent the hydrologic cycle with little attention to anthropogenic influences (Linsley et al., 1975; Sivapalan, 2018). However, as anthropogenic influences have significantly increased due to water resources and land developments, finding a watershed or aquifer without human impacts is difficult (Vörösmarty et al., 2010, 2013).

In 1955, the Harvard Water Program was one of the first to integrate the different disciplines of hydrology, economics, and sociology (Reuss, 2003), leading to the subfield of Water Resource Systems for optimal management of water resources (Maass et al., 1962). In the 1990s, Integrated Water Resource Management (IWRM) was introduced as a process in which societal concerns and hydrology are brought together to sustainably manage water resources while boosting economic efficiency and ensuring equal access to these resources (Global Water Partnership, 2009). At the same time, as efforts were being made to integrate different disciplines in water resource management, several scientists have become interested in the interaction and coevolution of hydrological and social systems – a component that is missing from IWRM. One of the first scientists to bring the interaction between social and hydrological systems to hydrologists’ attention was Falkenmark (1977), who wrote “Water and Mankind: A Complex System of Mutual Interaction.” Falkenmark (1979) advanced the subfield of hydro-sociology to “provide improved analysis of social consequences of water projects” (Falkenmark, 1979). Afterward, several subfields and frameworks emerged to investigate different aspects of the interaction between social and hydrological systems, including Coupled Human and Natural Systems (CHANS), game theory, and socio-hydrology. Although CHANS, hydro-sociology, and game theory involved human-water interaction, socio-hydrology, initiated by Sivapalan et al. (2012), focused mainly on quantitative models of co-evolutionary behaviors of humans and water systems with human decision-making processes.

Socio-hydrology focuses on the co-evolutionary dynamics of social and hydrological systems in which processes (e.g., runoff and crop pattern selection) interact over different time scales (Sivapalan et al., 2012a; Sivapalan & Blöschl, 2015). The coevolution of human decision-making (e.g., crop pattern selection) and hydrological processes (e.g., runoff) in a socio-hydrological system may result in emergent phenomena in the long term (Sivapalan & Blöschl, 2015). As noted by Grimm & Railsback, (2005), emergent phenomena refer to an observed system behavior that cannot be simply explained by the sum of the underlying system properties. The rebound effect in agriculture is an example of these emergent phenomena, which might occur due to modernizing traditional irrigation systems. Although this has long been recognized as a means to reduce water use, empirical evidence shows that this practice may not necessarily reduce water use in the long run; in fact, in many cases, the converse is true—a concept known as the rebound phenomenon (Berbel et al., 2014; Ward & Pulido-Velazquez, 2008).

Emergent phenomena can be place-specific and scale-dependent. In other words, an emergent phenomenon that is found in a few places may not exist in all other places. Also, these phenomena can arise at not only a local scale (e.g., the agricultural sector in a small catchment), but also at a continental or global scale (e.g., transboundary rivers). On both sides of the boundary in a transboundary river, and across the boundary, the cooperation and conflict phenomena can be treated as an emergent phenomenon (Di Baldassarre et al., 2019). This phenomenon can be explained by the complex interaction of hydrological (e.g., runoff), political (e.g., national power), and socio-economic (e.g., potential economic gains from a river) factors (Zeitoun & Warner, 2006; Zeitoun et al., 2011b). The primary purpose of socio-hydrology is to investigate the interactions (feedback mechanisms) between hydrological and human systems and the phenomena that emerge due to these interactions. Therefore, socio-hydrology can help explore why different water management outcomes have emerged, and thus, provides insights into future water planning.

The current research gaps in socio-hydrology can be categorized into three types: (1) the theoretical basis of socio-hydrology, (2) the types of socio-hydrological models adopted, and (3) the use of advanced methods for analyzing socio-hydrological systems. The current state-of-the-art in socio-hydrology is still in its infancy and mostly suffers from a lack of proper connection with broader research on social, economic, and policy aspects of water resources. For example, to link physical flood dynamics to policy response, Di Baldassarre et al. (2015) used social memory as a variable reflecting a society's knowledge about flood hazard decaying over time as a result of building infrastructure that decreases the society's experience with flood hazards. However, although the use of social memory was a good initial step for socio-hydrological models, the social processes defined by Di Baldassarre et al. (2015) are oversimplified compared to the real world. For example, many people adapt to floods based on the media rather than their personal experiences (Gober & Wheater, 2015; Kasperson & Kasperson, 1996). In another example, although the study by Elshafei et al. (2014) showed a reasonable initial step for model developments in socio-hydrology, the lack of general social theories on the social processes is one of the deficiencies of this model. Such models (e.g., Di Baldassarre et al., 2015; Elshafei et al., 2014) mostly used conceptual parameters that cannot be well connected to broader research on the socio-economic aspects of water resources, and thus, collecting data for such models is a challenging task. To connect the state-of-the-art practices in socio-hydrology with broad research in social sciences, choosing a proper human decision-making theory is an important step.

One of the popular and common human decision-making theories is the “rational choice” or “homo economicus” theory in economic theory (Simon, 1978). This theory assumes that humans access perfect information and maximize their utility (Frank, 1987; Monroe, 2001; Simon, 1978). However, this theory is based on idealized assumptions and it is inconsistent with empirical evidence of human decision-making in natural resources (Hukkinen, 2014; Levine et al., 2015; Siebenhüner, 2000; Van Den Bergh et al., 2000). Nevertheless, this theory has been frequently used in human decision-making in natural resources as it is straightforward to be translated into mathematical equations (Kremmydas et al., 2018; Schlüter et al., 2017). The theory of “bounded rationality” is another popular human decision-making theory in economics and psychology disciplines, and is more consistent with the real world (Simon, 1955). As opposed to “rational choice” theory, the theory of “bounded rationality” is based on the assumption that humans are limited to imperfect knowledge about the real world and seek satisficing solutions rather than optimal ones (Epstein, 1999; Gigerenzer & Selten, 2001; Simon, 1955). In fact, the important advantage of the theory of “bounded rationality” over “rational choice” theory is to better capture the observed behavior in reality, as previous studies have quantitatively indicated (e.g., Wens et al., 2020). Compared to the “rational choice” theory, the theory of “bounded rationality” is more complicated to be represented by mathematical equations, and it needs several assumptions by a modeler in a given context (Schlüter et al., 2017). With all challenges associated with the theory of “bounded rationality”, because this theory can better capture the human behavior in the real world, it is important to present a case study that exemplifies its use with a socio-hydrological model to capture emergent phenomena.

Another widespread debate in socio-hydrology is the capability of socio-hydrological models to capture human behavior by generic conceptualized social processes (Di Baldassarre et al., 2015; Gober & Wheater, 2015; Loucks, 2015; Montanari, 2015; Sivapalan, 2015; Troy et al., 2015). In the context of hydrology, physically-based models (e.g., MIKE-SHE and MESH) simulate hydrological processes over grid scales using the universal laws (e.g., the partial differential equations of mass, momentum, and/or energy conservation), and thus they can be extrapolated to other places (Pietroniro et al., 2007; Refsgaard et al., 1995). However, in the context of socio-hydrology, although several studies developed stylized models that reduce coupled human and natural systems into a small number of interconnected subsystems (Di Baldassarre et al., 2015; Srinivasan, 2015; Van Emmerik et al., 2014; Yaeger et al., 2014), a few studies pointed out that human behavior is quite different in various places (Gober & Wheater, 2015; Loucks, 2015). For example, Gober and Wheater (2015) noted that the policy responses to flooding events are widely different in various places based on socio-economic interests (e.g., U.S., U.K., and Canada). Thus, it is interesting to present contrasting case studies showing that different variables and phenomena need to be considered in socio-hydrology, depending on the place, scale, and nature of a problem.

A wide range of model types has been used in socio-hydrology: conceptual models, system dynamics models and agent-based models. As one of the initial modeling steps, conceptual models have been widely used in socio-hydrology (e.g., Giuliano Di Baldassarre et al., 2018; Wens et al., 2019; Westerberg et al., 2017). This model type creates a general understanding of a socio-hydrological system by representing the abstractions of the real world. For example, Wens et al. (2019) proposed a framework that extends the traditional risk modeling approach to capture the feedback mechanisms of the human adaptation decisions and drought exposure, vulnerability, and hazard. Many of these conceptual models in socio-hydrology lack quantitative representation of the system and are not verified by real case studies.

Another type of modeling in socio-hydrology is system dynamics. System dynamics as a top-down approach is used when there is proper knowledge about the entire system (Sterman, 2001). Using this knowledge, researchers attempt to replicate the system structure by modeling system behavior. For example, Gunda et al. (2018) developed a participatory model through a system dynamics approach to investigate the adaptation effect in the agricultural sector and simulate streamflow under climate change. This participatory modeling enabled them to involve the community experiences and information in their model.

On the other hand, using agent-based modeling as a bottom-up approach, researchers attempt to explore possible emergent behaviors and system pathways by simulating all agents and their possible interactions (Wilensky & Rand, 2015). Conventional agent-based models have been built based upon optimization (maximization of benefits) (e.g., Ng et al., 2011; Schreinemachers & Berger, 2006, 2011), heuristics (decisions based only on past experience) (e.g., Barreteau et al., 2004; Kerridge et al., 2001), or surveys (e.g., Castella et al., 2005; Dia, 2002) for decision-making principles. For example, Noël and Cai (2017) used agent-based modeling to explore the role of individual farmers in groundwater exploitation. This approach enabled them to capture the heterogeneity in farmers' decision-making. Other studies have conducted statistical analysis for model parameterization or to investigate relationships among system components (Breyer et al., 2018; Marston & Konar, 2017). For example, Breyer et al. (2018) explored the adaptation effect in Austin, Texas and showed the influence of water conservation on runoff in response to drought.

The use of advanced methods for analyzing socio-hydrological systems is an important challenge in existing socio-hydrological models. Due to the limited historical socio-economic data, many of the models lack proper calibration and validation processes (e.g., Di Baldassarre et al., 2017; Garcia et al., 2016; Giuliani et al., 2016). Gaps in spatio-temporal data of climate, hydrology, economics, and policy lead to large uncertainties in model output (Gleick et al., 2013; Nazemi & Wheater, 2015b; Wood et al., 2011). For example, limited data are available on local and global actual water use in different sectors (Nazemi & Wheater, 2015b, 2015a). Therefore, some studies have captured the observed general dynamics of the socio-hydrological systems rather than mere observations (e.g., Ciullo et al., 2017). Moreover, another challenge is the lack of quantitative data on some social variables such as cooperation and conflict (Lu et al., 2021). Therefore, modelers in the socio-hydrological context often need to be innovative in model validation (Gonzales & Ajami, 2017a). Among different modeling approaches, the calibration and validation processes are more challenging in the agent-based modeling approach for several reasons. First, this approach requires intensive data to represent the heterogeneity in the socio-hydrological system. Second, as a bottom-up approach, the agent-based model usually possesses a relatively high number of parameters.

Third, due to the stochastic feature in agent modeling, such models generate different results in each model run, so the calibration and validation process is challenging in such models.

Another research gap in the use of advanced methods for analyzing socio-hydrological systems is an under-appreciation of the need for proper sensitivity analysis (SA) of models developed. SA quantifies how model outputs are influenced or controlled by variations in model inputs (Razavi et al., 2021). Although SA applications have been widely used in hydrology (e.g., Razavi & Gupta, 2019; Sheikholeslami et al., 2021), little attention has been paid to the SA of feedback loops between the human and hydrological systems (Elshafei et al., 2016; Wens et al., 2020). Due to the complex behavior of socio-hydrological systems and high interactions among components, one fundamental research gap is to indicate factor importance in the variability of model behavior with feedback loops between the human and hydrological systems. Therefore, an analysis of the sensitivity of socio-hydrological models to different endogenous system properties and exogenous socio-hydrological contexts can provide insights into the co-evolutionary dynamics of emergent phenomena (e.g., agricultural rebound phenomenon), thus, informing future water planning.

1.2 Research Objectives

With the growing complexity of coupled human and natural systems, socio-hydrology has focused on the co-evolutionary behavior between human and hydrological systems that can lead to emergent phenomena. However, as discussed, the current state-of-the-art in socio-hydrology faces several challenges that include (1) a tenuous connection of socio-hydrology to broader research on social, economic, and policy aspects of water resources, (2) the (in)capability of socio-hydrological models to capture human behavior by generic feedback mechanisms that can be extrapolated to other places, and (3) unsatisfying calibration or validation processes in modeling. To address the first gap, a socio-hydrology study needs to connect proper social theories with a water resource model based on a given context and scale. These theories define how humans make water-related decisions, which impact a hydrological system. Addressing the second gap calls for socio-hydrology research with case studies in different and contrasting regions and at different scales. In fact, such research can shed light on the similarities and differences in socio-hydrological systems in different contexts and scales. Thus, as an initial step, such a study can pave the way for future research to investigate similarities in conceptualizing a socio-hydrological system in different regions and at different scales, and thus search for potential generic social processes. The third research gap calls for a socio-hydrology study that improves calibration and validation processes. Due to the limited quantitative data on some emergent phenomena (e.g., cooperation and conflict), such research can provide innovative calibration and validation processes for different emergent phenomena at different scales. Thus, to address all these gaps in one thesis, two case studies with completely different environments are chosen to investigate various phenomena at different scales.

The overarching goal of this thesis is to provide a better understanding of coupled human and hydrological systems by investigating: (1) the feedback mechanism for specific emergent phenomena (i.e., the agricultural rebound phenomenon and the cooperation and conflict phenomena) in different contexts and at different scales, (2) calibration and validation processes for socio-hydrological models, (3) the important factors that control those phenomena, and (4) the practical strategies that policymakers can use to avoid those phenomena. In other words, the first information gap on any emergent phenomenon is why it emerges and what factors play significant roles in the phenomenon. These questions are addressed in socio-hydrology by developing quantitative models and system analyses. These models need to be innovatively calibrated and validated with limited quantitative data. After developing such models, the important question is what practical strategies can be designed out of these complex and mathematical models for sustainable water management. Indeed, using socio-hydrological models, designing these strategies is a way to communicate with policymakers and help them with their decision-making on sustainable water management.

To achieve the overarching goal of this thesis, two case studies with completely different environments are chosen: (1) The Bow River Basin (BRB) in Alberta, Canada and (2) the Eastern Nile Basin (ENB) in Africa, which includes Ethiopia, Sudan, and Egypt. The former is from a prosperous and developed country and is bounded within one jurisdiction (i.e., the province of Alberta) with a cold environment. The latter is from an economically and technologically challenged region, characterized by a hot climate with a shortage in basic needs and a high population growth rate. It is part of a transboundary river with a history of conflicts and is charged with multidimensional environmental, socio-economic, and political motivations.

The first case study (BRB) helps look into and simulate changes in cropping patterns and irrigation systems, and their effects on agricultural water demand in the BRB under drought and regulatory policies. This analysis will provide a new way of understanding the co-evolutionary dynamics of agricultural water demand and pave the way for future sustainable water planning. The second case study (ENB) helps investigate the feedback mechanisms of the cooperation and conflict phenomenon in a transboundary river.

Based on the defined overarching goal, the next sub-sections outline the three specific objectives of this thesis that are broken into three manuscripts. These sub-sections also provide information on how the selected case studies pave the way for this dissertation to achieve its research objectives.

1.2.1 Simulating the Long-term Agricultural Water Demand under Human Adaptation to Drought

Although a few agricultural socio-hydrological models have been developed (Becu et al., 2003; Berger & Troost, 2014; Kandasamy et al., 2014; Pande & Savenije, 2016), the remaining gap is to investigate the dynamics of agricultural irrigation water demand in the long term in response to drought conditions and the potential agricultural rebound phenomenon. Indeed, This complexity cannot be explored by traditional agricultural water demand models because these models consider the effects of water conservation policies (e.g., changing crop patterns and water-saving technologies) through different scenarios (Hejazi et al., 2014; Tubiello & Fischer, 2007).

Therefore, to capture the complexity of co-evolving human-hydrological systems, the agricultural water demand modeling needs to be simulated through socio-hydrological modeling.

The BRB's major water users are agricultural districts, the city of Calgary, industries, and hydropower. The province of Alberta, including BRB, has been impacted several times by considerable droughts in the last decades (Khandekar, 2004). As a reaction to these droughts, both the government and farmers adapted their behavior to address the drought situations, impacting water demand in agricultural sectors (Alberta Irrigation Projects Association, 2015). In particular, in 2005, the government of Alberta initiated the Water for Life program that intended to decrease the agricultural water demand by 30% through conservation, productivity, and efficiency by the year 2015 relative to the levels in 2005. To achieve this goal, this program used several measures, including upgrading on-farm irrigation systems and changing crop patterns (Alberta Irrigation Projects Association, 2015).

To fulfill the first objective of this thesis on investigating the effect of human adaptation on agricultural water demand, an agent-based agricultural water demand (ABAD) model is developed for the BRB. The model development is followed by multi-objective calibration and validation. This agent-based model simulates water demand at the level of the individual farmers, as agents, and captures their interactions within a socio-hydrological system. The use of the agent-based model enables this research to consider the heterogeneity in human decision-making.

1.2.2 The Use of Global Sensitivity Analysis for a New Way of Understanding the Long-term Agricultural Water Demand Dynamics

After investigating the essential socio-economic factors in farmers' decision-making for water demand and the underlying feedback loops among the human and water systems, an important question is how to avoid the agricultural rebound phenomenon. This important issue calls for an explicit evaluation of the co-evolutionary dynamics and interactions among socio-economic factors that would prevent the agricultural rebound phenomenon. Time-varying global sensitivity analysis (GSA), as a powerful method for systems analysis (Razavi & Gupta, 2019), can unravel the extent to which different time-varying dimensions of co-evolutionary dynamics influence the rebound phenomenon.

The application of GSA to coupled human-natural systems can be found in the literature of agent-based models (e.g., Becu et al., 2003; Brown & Robinson, 2006; Burke et al., 2006; Li & Liu, 2007; Ligmann-Zielinska & Sun, 2010; Schlüter & Pahl-Wostl, 2007). The past studies mostly used a time-invariant model output or an aggregated model output as a system response for sensitivity analysis (An et al., 2005; Becu et al., 2003; Schlüter & Pahl-Wostl, 2007). These system responses can result in a loss of valuable information about the time-varying nature of the model behavior and cannot provide comprehensive insight into the co-evolutionary dynamics of the underlying system (Ligmann-Zielinska & Sun, 2010; Richiardi et al., 2006; Wagener et al., 2001). Time-varying GSA offers detailed information on how variability in model factors affects the dynamics of the model outputs (Gupta & Razavi, 2018; Ligmann-Zielinska & Sun, 2010; Razavi & Gupta, 2019). Therefore, this type of analysis can deepen the understanding of the co-evolutionary dynamics of complex phenomena in water management, thus, providing insights into future water planning.

To achieve the second objective of this thesis on identifying the influential socio-economic factors in the agricultural rebound phenomenon, the previously calibrated ABAD model that is developed in the first part of this thesis is used. This study performs a time-dependent variance-based global SA on the ABAD model to examine the direct impact of socio-economic factors as well as their joint influence due to interactions on the rebound phenomenon.

1.2.3 Simulating the Cooperation and Conflict Phenomenon in a Transboundary River Basin

Conflict and cooperation phenomena in transboundary water resources have been widely investigated in different contexts. Studies include those focused on resolving conflicts (e.g., Madani et al., 2014; Rogers, 1969; Zarezadeh et al., 2012), analyzing conflict and cooperation (e.g., Mirumachi & Van Wyk, 2010; Wolf, 2007; Wolf et al., 2003), and investigating influential factors in conflict and cooperation (e.g., Dinar et al., 2010; Zeitoun et al., 2011). A question in socio-hydrology research arises about why conflict and cooperation dynamics emerge in a socio-hydrological system and how these dynamics evolve over time (Di Baldassarre et al., 2019). Importantly, socio-hydrology aims to quantitatively explain the cooperation and conflict dynamics as a problem that arises from the co-evolutionary behavior of hydrological and socio-political systems. The ultimate goal of this exploration is to investigate how a socio-hydrological model can be used for future sustainable water planning to avoid conflicts in a transboundary river basin.

Traditional studies in the Nile River basin have concentrated on the trade-offs among the riparian countries' interests as a water apportionment problem (Arjoon et al., 2014; Block & Strzepek, 2010; Digna et al., 2018; Geressu & Harou, 2015; Jeuland & Whittington, 2014; Kahsay et al., 2015; Nigatu & Dinar, 2016; Sangiorgio & Guariso, 2018; Strzepek et al., 2008; Wheeler et al., 2018, 2020, 2016). However, an important research gap is to quantitatively explain the cooperation and conflict dynamics in the history of the ENB with the co-evolutionary behavior of hydrological and socio-political systems, and thus, investigate basin-wide cooperation opportunities.

The last part of this study aims to quantify and simulate the riparians' willingness to cooperate in the ENB, and thus the basin-wide cooperation dynamics as a problem that is hypothesized to arise due to the interaction of hydrological and socio-political factors. By developing a socio-hydrological model, this study explains how hydrological and socio-political factors can lead to the dynamics of cooperation in the ENB from 1983 to 2016. This study ultimately proposes a socio-hydrological transboundary framework that indicates how the developed model can be coupled with a water resources model. This framework can enable future studies to explore the evolution of cooperation pathways among the riparians, which can highlight actions leading to conflict in the ENB.

1.3 Thesis Outlines

This thesis is a paper-based thesis that contains published or submitted papers in peer-reviewed journals. The titles of these papers are reflected in the titles of **Chapters 2-4**. **Chapter 1** introduces the research background, motivation, and the objective of the dissertation. **Chapter 2** develops an agent-based model to simulate the agricultural water demand in the BRB. This developed model is used in **Chapter 3** to conduct a GSA and provide insights for avoiding the potential agricultural rebound phenomenon. **Chapter 4** simulates the cooperation and conflict phenomenon in the ENB and provides a transboundary socio-hydrological framework to explore the evolution of coordination pathways among the riparians. Finally, **Chapter 5** concludes the findings of this dissertation that includes contrasting case studies at different scales, and it outlines similarities and differences between the socio-hydrological studies.

Chapter 2

Understanding Human Adaptation to Drought: Agent-Based Agricultural Water Demand Modeling in the Bow River Basin, Canada

This chapter is a slightly modified version of the following paper to increase its consistency with the body of the Thesis. References are unified at the end of the dissertation.

Ghoreishi, M., Razavi, S., & Elshorbagy, A. (2021). Understanding human adaptation to drought: agent-based agricultural water demand modeling in the Bow River Basin, Canada. *Hydrological Sciences Journal*, *66*(3), 389-407. https://doi.org/10.1080/02626667.2021.1873344

Synopsis

The farmers in the Bow River Basin (BRB), Canada, have adopted water conservation strategies to reduce water needs. This reduction, however, encouraged irrigation expansion, which may rebound agricultural water demands. This paradox requires an understanding of human adaptation to drought by mapping individual farmers' water conservation decisions to the dynamics of the basin-wide water demand. We develop an agent-based agricultural water demand (ABAD) model, simulating farmers' behavior in adopting new on-farm irrigation systems and/or changing crop patterns in response to drought conditions in the BRB. ABAD demonstrates how (1) farmers' attitude towards profits, risk-aversion, environmental protection, social interaction, and irrigation expansion explains the dynamics of the water demand and (2) the conservation program may paradoxically lead to the rebound phenomenon. ABAD, subject to its conceptualization limitations, can be used for exploration and scenario analysis of future agricultural water demand in response to water conservation programs in the BRB.

2.1 Introduction

As extreme events, such as drought, have become increasingly widespread, human behaviors have evolved, impacting both water supply and demand (Gonzales & Ajami, 2017a; Sivapalan & Blöschl, 2015). Policymakers have managed water demand in many regions for adaptation to drought. Water demand in many urban areas has reduced due to drought-related actions (Booysen et al., 2018; Quesnel & Ajami, 2017). In the same way, farmers have adapted to drought using several strategies, including water-saving technologies and changing crop patterns, to reduce agricultural water demand. However, this reduction can result in farmers' motivation to expand the irrigation area, which might result in rebounding agricultural water demand as an emergent phenomenon. Such rebound phenomena have been observed in Spain and China (Berbel et al., 2014; Song et al., 2018). Farmers have carried out these water conservation activities for several socio-economic reasons, including conservation purposes, maximizing profits, risk-aversion, environmental protection, and social influence (Hoag et al., 2012; Nowak, 1992; Wheaton et al., 2005). These socio-economic factors change over time (Elshafei et al., 2014; Garcia et al., 2016b; Liu et al., 2014; Roobavannan et al., 2018) through feedback loops between hydrological and human systems, leading to considerable complexity for water management modeling (Razavi et al., 2020). The co-evolutionary dynamics between hydrological and human systems have been recently investigated using socio-hydrological models, highlighting the role of humans in human and natural systems. The socio-hydrological models can provide a better understanding of complex phenomena in agricultural water demand due to evolving farmers' behavior (Van Emmerik et al., 2014), thereby, enabling policymakers to enhance long-term water planning.

The socio-hydrological models have increasingly focused on an interaction between human and hydrological systems (Pande & Sivapalan, 2017; Roobavannan et al., 2018; Sivapalan et al., 2012b). Several studies have investigated the endogeneity of humans within water systems in several ways: by incorporating socio-economic drivers (Elshafei et al., 2014; Giacomoni et al., 2013; Veena Srinivasan, 2015), or employing concepts such as social memory (Di Baldassarre et al., 2013; Gonzales & Ajami, 2017a) and collective behaviors (Du et al., 2017a; Garcia et al., 2016b). In contrast to these studies that account for the two-way interactions of water and humans, other studies have investigated only cause-and-effect mechanisms between hydrological and human systems (Quesnel & Ajami, 2017; Roby et al., 2018; Yoshikawa et al., 2014; Zhang et al., 2014).

Many socio-hydrological studies have focused on agricultural water systems (Becu et al., 2003; Berger & Troost, 2014; Kandasamy et al., 2014; Pande & Savenije, 2016). However, investigating the dynamics of agricultural water demand in response to drought conditions through socio-hydrological modeling remains elusive. To model agricultural water demand, the traditional models consider the effects of water conservation policies (e.g., changing crop patterns and water-saving technologies) through different scenarios (Hejazi et al., 2014; Tubiello & Fischer, 2007). However, these traditional models cannot explain the complexity of co-evolving human-hydrological systems, because the scenarios are considered explicitly in modeling (Sivapalan et al., 2012b); i.e., exogenous set of variables that are not dynamically updated based on feedback from the human interaction with the water system. Therefore, to capture the complexity of co-evolving human-hydrological systems, the agricultural water demand modeling needs to be simulated through socio-hydrological modeling.

System dynamics and agent-based models have attracted attention as tools for developing socio-hydrological models that account for the feedback loops between human and hydrological systems (An, 2012; Berglund, 2015; Di Baldassarre et al., 2013; Garcia et al., 2016; Gonzales & Ajami, 2017a). System dynamics as a top-down approach is used when there is comprehensive knowledge about the entire system and its governing equations. Using this knowledge, researchers attempt to replicate the system structure by modeling system behavior. On the other hand, agent-based modeling, as a bottom-up approach, starts a simulation at the level of an autonomous entity, an agent, which might be a member of a heterogeneous group. By simulating all agents and their possible interactions, researchers attempt to explore possible emergent behaviors and system pathways. Therefore, to account for both heterogeneity and possible interactions in a complex socio-hydrological system, we use agent-based modeling in this study.

A considerable amount of literature has been published on the application of Agent-Based Models (ABMs) in agricultural systems (Groeneveld et al., 2017; Kremmydas et al., 2018). Conventional agent-based models have been built based upon optimization (maximization of benefits) (e.g., Ng et al., 2011; Schreinemachers & Berger, 2006, 2011), heuristics (decisions only based on the past experience) (e.g., Barreteau et al., 2004; Kerridge et al., 2001), or surveys (e.g., Castella et al., 2005; Dia, 2002) in support of decision-making in a range of contexts including farming (Kremmydas et al., 2018). However, many researchers have argued that these principles are based on simplified rules or the rational behavior (Jager et al., 2000; Parker et al., 2003; Wilensky & Rand, 2015). For example, the "rational choice" theory has been frequently used to explain human decision-making about natural resources, including hydro-economy, as it is simple and straightforward to be translated into mathematical equations (Kremmydas et al., 2018; Schlüter et al., 2017). However, this theory is based on idealized assumptions that are inconsistent with empirical evidence of human decision-making (Hukkinen, 2014; Levine et al., 2015; Siebenhüner, 2000; Van Den Bergh et al., 2000). Using an agent-based model, Wens et al. (2020) indicated that the theory of "rational choice" underestimates the farmers' profits compared to historical data in response to drought conditions; thus, farmers' adaptation to drought cannot be explained by economic factors alone. The authors noticed that human adaptation to drought can be better explained by the theory of bounded rationality. In this study, we use the theory of bounded rationality to address the shortcomings of the "rational choice" theory. This theory implies that humans make decisions with limited rationality; therefore, they look for satisficing solutions rather than optimal ones. In this regard, agent-based modeling enables us to use such social theories as this approach starts simulations at the level of an individual agent.

This study builds on the methodology previously developed by Dziubanski (2018) and Dziubanski et al. (2019), and applies it in the context of droughts. Dziubanski (2018) and Dziubanski et al. (2019) built an ABM to simulate flooding in which the "city agent" subsidizes "farmer agents" to convert their irrigated land into conservation in Iowa, USA. These farmer agents decide to switch to conservation based on factors on profits, past land use, and willingness. Using different scenarios, Dziubanski (2018) and Dziubanski et al. (2019) showed how flooding could be controlled while human responses co-evolve as a result of changing hydrological conditions. This study modifies and adapts that study to investigate the rebound phenomenon in agriculture in the drought context as a significant gap in socio-hydrology. Many of the previously developed socio-hydrological models are "stylized" in that they lack necessary analyses for credible model development, such as calibration, validation, parameter uncertainty, and sensitivity analysis. Therefore, our study intends to contribute to this area.

In this study, we look at the change in cropping patterns, irrigation systems, and their effects on agricultural water demand in the Bow River Basin (BRB), located in Alberta, Canada, as it has experienced drought in recent years. The objective of this paper is to better understand the complexity of a socio-hydrological system in farmers' adaptation to drought under water-saving technologies and changing crop patterns. To fulfill this purpose, we develop an agent-based model for simulating individual farmers, as agents, and their interactions in their community.

2.2 A Brief Overview of Water Resources Management in Alberta – Case Study

BRB, one of the important sub-basins of the South Saskatchewan River, Canada, accounts for 43% of its 9.5 billion cubic meters of average annual flow (Bow River Basin Council, 2010). This river basin's major water users are agricultural districts, the city of Calgary, industries, and hydropower. The hydrological system of BRB is made up of three main parts: mountains, foothills, and prairies (see Figure A.1 in the supplementary material). The main water sources are snowmelt (contribution of 80% to the annual streamflow), rain, groundwater, and glacial melt (Turner et al., 2005), with the annual precipitation of 412 millimeters in Calgary (78% of this precipitation is rain) (Bow River Basin Council, 2010). With the full allocation of this limited water supply, the BRB authority has not accepted new applications for water allocations since 2006 (Alberta Queen's Printer, 2000).

In 1999, the Water Act changed the prior-allocation system in Alberta to address water scarcity issues (Alberta Queen's Printer, 2000). Before this change, in periods of water shortage, senior licenses took precedence over more recent (junior) licenses. This principle was called "first in time, first in right" (FITFIR). Through the Water Act, all domestic water use has the priority above all other licenses, regardless of the priority of the senior licenses. While the Water Act maintained the previous allocation, the new licenses were typically issued for five years. In 2001, the total water allocation exceeds the total water availability in the South Saskatchewan River basin as a result of the severe drought (J. J. Schmidt, 2007). In response to this severe drought, a water-sharing program was initiated in which irrigation districts voluntarily withdrew 60% of their baseline consumption, thereby enabling all the licenses in the South Saskatchewan River basin to be partially filled (Rush et al., 2004). The experience of the drought in 2001 declared that a few irrigation districts of the South Saskatchewan River basin are over-allocated — junior licenses are at the risk of not being filled in drought (Shapiro & Summers, 2015). In response, in 2006, the South Saskatchewan River Basin Water Management Plan recommended that no new allocations should be allowed in this river basin (Alberta Environment, 2006).

2.3 History of Drought and Drought Policies in Alberta – Case study

The province of Alberta, including BRB, has been impacted several times by considerable droughts in the past nine decades (Figure 2.1). The Alberta drought in the 1930s, known as "Dirty Thirties," was very severe, resulting in severe impacts on Alberta's crops and considerable emigration (Environment and Parks, 2017). Starting in 1979, another series of droughts, as severe as the 1930s drought, devastated parts of Alberta: 1984 marked the driest year since 1916 (Water & Project, 2017), and the 2001-2002 drought caused Can$5.8 billion in damage and 41,000 job losses in agriculture (CBC News, 2009; Sauchyn et al., 2010). Alberta experienced a severe drought in 2009-2010 that caused an emergency situation in 10 counties located in central Alberta when they suffered from the lowest precipitation in 50 years (Water & Project, 2017). Alberta recently experienced other droughts in 2015 and 2017 ("2017 Annual Report of Agroclimate Conditions Across Canada - Agriculture and Agri-Food Canada (AAFC)," 2017; King, 2015).

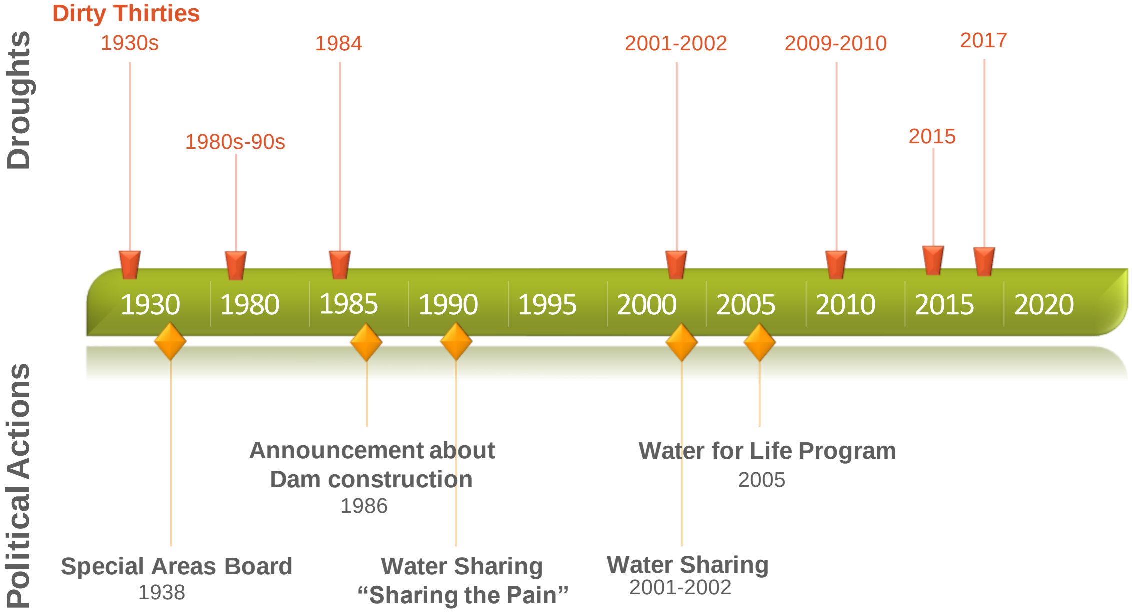

Figure 2.1 Timeline of droughts in Alberta and the related political actions

As a result of these droughts, both the government and local people adapted their behavior to address the drought situations (Figure 2.1), impacting water demand in industrial, urban, and agricultural sectors. In the 1930s, the government of Alberta created the Special Areas Board to govern the areas affected by the drought ("Drought in 20th Century Alberta," 2018). Because of the decreased water supply caused by the droughts of the 1980s and 1990s, major water users in the BRB decided to share the available water under the idea of "sharing the pain" although they could have used their water licenses based on the priority systems under the Water Resource Act (AMEC Earth & Environment, 2009). In addition to this water sharing, the government of Alberta announced the construction of the Oldman River Dam in 1986 ("Drought in 20th Century Alberta," 2018), and water sharing also arose in the basin during the 2001-2002 drought (AMEC Earth & Environment, 2009; Nicol & Klein, 2006). Because of water shortage in 2001-2002, it was determined that the water storage only supported the water license holders with the priorities before 1950, resulting in the suspension of water diversions for the remaining water license holders. The water users in the Oldman River basin finally decided to share the available water and the economic consequences. The experience of the drought in the 1980s and 2001 indicated that "the well-being of water users in the region as-a-whole takes precedence over individual prosperity" (AMEC Earth & Environment, 2009).

To achieve water security objectives, the government of Alberta announced the Water for Life Program in 2005 (Alberta Irrigation Projects Association, 2015). This program emphasized the need to decrease the water demand by 30% through conservation, productivity, and efficiency by the year 2015 relative to the levels in 2005, which was achieved through several measures, including upgrading on-farm irrigation systems and changing crop patterns (Alberta Irrigation Projects Association, 2015). This program was renewed in 2008 to run until 2018 (Alberta Environment, 2008). The government of Alberta partially subsidized the farmers to switch from less efficient irrigation systems like flood irrigation to more efficient ones like sprinklers; therefore, the areas under flood irrigation systems continuously decreased until 2015 (Figure 2.2c). In addition to the irrigation system improvement, the goal of the Water for Life Program was achieved by changing the crop types to those requiring less water to grow. The crop patterns in BRB were switched from forage to other crops like cereals, oilseeds, and specialty crops (e.g., potato), which require 150 to 200 mm less water during the growing season (Figure 2.2a). Although this policy enabled farmers to initially reduce their water demand, farmers were motivated to use the saved water to expand their irrigation to increase their revenue (Figure 2.2b), thereby gradually rebounding agricultural water demand after 2010 (Figure 2.2d). It is worth mentioning that the sudden drop in 2010 is due to an extremely wet year (Diaz et al., 2016). This emergent pattern in water demand occurred by not only hydrological factors (i.e., drought) but also socio-economic effects (i.e., water conservation).

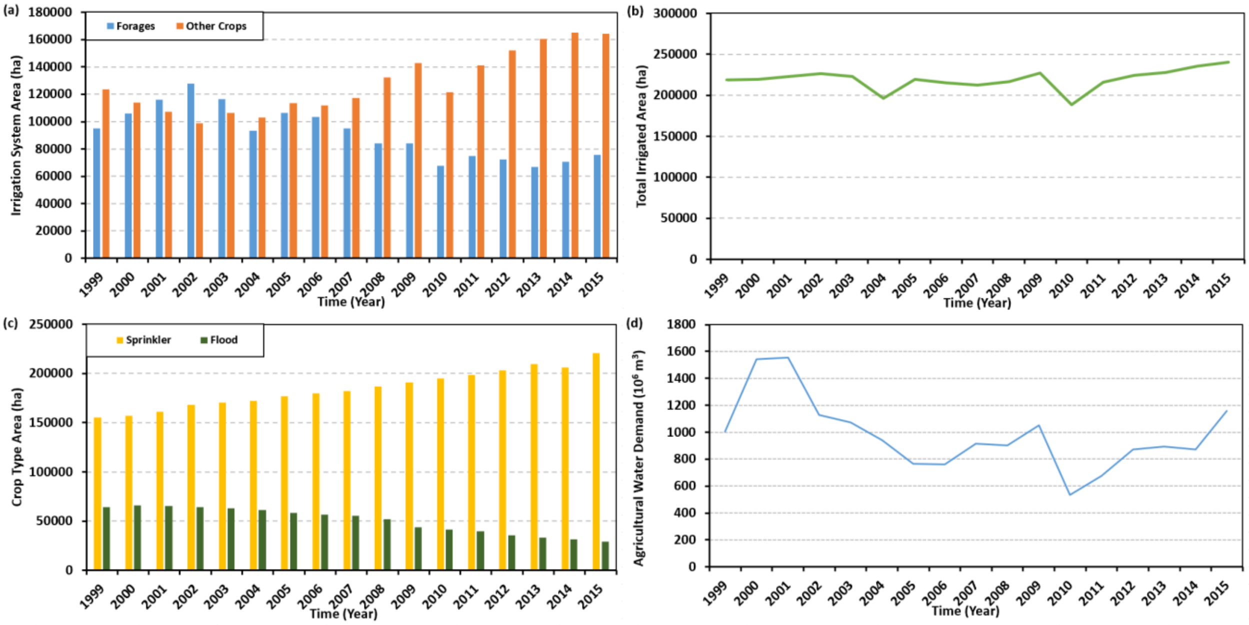

Figure 2.2 (a) the crop type areas in BRB from 2005 to 2015, (b) the total irrigated area in BRB from 2005 to 2015, (c) the irrigation system areas in BRB from 2005 to 2015, and (d)the agricultural water demand in BRB from 1999 to 2015 (Source: Alberta Agriculture and Rural Development 2015).

The previous studies have shown important socio-economic factors in water conservation decisions in BRB, using surveys of farmers (Kulshreshtha & Brown, 1993, 1994; L. A. Nicol et al., 2008). Kulshreshtha and Brown (1993) showed the importance of economic and environmental protection factors in the farm-level decision to adopt a new irrigation system. They indicated that the farmers adopt a new irrigation system with a positive role of the economics of irrigation and environmental quality (e.g., soil salinity). In addition, Kulshreshtha & Brown (Kulshreshtha & Brown, 1994) revealed the significance of government grants, as an economic motivation, and the farmers' neighbors in the farmers' decision making. This finding is consistent with that of Ramirez (2013), who showed the key influence of social networks on agricultural technology adoption. In addition, the results of the past studies (Kulshreshtha & Brown, 1993, 1994) were supported by the finding of Nicol (2008), who particularly emphasized that the level of economic factors is an important element in the Alberta's Water for Life Program. Moreover, this study showed that irrigation expansion is another motivation for farmers in Alberta's Water for Life Program. The complexity of this behavior motivated us to map the relationship between the macro-scale outcomes (i.e., the dynamics of water demand) and micro-scale decisions (i.e., individual farmers' water conservation decisions) in BRB using an agent-based modeling approach.

2.4 A Conceptual Model for Complex Agricultural Water Systems

According to the observation in BRB, we only conceptualized the feedback mechanisms associated with the potential rebound phenomenon to capture the co-evolutionary dynamics of social and hydrological systems. Feedback loops emerge in complex agricultural water systems because water conservation affects water availability in a river basin, which in turn affects water conservation. Upgrading the irrigation system and changing cropping patterns are considered as water conservation measures in this study, which are partially subsidized by policymakers. Figure 2.3 shows two causal loops in the complex agricultural water system. The causal loop diagram, the foundational structure of systems thinking, represents the causes, the effects, and their relations in a system (Ford & Ford, 1999). This diagram, which depicts a closed chain, can be a balancing loop (-) or a reinforcing loop (+). The odd numbers of negative links lead to a balancing loop; on the other hand, the even numbers of negative links result in a reinforcing loop. These negative links represent the opposite direction of a change between two variables, while the positive links show the same direction of change. The first loop shows the relations between water availability, crop yield, gross margin, water conservation, and agricultural water demand. This causal loop shows how water conservation affects water availability in a river basin. Drought as an extreme event (not shown in the Figure) affects water availability, leading to a decrease in farmers' crop yields and gross margins. As a result, farmers adapt to a new situation by water conservation through policymakers' subsidy and self-finance, resulting in a decrease in water demand. However, this water conservation, which can increase water availability in a river basin, might encourage farmers to increase their irrigated area. This increase in the irrigated area could increase agricultural water demand, resulting in a reduction in water availability through the other loop. Using systems thinking, these feedback loops can finally result in rebounding water demand in the system. Therefore, this complex behavior should be considered in agricultural water demand modeling.

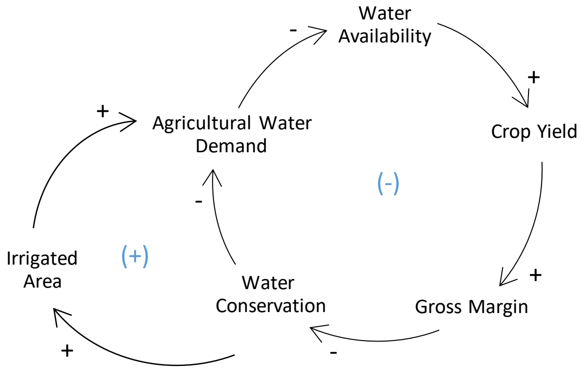

Figure 2.3 Feedback loops in a complex agricultural water system

2.5 Methods

ABAD simulates yearly agricultural water demand from 1999 to 2015, and it has two submodels: The human submodel and the water submodel. In this study, we used Netlogo as a tool because of its important features: open source code, free availability, supportive documentation and community, and a good connection with R. The connection of Netlogo with R paves the way for further model analyses (e.g., calibration and sensitivity analysis) as Netlogo provides limited capabilities for analyzing ABMs.

2.5.1 Model Overview

The human submodel focuses on the agricultural sector (only irrigated areas), including individual farmers as agents (Figure 2.4). In this study, we did not capture alternative forms of production (e.g., the farmers' ability to change to dryland or pasture) in response to low water availability, and this is one of the study limitations. We determined 2000 agents based on the number of the farms in BRB with a random social network and specific characteristics sampled from probability distributions. This social network implies that the connected farmers observe their neighbors' decisions. These connections were selected randomly during the model setup. In fact, in the model setup, each agent randomly creates a connection with another agent in the community, leading to a social network. In response to their profits, the agents decide to conserve water at the beginning of each year as they envision any forthcoming insufficient water availability. The agents make three different decisions: adopting an improved new on-farm irrigation system (i.e., a sprinkler system in this study), changing crops, and area to be irrigated. These decisions have interactions in that if an agent saves water by a new irrigation system, he/she may choose to use the saved water, within their water permit, to expand the irrigation.

Following the mentioned local studies in BRB and the other previous studies (Arbuckle Jr, 2013; Du et al., 2017b; Hoag et al., 2012; Nowak, 1992; Pfrimmer et al., 2017; Wheaton et al., 2005), we determined several socio-economic factors, relevant to farmers' water conservation decisions:

conservation purposes, future profits, past profits, risk-aversion, environmental protection, social interaction, and willingness to expand irrigation. The conservation purposes account for water conservation targets set by the government. The future profit is based on the expected gross margin of 1 ha of conservation. An agent decides to conserve water if he/she earns more benefits by conservation. This benefit can be received by the government subsidy and market. The past profit is based on the same idea; however, the economic evaluation is based on the past information of an agent (or the agent's memory). The risk-aversion shows the degree to which an agent changes his/her past decision on water conservation. Therefore, if an agent is risk-averse, this agent continues his/her last decision on water conservation (only if it does not cause losses). The environmental protection factor implies the extent to which an individual farmer conserves water for environmental protection regardless of economic consequences. The social interaction accounts for the extent to which an agent is affected by neighbors. All these socio-economic factors lead to a final decision on water conservation. When individual farmers conserve water, a proportion of the saved water may be used for irrigation expansion. In this regard, the irrigation expansion factor shows the amount of the saved water that is used for irrigation expansion.

We assumed that farmers assign different weights to their different factors to make a final yearly decision, following the work of Dziubanski (2018), Dziubanski et al. (2019), and Roobavannan et al. (2018). These weights show the extent to which farmers emphasize each of their socio-economic factors. Considering these weights for each farmer in this study in the agent-based modeling framework allowed us to appropriately capture the heterogeneity of farmers' decision making in their community. In other words, each farmer has a specific set of weights for decision making in the ABAD model.

To account for the uncertainty associated with human decision-making, ABMs are generally developed using stochastic models given that human decision making is presumably stochastic (Acuna & Schrater, 2008; Cohen et al., 2007; Steyvers et al., 2009; Wilson et al., 2011; Zhang & Yu, 2013). Indeed, compared with physical systems that are generally defined by deterministic physical laws (e.g., gravity), social systems are more stochastic due to their uncertain and complex governing mechanism. In contrast to a deterministic model, a stochastic model generally generates different outputs for a specific set of model inputs. This stochasticity is reproduced in the model by sampling from probability distributions for some variables representing human decision-making factors. In this study, the stochasticity was captured when farmers intend to change their crops for the next year regarding the future economic values of crops. Even though farmers are influenced by future economic values of crops given the market prediction, they have different perceptions of crop prices and costs over time, which were defined by the stochastic process (i.e., sampling from assumed distributions from moment to moment, further discussed in section 2.5.3).

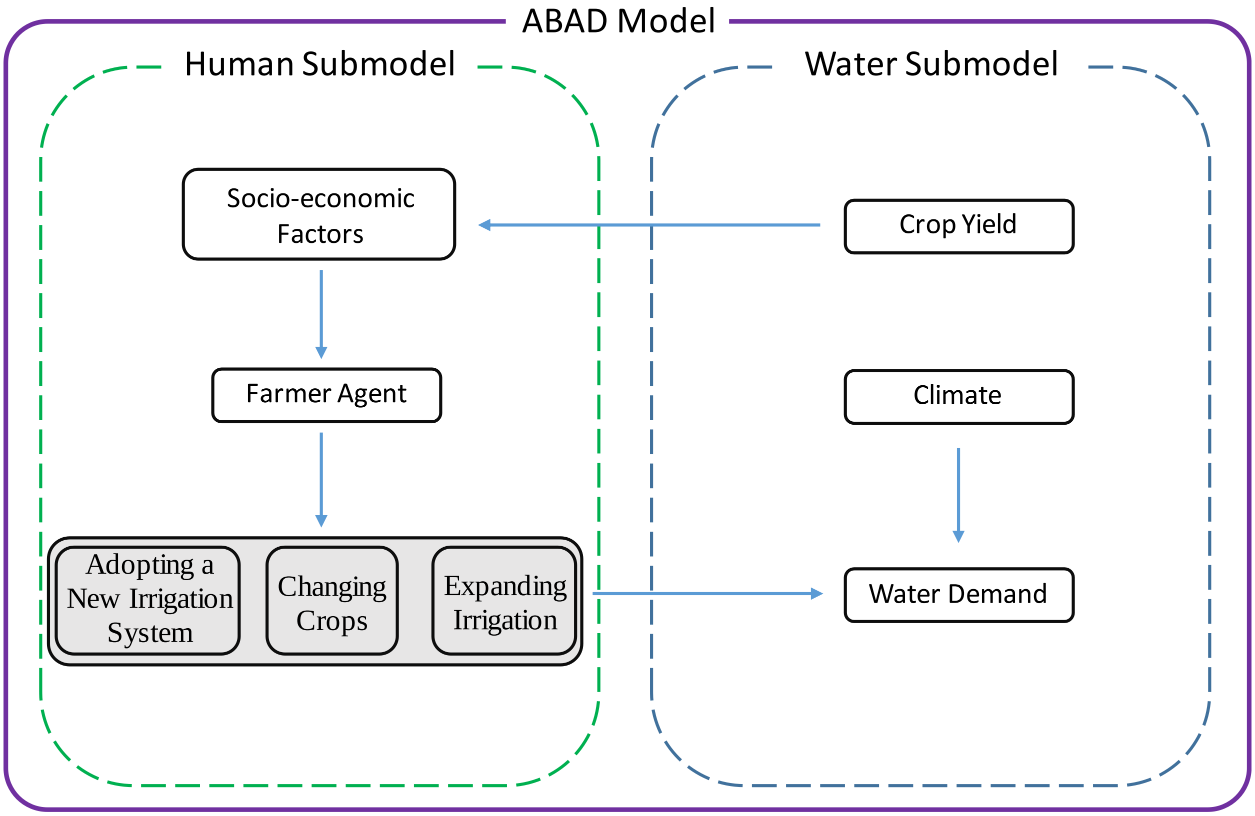

Figure 2.4 The ABAD model framework

2.5.2 Model Input

The inputs to the human submodel are based on several yearly socio-economic data from 1999 to 2015. The yearly irrigated area, irrigation system area, crop patterns, and agricultural water demand data were used from the Alberta Government information (Agriculture and Forestry, 2015). The information on the conservation goal of the Water for Life Program was obtained from the Alberta Water Council report (Irrigation Sector Conservation, Efficiency, Productivity Plan 2005-2015). The yearly crop yield data were represented by lumped values, which were obtained from Statistics Canada (2021). These time series account for the trend over time, but we are not simulating crop yield in this study; this is one of the study limitations. We assumed that the crop yields for both sprinkler and flood irrigation are the same. The data on the subsidy were used from the Canadian Agricultural Partnership (2019). The subsidy for adopting sprinklers covers 40% of the cost of the irrigation system, and the rest of the cost should be self-financed (Canadian Agricultural Partnership, 2019). The production cost and crop price data were represented by a lumped value and obtained from the Alberta government (Agriculture and Forestry, 2015; see Table A.1 in the supplementary material for the items of production costs).

The inputs to the water submodel are the meteorological data: radiation at the crop surface, soil heat flux density, psychometric constant, mean daily air temperature at 2 m height, the wind speed at 2 m height, saturation vapor pressure, actual vapor pressure, the slope of the vapor pressure curve, and the crop coefficient. We used the daily meteorological data produced by the Water and Global Change (WATCH) from 1999 to 2015, which are available at http://www.eu-watch.org.

2.5.3 Human Submodel

The farmers' decisions (i.e., adopting sprinklers, changing crop patterns, and area to be irrigated) are made separately by individual agents, but influenced by other agents (All Equations of human submodel are shown in Table 2.1). The decision on the area to be irrigated includes expanding irrigation through adopting sprinklers (Equation 2.1) as it increases the irrigated area in the river basin, which was defined in the decision on changing crop patterns (Equation 2.4). In other words, when individual farmers adopt technology to reduce their water demand, they use the saved water to expand their irrigation. Therefore, two main formulations were defined for the three decisions, which are based on the mentioned socio-economic factors. This study modified the formulation of a previous study by Dziubanski (2018) and Dziubanski et al. (2019), which was applied to water conservation in a flood situation. We applied the modified formulation in drought conditions and added another decision-making formulation on adopting sprinklers, which was interacting with crop changing decisions (Equations 2.1 and 2.4).

Table 2.1 Summary of the main equations, variables, and factors in the human submodel of the ABAD model

Model Component	Equation	Variable/Factor
Farmer's decision on adopting sprinkler	$\Delta IS_{s,t} = W_{ra}(\Delta IS_{s,t-1}) + W_{pp}(\Delta IS_{s,t-1} + \Delta IS\_PP_{\mathrm{t}}) + W_{fp}(\Delta IS_{s,t-1} + \Delta IS\_FP_{\mathrm{t}}) + W_e(\Delta IS_{s,t-1} + \Delta IS\_E_{\mathrm{t}}) + W_s(\Delta IS\_S_{\mathrm{t}})$ (2.1) $IS_{s,t} = \sum_{\mathrm{t}=\mathrm{t}_0}^{\mathrm{t}} \Delta IS_{s,t}$ (2.2) $IS_{tot,t} = IS_{s,t} + IS_{f,t}$ (2.3)	$\Delta IS_{s,t}$ (ha): the change in a farmer's land area that is switched to sprinklers W_{ra} $(-)$: the weight for risk aversion factor W_{pp} $(-)$: the weight for past profit factor $\Delta IS\_PP_{\mathrm{t}}$ (ha): the change in a farmer's land area that is intended to switch to sprinklers given an individual's past gross margin

		W_{fp} $(-)$: the weight for future profit factor $\Delta IS\_FP_{\mathrm{t}}$ (ha): the change in a farmer's land area that is intended to switch to sprinklers given the expected gross margin W_e $(-)$: the weight for environmental protection factor ΔIS_E_{t}: (ha) is the change in a farmer's land area that is intended to switch to sprinklers given the environmental protection factor W_s $(-)$: the weight for social interaction factor ΔIS_S_{t} (ha): the change in a farmer's land area that is intended to switch to sprinklers given the social interaction $IS_{tot,t}$ (ha): the total farmer's irrigated area under irrigation system $IS_{s,t}$ (ha): the total farmer's irrigated area under sprinkler irrigation system $IS_{f,t}$ (ha): the total farmer's irrigated area under flood irrigation system
Farmer's decision on changing crop patterns	$\Delta A_{o,t} = W_{ra}(\Delta A_{o,t-1}) + W_{pp}(\Delta A_{o,t-1} + \Delta A\_PP_t) + W_{fp}(\Delta A_{o,t-1} + \Delta A\_FP_t) + W_e(\Delta A_{o,t-1} + \Delta A\_E_t) + W_s(\Delta A\_S_t) + W_{ie}(\Delta IS_{s,t-1})$ (2.4) $A_{o,t} = \sum_{t=t_0}^{t} \Delta A_{o,t}$ (2.5) $A_{tot,t} = A_{o,t} + A_{f,t}$ (2.6)	$\Delta A_{o,t}$ (ha): the change in a farmer's land area that is intended to switch to other crops ΔA_PP_{t} (ha): the change in a farmer's land area that is intended to switch to other crops given an individual's past gross margin ΔA_FP_{t} (ha): the change in a farmer's land area that is intended to switch to other crops given the expected gross margin ΔA_E_{t} (ha): the change in a farmer's land area that is intended to switch to other crops given the environmental protection factor ΔA_S_{t} (ha): the change in a farmer's land area that is intended to switch to other crops given the social interaction W_{ie} $(-)$: the percentage of the increase in annual irrigation for each agent

		$A_{tot,t}$ (ha): the total farmer's irrigated area $A_{o,t}$ (ha): the total farmer's irrigated area under other crops $A_{f,t}$ (ha): the total farmer's irrigated area under forage
Farmer's decision given the past gross margin	$NITech_t = Incentive_t + Subsidy - CostTech$ (2.7) $Incentive_t = U(0,1) \times (Price_{t-1,specialty} * Yield_{t-1,specialty} - Cost_{t-1,specialty})$ (2.8)	$NITech_t$ (Can$/ha): the net gain in income from adopting 1 ha of sprinklers at the current year (i.e., opportunity cost) $Incentive_t$ (Can$/ha): the incentive to an individual farmer for adopting sprinklers (i.e., the opportunity for irrigating specialty) $Subsidy$ (Can$/ha): the financial support, by the government, for the adoption of sprinklers $CostTech$ (Can$/ha): the cost of installing sprinklers $U()$: a uniform distribution $Price_{t-1,specialty}$ (Can$/Ton): the price for cereals at the previous year $Yield_{t-1,specialty}$ (Ton/ ha): the crop yield for the cereals at the previous year $Cost_{t-1,specialty}$ (Can$/ha): the production cost for the cereals at the previous year $NICrop_t$ (Can$/ha): the net gain in income from irrigating 1 ha of forage crops versus the other crops (oil seeds, cereals, and specialty) at the current year (i.e., opportunity cost) $GrossMargin_{t-1,forage}$ (Can$/ha): the gross margin of 1 ha of forage $GrossMargin_{t-1,OtherCrops}$ (Can$/ha): the average gross margin of 1 ha over three crops, namely specialty, cereals and oil seeds at the previous year $Price_{t-1,cereals}$ (Can$/Ton): the price for cereals at the previous year

		$Yield_{t-1,cereals}$ (Ton/ ha): the crop yield for the cereals at the previous year $Cost_{t-1,cereals}$ (Can$/ha): the production cost for the cereals at the previous year $Price_{t-1,oilseeds}$ (Can$/Ton): the price for oilseeds at the previous year $Yield_{t-1,oilseeds}$ (Ton/ ha): the crop yield for the oilseeds at the previous year $Cost_{t-1,oilseeds}$ (Can$/ha): the production cost for the oilseeds at the previous year $Price_{t-1,forage}$ (Can$/Ton): the price for forage at the previous year $Yield_{t-1,forage}$ (Ton/ ha): the crop yield for the forage at the previous year $Cost_{t-1,forage}$ (Can$/ha): the production cost for the forage at the previous year
	$NICrop_t = GrossMargin_{t-1,OtherCrops} - GrossMargin_{t-1,forage}$ (2.9) $GrossMargin_{t-1,OtherCrops} = \frac{1}{3} * (Price_{t-1,specialty} * Yield_{t-1,specialty} - Cost_{t-1,specialty} + Price_{t-1,cereals} * Yield_{t-1,cereals} - Cost_{t-1,cereals} + Price_{t-1,oilseeds} * Yield_{t-1,oilseeds} - Cost_{t-1,oilseeds})$ (2.10) $GrossMargin_{t-1,forage} = Price_{t-1,forage} * Yield_{t-1,forage} - Cost_{t-1,forage}$ (2.11)	

Farmer's decision given the environmental protection	$\Delta IS\_E_{t} = W_c * (IS_{tot,t})$ (2.12) $\Delta A\_E_{t} = W_c * (A_{tot,t})$ (2.13)	W_c $(-)$: the degree to which an agent is following the conservation target of the program
Farmer's decision given the social interaction	$\Delta IS\_S_{t} = \left(\frac{\sum_{k=1}^{m} \Delta IS_{s,t-1,k}}{\sum_{j=1}^{n} \Delta IS_{s,t-1,j}}\right) * IS_{tot,t}$ (2.14) $\Delta A\_S_{t} = \left(\frac{\sum_{k=1}^{m} \Delta A_{o,t-1,k}}{\sum_{j=1}^{n} \Delta A_{o,t-1,j}}\right) * A_{tot,t}$ (2.15)	k and j: the neighbors and agents, respectively $\left(\frac{\sum_{k=1}^{m}}{\sum_{j=1}^{n}}\right)$ stands for the ratio of an individual's decision (on changing crops or adopting sprinklers) to all other individuals' decisions.

Equations 2.1 and 2.4 have five and six mentioned socio-economic factors (weights) plus one implicit factor, which is discussed in equations 2.12 and 2.13, resulting in seven different factors (weights) in total. The different weights reflect the degree to which each socio-economic factor plays a role in a final decision for each individual farmer. In this study, we assumed the weights are independent of each other. Following the previous studies (Bertella et al., 2014; Du et al., 2017a; Marino et al., 2008), we assumed each different weight for individual agents is sampled from a normal distribution of the community. Although these weights were set to be the same for all individuals by Dziubanski (2018) and Dziubanski et al. (2019), in our study, each of the weights was randomly sampled from a normal distribution with the mean and variance for the whole community being calibration parameters of the model (Figure 2.5). As this model has seven factors for decision making, we need two parameters for sampling each weight (i.e., mean and standard deviation), resulting in 14 parameters in the ABAD model (Table 2.2 and Figure 2.5). The remainder of the method section explains the main socio-economic components in farmers' decision making.

Table 2.2 The ABAD parameters, their descriptions, and units

Parameters	**Description**	**Lower Bound**	**Upper Bound**
μ_{ra}	Mean of a normal distribution for risk-aversion factor	0	1
μ_{pp}	Mean of a normal distribution for past profit factor	0	1
μ_{fp}	Mean of a normal distribution for future profit factor	0	1
μ_{e}	Mean of a normal distribution for environmental protection factor	0	1
μ_{s}	Mean of a normal distribution for social interaction factor	0	1
μ_{c}	Mean of a normal distribution for conservation goal factor	0	Target of Water conservation program per year
μ_{ie}	Mean of a normal distribution for irrigation expansion factor	0	Possible irrigation expansion per year in a river basin
σ_{ra}, σ_{pp}, σ_{fp}, σ_{e},σ_{s}, σ_{c}, and σ_{ie}	corresponding to the same factors as the first seven mean values	0	-

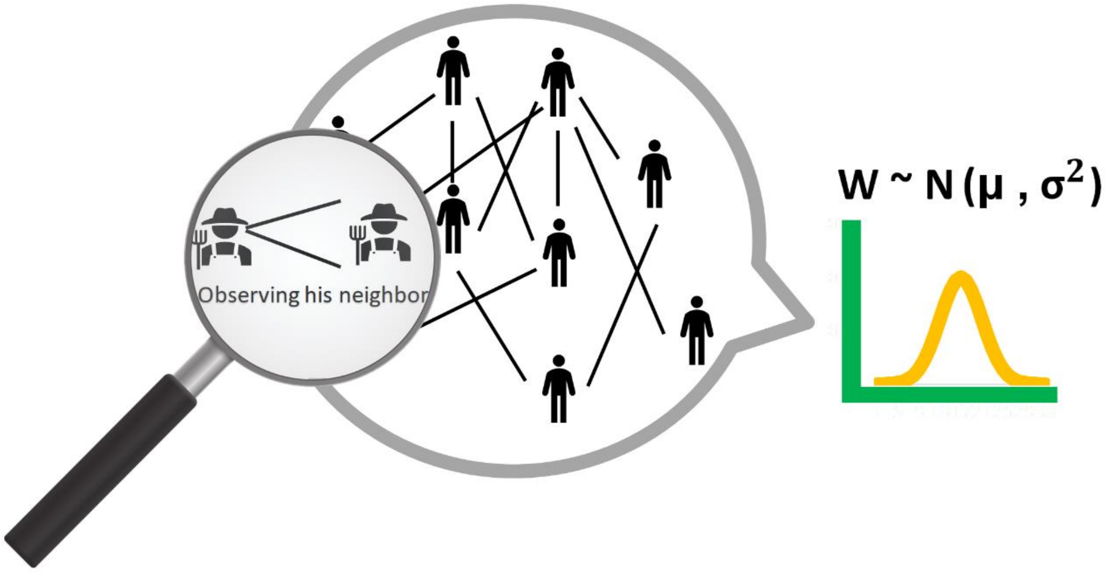

Figure 2.5 Individual farmers make their decisions about sprinklers and crop changes, given their different socio-economic factors. "W" shows a weight for a socio-economic factor. For each individual, a weight for socio-economic factor is sampled from a normal distribution of the community (i.e., N(μ , σ^2)). The lines between the individuals represent their social interaction with each other. In other words, a line shows both farmers observe each other for their decisions

Risk-aversion factor: The risk-aversion factor, in Equations 2.1 and 2.4, implies the extent to which individual farmers change their last decisions on water conservation. Therefore, if an agent is risk-averse, this agent continues the previous practice (last year's decision) for the current year. The past profit factor is based on the memory of the agent regarding their past gross margins of 1 ha of conservation. Following Dziubanski (2018) and Dziubanski et al. (2019), the past profit was formulated by a quadratic function (see Equation A.1-A.8 in supplementary material). The decisions, based on past profit, were restricted by the conservation goal of the program (i.e., Water for Life Program). For adopting sprinklers, an agent evaluates the net income from adopting 1 ha of this irrigation system. Similarly, for changing crops, an agent calculates the net income from irrigating 1 ha of forage crops versus the other crops: oilseeds, cereals, and specialty.

Past Profit Factor: An agent calculates the net income from adopting 1 ha of a sprinkler system based on the incentive, the subsidy, and the cost (Equations 2.7 and 2.8). The incentive to farmers is a profit, which can be earned because of adopting sprinklers. In this study, this incentive is a function of irrigated specialty, given the past report in our case study (Alberta Irrigation Projects Association, 2015). As an improvement on the past study by Dziubanski (2018) and Dziubanski et al. (2019), we also considered stochasticity in Equation 2.8 by assuming a uniform distribution because different farmers can have different perceptions about this value. In our case study, one incentive for farmers to adopt sprinklers is the potential to irrigate more lands and to plant crops like specialty crops, and therefore, we assume the gross margin of specialty crops as an incentive in this study (Equation 2.8). An agent calculates the net income from irrigating 1 ha of forage crops versus the other crops regarding their gross margin difference between forage and other crops (Equations 2.9-2.11). After calculating the net income from each of the two main formulations (adopting sprinklers and changing crop patterns), an agent considers the first, second, and third quartile of his/her historical net income distribution as the satisfaction points based on the theory of bounded rationality. This agent considers all positive historical net income from the year 1999 to the current year of simulation if he/she observes the positive net income at the current year. Similarly, the agent considers all negative historical net income from the year 1999 to the current year if he/she observes the negative net income in the current year. If the positive current net income equals the third quartile of the positive historical income, an agent carries out the maximum conservation, which was restricted to both his/her available irrigated area and the degree to which a farmer follows a conservation target set by the government. Additionally, if the positive current net income equals the second quartile of the positive historical income, an agent carries out the conservation on half of his/her irrigated land. However, we assumed that an agent does not conserve water if he/she observes small net income, less than the first quartile. Similarly, an agent behaves similarly when observing the negative net income in the current year. These water conservation decisions were defined based on the second-degree polynomial equation (see Equation A.1-A.2 in supplementary material).

Future Profit Factor: Future profit factor was defined based on the expected crop price and production cost for the future. Therefore, an agent calculates future profits ($\Delta IS\_FP_{\mathrm{t}}$ and ΔA_FP_{t}) similar to the past profits; however, in the formulations of the future profits, the crop price and production cost are their future values. Instead of deterministic equations, we sampled these future economic variables from a normal distribution with a variance of Can$1. In other words, sampling from a normal distribution represents how the perception of a farmer is different from another one about future prices and costs. The small value was chosen in this case study because heterogeneity in farmers' decisions about future profits in this region is inconsiderable. In this study, the mean of the distribution equals the historical mean of price and production cost trend for each crop.

Environmental Protection Factor: The decision based on the environmental protection factor was defined to imply how an agent is in favor of environmental protection. This decision is a function of the conservation target factor. Given our modification of the study by Dziubanski (2018) and Dziubanski et al. (2019), the environmental protection factor was calculated for the conservation decisions based on Equations 2.12-2.13.

Social Interaction Factor: Individual agents' decisions are often influenced by the action of their neighbors due to their insufficient information (Centola, 2010; Kearns et al., 2009; Schelling, 1973; Watts, 2002). The social interaction factor implies the degree to which an agent is influenced by their neighbors' decisions. We modified the formulation of Dziubanski (2018) and Dziubanski et al. (2019) and added the social interaction factor to the decision making process. Following the work of Du et al. (Du et al., 2017b), we used a weighted average of a farmer's neighbors to calculate the social influence on farmers (Equations 2.14 and 2.15), with a random social network during model setup. Based on the initialized social network at the start time of simulation, the social interaction with n agents and m neighbors was calculated for the conservation decisions based on Equations 2.14-2.15.

2.5.4 Water Submodel

While the crop patterns and the adoption of new irrigation systems were simulated by the human submodel for the whole river basin, a lumped water submodel simulated the monthly agricultural water demand in BRB. Due to the availability of annual water demand data for our case study, we aggregated the monthly water demand to calculate the annual water demand for the purpose of model calibration and validation.

Using the Penman-Monteith method, daily reference evapotranspiration (ET_0) (mm/day) and crop evapotranspiration (ET_c) (mm/day) were calculated as follows (Food and Agriculture Organization of the United Nations (FAO), 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{2.16}$$

$$ET_c = K_c \times ET_0 \tag{2.17}$$

where R_n (MJ/m2.day) is net radiation at the crop surface, G (MJ/m2.day) is soil heat flux density, γ (kPa/°C) is psychometric constant, T (°C) is mean daily air temperature at 2 m height, U_2 (m/s) is the wind speed at 2 m height, e_s (kPa) is saturation vapor pressure, e_a (kPa) is actual vapor pressure, Δ (kPa/°C) is the slope of the vapor pressure curve, and K_c $(-)$ is the crop coefficient. We obtained the meteorological data from the WATCH forcing data (Weedon et al., 2014). Therefore, we calculated the water demand for a crop from irrigation ($WD_{c,t}$) (mm/month) as follows (United States Department of Agriculture, 1970):

$$WD_{c,t} = ET_{c,t} - P_{eff,t} \tag{2.18}$$

$$P_{eff,t} = SF \times (0.0493 \times P_t^{0.824} - 0.11556) \times 10^{0.000955 \times ET_{c,t}} \tag{2.19}$$

$$SF = 0.5317 + 0.0116 \times D - 8.94 \times 10^{-5} \times D^2 + 2.32 \times 10^{-7} \times D^3 \tag{2.20}$$

$$TotalWD_t = \beta \times \frac{\sum_{c=1}^{2} WD_{c,t} \times A_{c,t}}{IE_t} \tag{2.21}$$

$$IE_t = \left(\frac{IE_f \times IS_{f,t} + IE_s \times IS_{s,t}}{IS_{tot,t}} \right) \tag{2.22}$$

where $TotalWD_t$ (10^6 m^3/month) is the simulated total agricultural water demand of the river basin in million m3, $P_{eff,t}$ (mm/month) is the effective precipitation, SF is the soil water storage factor, P_t (mm/month) is precipitation, $ET_{c,t}$(mm/month) crop evapotranspiration for crop c, D (mm) is assumed to be the maximum crop's root depth, $A_{c,t}$ (ha) is the crop area (i.e., forage or other crops), IE_f is the flood irrigation system efficiency, IE_s is the sprinkler system efficiency, IE_t is the total efficiency, and β is the conversion factor $10^{-5} \frac{MCM}{mm.Hectare}$.

2.6 Design of Experiments

We performed all the analyses on the average of the model response (as a metric) with 20 replicates, given the stochastic nature of our model. Using such metrics with a number of replicates (e.g., 10, 20, 50) is a common way to deal with the stochastic nature of ABMs (e.g., (Salecker et al., 2019; Segovia-Juarez et al., 2004)). Using the average of the model response with 20 replicates can also address the uncertainty in the size and level of connectedness of social networks in the ABAD model. Basing an analysis on many replicates is a common way in the sensitivity analysis of ABMs (e.g., (Salecker et al., 2019; Segovia-Juarez et al., 2004)).

2.6.1 Global Sensitivity Analysis

One challenge of the ABAD model is the high number of the model parameters, i.e., 14 parameters, relative to the limited data available, i.e., 17 years. To address this challenge in calibration and validation parts, we conducted a global sensitivity analysis on the ABAD model's output to the potential ranges of the model parameters for identifying the most influential model parameters to be calibrated. We used the variogram-based framework, Variogram Analysis of Response Surfaces (VARS), which encompasses two commonly used approaches in global sensitivity analysis, namely derivative-based and variance-based approaches (Razavi & Gupta, 2016a, 2016b). Using variograms, VARS provides a set of metrics, named IVARS. Following Razavi & Gupta (2016a), we used IVARS_{50}, representing the integration of a variogram over the first 50% of the parameter perturbation scales. In this study, for parameter sensitivity analysis, we used NSE on the annual agricultural water demand (NSE(Water Demand)) as a model response with the following sampling settings: number of stars=100 and sampling resolution=0.1 (see Razavi & Gupta (2016a) for further information on VARS sampling strategy). This sampling setting resulted in 12,700 model runs.

According to Table 2.2, the first five parameters (μ_{ra}, μ_{pp}, μ_{fp}, μ_e, and μ_s) are the means for the corresponding socio-economic factors with their lower and upper bounds assumed to be 0 and 1

(See the details of the parameter ranges in Table A.2 supplementary material). These factors will be normalized to sum to one before being plugged into the model. The upper bound of conservation target per year (μ_c) was defined based on the long-term conservation target in Water for Life Program – based on this program, on average each year, 0.5% of the total irrigated land aimed to be under the water conservation program (Alberta Irrigation Projects Association, 2015). In addition, we assumed the upper bound of the mean for the irrigation expansion factor (μ_{ie}) based on the historic data. Accordingly, while changing crop patterns, individual agents expand their irrigated area (above or below the historical value). Importantly, we assumed large boundaries for all standard deviations to fully investigate the model.

In this study, crop yields are the main input data, as farmers mainly make decisions based on this information. Therefore, in addition to the sensitivity analysis of the model parameters, we perturbed the data on crop yields to assess the sensitivity of the model to this input. Using the method of Papalexiou (2018), we generated 1000 different realizations (i.e., time series) for different crop yields given a normal distribution with the same mean and variance of the historical data.

2.6.2 Multi-objective Optimization

To address the challenge of properly constraining the model with limited data, a general challenge to both socio-hydrological models and agent-based models (An, 2012; Ligtenberg et al., 2010; Noël & Cai, 2017; Pande & Sivapalan, 2017; Windrum et al., 2007), we used multiple, rather than single, model outputs for the calibration and validation of the ABAD model. Regarding the three main types of outputs in ABAD, i.e., water demand, irrigation system area, and cropping patterns, we calibrated the model based on two of these outputs (i.e., water demand and irrigation system area) and validate it based on the other output (i.e., cropping patterns). We used the Nondominated Sorting Genetic Algorithm II (NSGA-II) as the multi-objective optimization method. NSGA-II was proposed as an efficient multi-objective optimization method for complex and high dimensional problems (Deb et al., 2002). While we acknowledge that other optimization methods may have a better performance for finding optimum solutions, the NSGA method is a common approach that has been used for optimizing ABMs by many studies (Crooks et al., 2018; Lee et al., 2016). To account for the effect of variability within the optimization process and to find robust solutions, we ran optimization with 20 trials and the following setting: population size=100, generations=20, crossover probability=0.7, crossover distribution index=5, mutation probability=0.2, mutation distribution index=10. This optimization setting resulted in 40,000 model runs. We used the value of 0.5 for NSE as a satisfactory threshold (Moriasi et al., 2007) for filtering the optimization results.

2.6.3 Parameter Uncertainty Analysis

To address the equifinality issues, we investigated the different parameter sets that properly fit the observation data through parameter uncertainty analysis. Our purpose of this analysis is to evaluate whether there exist the unique parameter sets that lead to observation data. In this regard, using the same setting with the experiment on multi-objective optimization (section 2.6.2), we ran the optimization with 20 trials and investigated the parameter sets that correspond to the value of more than 0.5 for NSE of water demand and flood irrigation system area. We assumed this value for this experiment as a satisfactory model performance following the literature (Moriasi et al., 2007). Finally, we try to validate the result by qualitative data, namely existing reports and interviews in our case study.

2.7 Results

2.7.1 Sensitivity Analysis

Figure 2.6 shows the parameter sensitivity analysis of the ABAD model based on IVARS_{50}. The results show that the mean for the social interaction factor (μ_s) and the conservation goal factor (μ_c), and the standard deviation for social interaction factor (σ_s) are the most sensitive parameters controlling NSE(Water Demand) while the standard deviations for risk-aversion factor (σ_{ra}), future profit factor (σ_{fp}), and past profit factor (σ_{pp}) are the least important parameters for this purpose. Compared to other factors, the social interaction factor (μ_s, σ_s) highly affects NSE(Water Demand). However, most of the standard deviation parameters, which show the heterogeneity in the community, are the least sensitive, implying that the heterogeneity in socio-economic factors excluding social interaction control less NSE(Water Demand), compared to other factors.

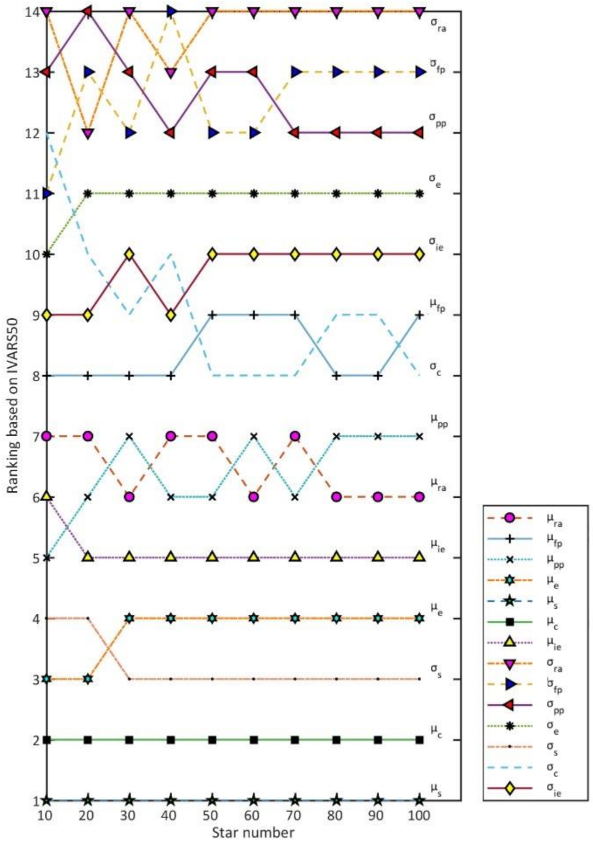

Figure 2.6 Parameter sensitivity analysis of the ABAD model versus star number (star-sampling is a sampling strategy to improve the computation of a full range of sensitivity information (more details in Razavi & Gupta, 2016b)) based on IVARS50: Rank 1 represents the most influential parameter, while rank 14 represents the least influential parameter. Here, the global sensitivity of NSE(Water Demand) to the model parameters is assessed.

The result of sensitivity analysis shows the dominant importance of all mean parameters as well as the standard deviations of social interaction (σ_S). In addition, to provide a better understanding of the importance of the standard deviations, we performed another sensitivity analysis with a narrower and more realistic range (See Table A.3 in the supplementary material for the parameter ranges of the sensitivity analysis). The result of this analysis indicates that all standard deviations drop in importance (See Figure A.2 in the supplementary material for the result of the sensitivity analysis). Besides, to the best of our knowledge, the heterogeneity (represented here by standard deviation) in this case study is not large. In other words, farmers make their decisions in a similar manner. Therefore, we reduced the number of the model parameters to seven parameters, namely the means of distributions of behavioral parameters (See Table A.4 in the supplementary material for the new setting for parameter sensitivity analysis). In this regard, following the past studies (Du et al., 2017b; Marino et al., 2008) and a good understanding of our case study, we fixed the rest of the parameters (all standard deviation parameters) to 0.01 for the calibration and validation purposes. We arbitrarily assumed this low value as an indicator of a small standard deviation in this study. The decrease in the number of parameters enables us to avoid over-fitting issues in this study that can arise due to the limitation on data availability. However, this issue can be challenging in other case studies in case the farmers' behavior is highly diverse, and it should be investigated further in future studies.

After fixing the variance parameters, the possible change in the results of the sensitivity analysis of mean parameters motivated us to conduct another experiment with the new setting (See Table A.4 in supplementary material). The new results show that μ_{ie} is the most sensitive parameter in the model after we fixed the less sensitive parameters (i.e., all standard deviations) (Figure 2.7). This means that the mean value of the irrigation expansion factor highly affects the results of NSE(Water Demand). Table 2.3 shows the comparison of parameter sensitivity analysis including all parameters with large standard deviations and the reduced set of seven parameters. The comparison shows that the social interaction factor plays a crucial role in the irrigation system growth and crop changing, leading to the water demand for agriculture, in a diverse society.

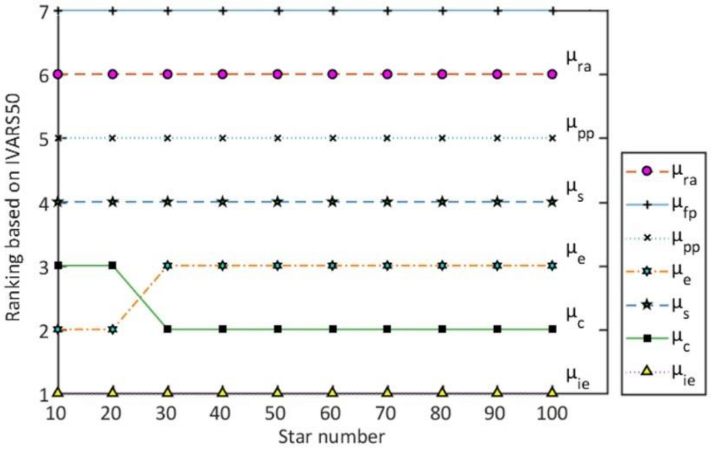

Figure 2.7 Parameter sensitivity analysis of the ABAD model parameters based on NSE(Water Demand) with a new setting

Table 2.3 The comparison of parameter sensitivity analysis with all parameters and seven parameters. The parameters with low ranking values are the most sensitive parameters.

Ranking	**Sensitivity Result with All Parameters**	**Sensitivity Result with Seven Parameters**
1	μ_s	μ_{ie}
2	μ_c	μ_c
3	σ_s	μ_e
4	μ_e	μ_s
5	μ_{ie}	μ_{pp}
6	μ_{ra}	μ_{ra}
7	μ_{pp}	μ_{fp}
8	σ_c	-

9	μ_{fp}	-
10	σ_{ie}	-
11	σ_{e}	-
12	σ_{pp}	-
13	σ_{fp}	-
14	σ_{ra}	-

Regarding the sensitivity of the model to input data, Figure 2.8 shows the envelope of the variability of model outputs under the crop yield uncertainty. This result implies that the forage and other crop areas are more sensitive, compared to other outputs, to the change in crop yield. This result also shows that the variability of the crop yields highly affects the change in crop patterns as crop yield is important to farmers for their decision making.

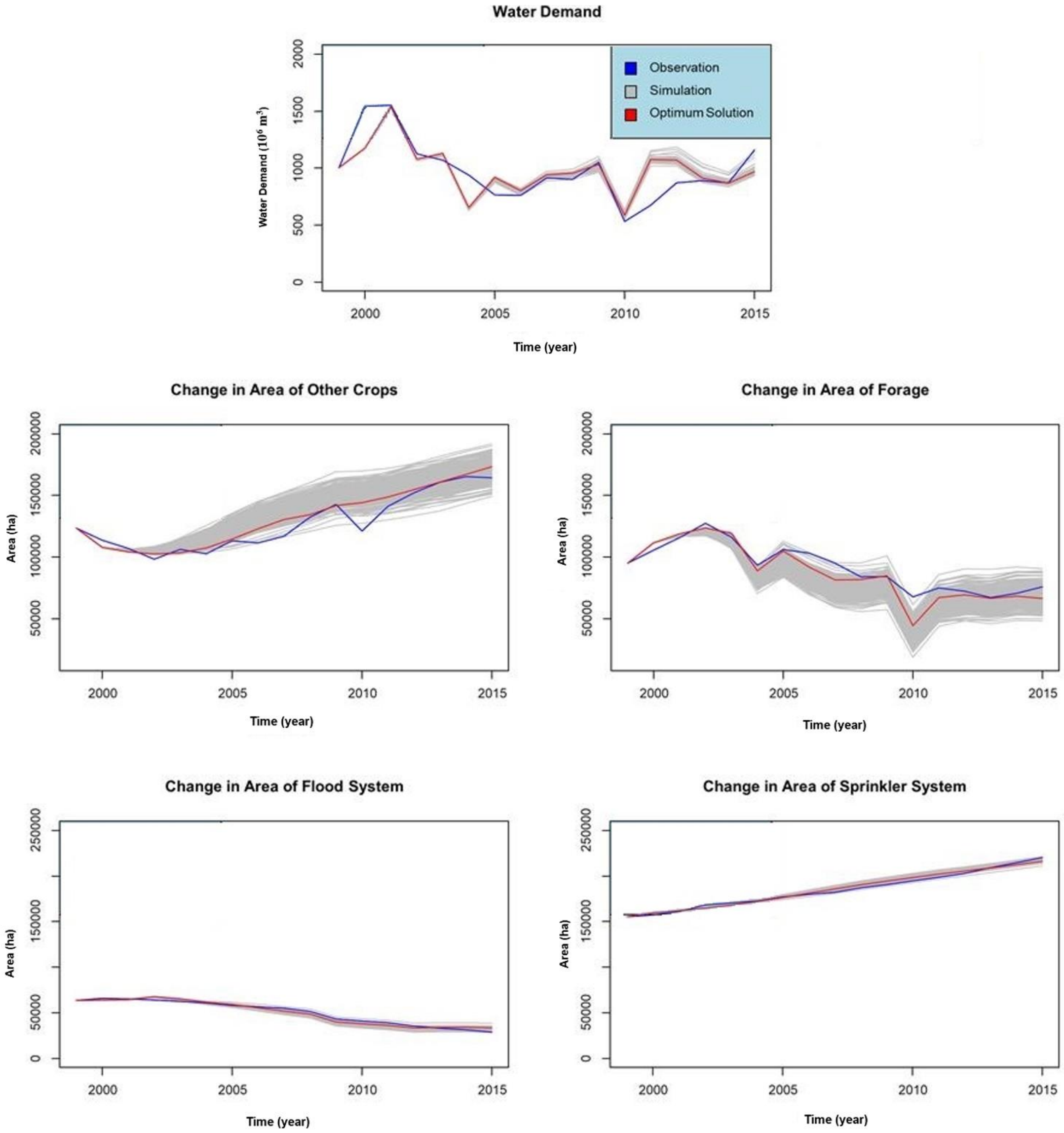

Figure 2.8 The effect of crop yield uncertainty on the model outputs

2.7.2 Multi-objective Calibration and Validation

After screening the uninfluential model parameters by SA, we calibrated the remaining parameters with the new setting (See Table A.4 in supplementary material). Figure 2.9 shows the Pareto front based on two objective functions, i.e., NSE(Water Demand) and NSE(Area of Flood irrigation System). The best solutions for the optimization have NSE values of 0.98 and 0.59 for the Area of Flood System and Water Demand, respectively.

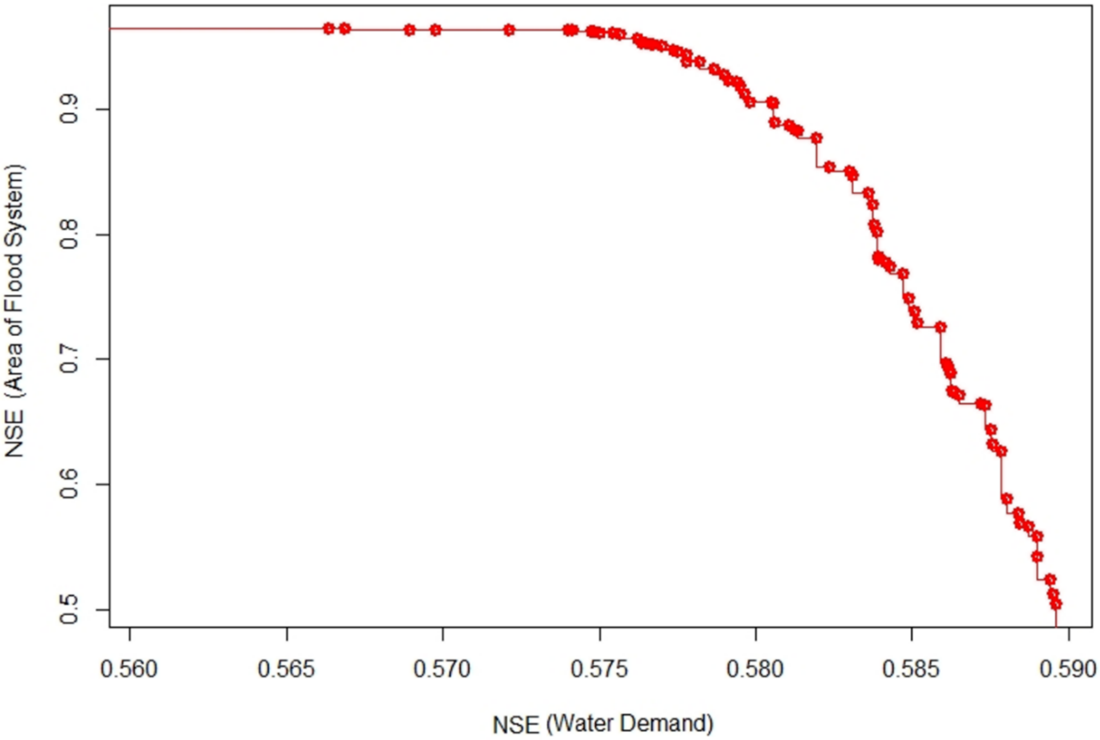

Figure 2.9 The result of Pareto front based on NSE(Water Demand) and NSE(Area of Flood System)

Figure 2.10 shows the Probability Distribution Function (PDF) plots of model performance based on the multi-objective functions. Given the results of 20 trials in multi-objective optimization, we derived a PDF to each NSE of the model outputs (water demand, flood irrigation system area, sprinkler irrigation system area, forage area, and other crop areas). Two of these PDFs (water demand and forage area), which were filtered by the value of 0.5 for NSE, were used for the calibration purpose. The other three PDFs were used for the validation purpose. This result shows that the PDF of water demand shows the smallest variability, representing that all model performances on water demand are relatively robust. However, the PDFs of the other model performance metrics show large variability.

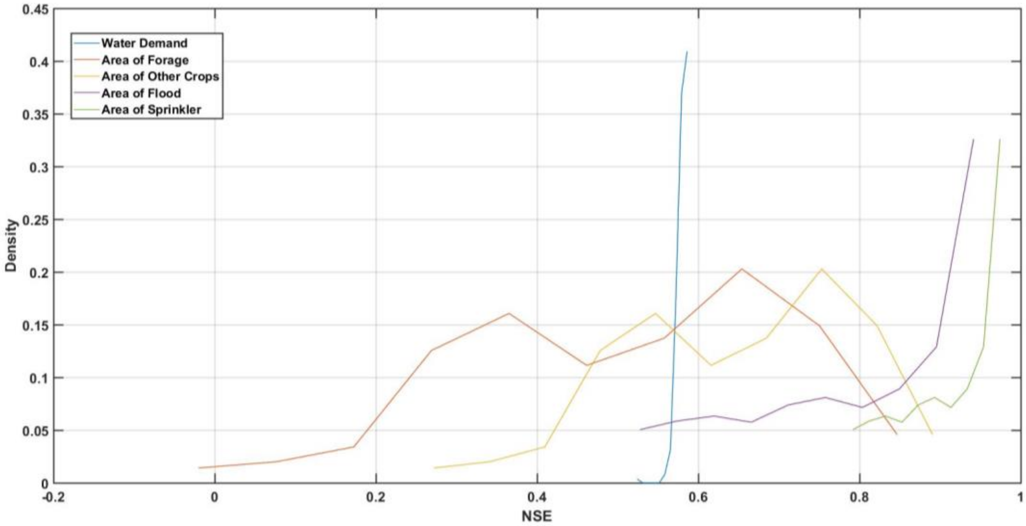

Figure 2.10 Probability Distribution Function (PDF) plots of NSE values for different model outputs based on all the Pareto-front points of the 20 trials in multi-objective optimization. “Water demand” and “area of flood” were used as the optimization objective functions, and the other outputs were used for validation.

Figure 2.11 shows the result of one optimum solution given calibration and validation results. This optimum solution generated NSE(water demand)=0.57 and NSE(area of the flood)=0.96. We choose this model for further analysis in section 2.7.3. The performance of the model for this solution is acceptable, given the NSE for different outputs. The optimum solution shows a good performance on the water demand output, although the model does not fully capture the observed data in the years 2000, 2004, 2011, and 2012. However, the model implies a much better performance on the outputs of the human submodel. One reason for the better performance of the human submodel is that the outputs of the human submodel (area of crops and irrigation systems) have more linear behavior than water demand. The model captures the overall nonlinear behavior of the forage and other crop areas with a satisfactory NSE. In addition, the model outputs on irrigation system areas are well-fitted to the observed data, which is due to the relatively linear behavior of these state variables.

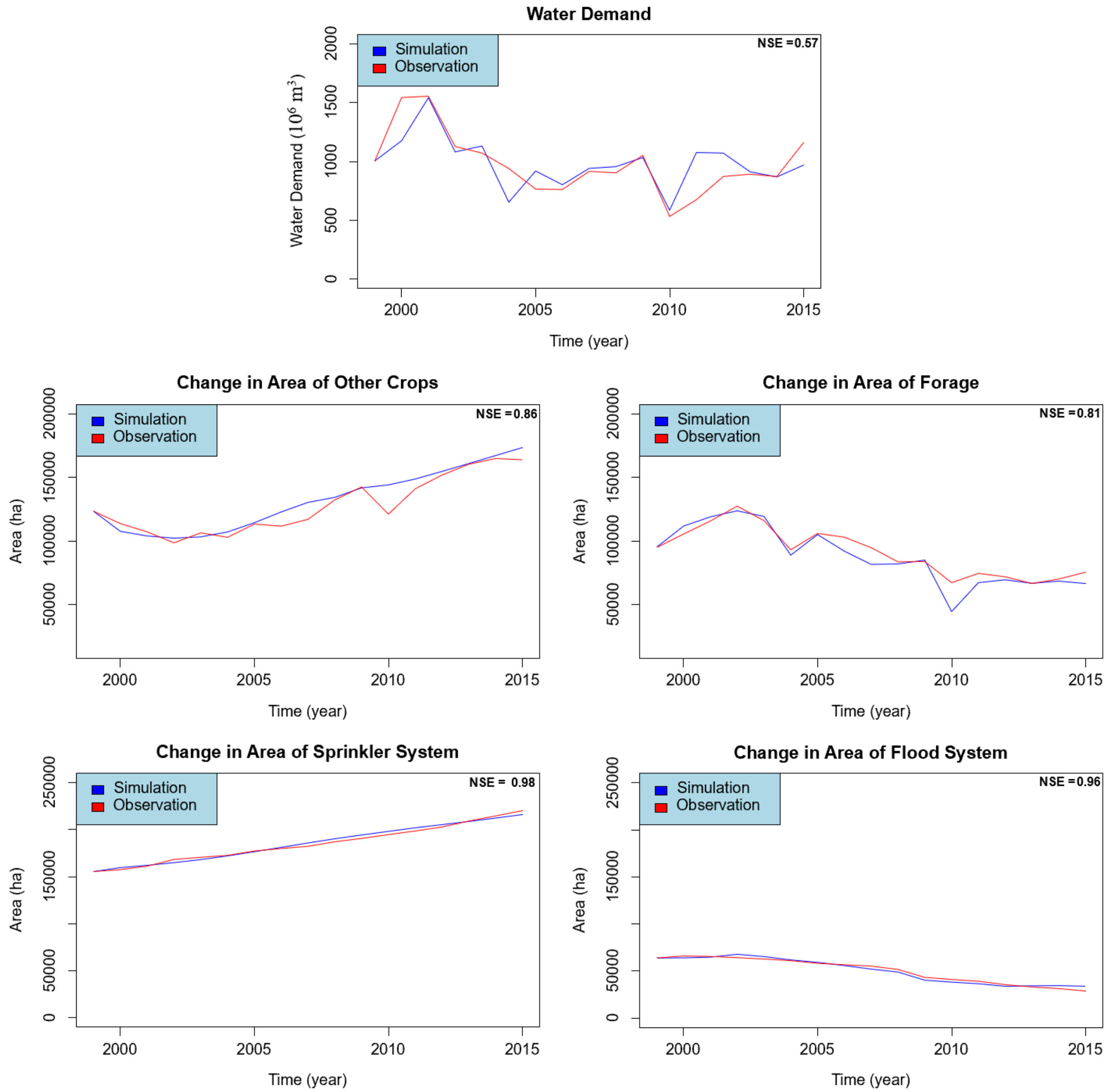

Figure 2.11 The result of an optimum solution based on multi-objective optimization and the model performance for calibration and validation

The result of the model optimal solution shows that the model is more sensitive to gradual trends rather than abrupt changes over time. For example, the model cannot simulate the abrupt changes in the area of other crops in 2010 (Figure 2.11). However, capturing overall trends in socio-hydrological models can satisfy the goal of socio-hydrology as the purpose of such models is not to merely predict the future, but rather explore co-evolving trajectories of human and water systems (Srinivasan et al., 2017). Nevertheless, modifying the hydrological submodel to become a spatially distributed one is likely to enhance the model in capturing the abrupt changes.

2.7.3 Parameter Uncertainty

The results of the parameter uncertainty imply that three out of seven parameters are more identifiable (smaller range of variability in Figure 2.12) in this study (i.e., μ_{ra}, μ_c, and μ_{ie}). The mean of risk-aversion factor (μ_{ra}) assumes a low value, implying that the farmers are risk-takers on average in this case study. The risk aversion values are meaningful given the existing reports in Alberta province (Alberta Agriculture and Forestry, 2017; Statistics Canada, 2016), and the study by Kulshreshtha and Brown (Kulshreshtha & Brown, 1994), who showed the level of risk aversion is controlled by age and education of farmers. Accordingly, as a large number of farmers in Alberta are educated and younger than 55 years old (Alberta Agriculture and Forestry, 2017; Statistics Canada, 2016), they can be more risk-takers.

Additionally, the mean of the conservation goal factor (μ_c) stands out as a high value, showing that the farmers highly follow the conservation target of the program (i.e., Water for Life Program). This result is supported by the report by the Alberta Irrigation Projects Association (2015), confirming that "… efficiency gains amounted to 26%, measured by the reduction in diversions…". The mean of the irrigation expansion factor (μ_{ie}) appears as a high value, implying that adopting sprinklers explains the irrigation expansion in BRB. Although this finding may contain uncertainty (e.g., due to the model structure), it is also supported by the past report and interviews (Alberta Irrigation Projects Association, 2015; Kulshreshtha & Brown, 1994). The report by the Alberta Irrigation Projects Association (2015) shows that technology is an incentive to farmers for shifting crops from forage to other crops. In addition, Kulshreshtha & Brown (1994) show that, by reviewing different surveys, irrigation expansion in the South Saskatchewan River Basin is the result of a change in technology. The results of the parameter uncertainty analysis are closely aligned with the different reports and interviews in our case study, which further validate the ABAD model.

On the other hand, the result of parameter uncertainty shows that the means of future profit (μ_{fp}), past profit (μ_{pf}), environmental protection (μ_e), and social interaction (μ_s) are not quite identifiable in this study. Although it is difficult to identify the exact sources of the uncertainty, this issue is basically based on the model structure, forcing dataset, or model and observation errors.

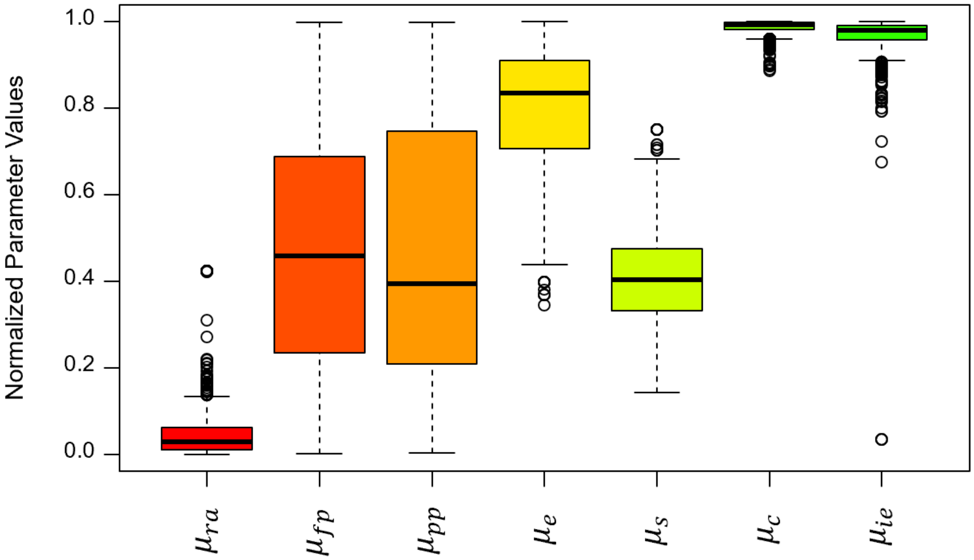

Figure 2.12 The result of parameter uncertainty analysis based on multi-objective optimization

2.8 Conclusion

A better understanding of co-evolving human behaviors with hydrologic systems can enable policymakers to enhance their long-term planning as these behaviors affect the watershed system. An irrigation system improvement is one of the adaptation decisions, which not only affects agricultural water demand but also leads to changing crop patterns and irrigation expansion. To assess the effects of both water-saving technologies and changing cropping patterns on estimates of agricultural water demands, we developed an agent-based agricultural water demand (ABAD) model for the Bow River Basin (BRB) in Alberta, Canada. In comparison with traditional water demand models, which consider the role of humans through exogenous scenarios, the ABAD model attempts to endogenize the relationship between the human and the hydrological systems. The ABAD model revealed a mapping between the basin-scale rebound phenomenon and the socio-economic factors in individual farmers' water conservation decisions, which can help understand the rebound phenomenon and possibly control it through future long-term water policies. Some of the conclusions and highlights of this study include:

- The social interaction factor plays a crucial role in water demand when the farmers' behavior is highly diverse in a society. The social interaction between farmers highly affects the adoption of technology, aligned with the previous study (L. A. Nicol et al., 2008; Ramirez, 2013), and it is an effective factor in the rebound phenomenon.
- The irrigation expansion factor is highly important in water demand in BRB in which the heterogeneity in farmers' behavior is not large. Consistent with previous studies (Berbel & Mateos, 2014; Graveline et al., 2014; Scheierling et al., 2006; Soto-García et al., 2013), this study suggests that irrigation expansion should be restricted to avoid the rebound phenomenon. However, this policy is completely contrary to the main targets of Alberta's

Water for Life Program (Alberta Irrigation Projects Association (AIPA), 2015). Therefore, continuing the purpose of this target could lead to repeated occurrences of the rebound phenomenon. It is also worth mentioning that the irrigation expansion would not be a critical issue in wet years if the irrigated area decreases in dry years.

- The conservation goal factor implies a significant role in any level of heterogeneity. This implies that farmers pay significant attention to the mentioned factors for agricultural water demand. However, the conservation program does not provide any guarantees to avoid the rebound phenomenon; this has also been supported by a previous study (Ward & Pulido-Velazquez, 2008).

This research has raised a few questions worthy of further research. In contrast to many universal laws in physics defined by straightforward mathematical equations, translating human decision-making theories to mathematical equations requires assumptions on modeling details. This research used the theory of bounded rationality for simulating farmers' decision making with certain assumptions on modeling conceptualizations. Future studies need to assess the structural sensitivity of the ABAD model. In other words, it is important to evaluate the model performance under the theory of bounded rationality compared to other social theories in the BRB. Moreover, further research is needed to collect more data on the socio-economic factors of the ABAD model for further model calibration and validation. We believe that socio-hydrological issues are place-specific; therefore, developing a generalized model or transferable methods is not a straightforward task. However, As the ABAD model is built based on a general social theory (i.e., bounded rationality theory), applying this model to other case studies can be helpful for further comparative analysis and the contribution to a generalized model. This model can be integrated with water management models (e.g., MODSIM-DSS) to provide a better understanding of the role of water conservation policy in future long-term planning in the BRB. This research also investigated the feedback mechanism, which can lead to the agricultural rebound phenomenon. Regarding the issue of rebounding agricultural water demand, future studies could explore the most important socio-economic factors in the rebound phenomenon in BRB and investigate how they co-evolve with a hydrological system over time, using sensitivity analysis and scenario analysis. Additionally, it could be investigated how this phenomenon can lead to a system collapse or tipping point in the future due to the limitation on water availability. Addressing these challenges can give us insights to decelerate the effect of rebounding water demand in this complex socio-hydrological system as this phenomenon occurred due to unintended water management consequences.

Author Contributions

Mohammad Ghoreishi developed the methodology under supervision of Amin Elshorbagy and Saman Razavi. Mohammad Ghoreishi wrote the computer codes, conducted all the experiments, and analyzed the results under supervision of Amin Elshorbagy and Saman Razavi. Mohammad Ghoreishi prepared the manuscript, and all the co-authors contributed to the editing of the paper and critically reviewed the manuscript.

Chapter 3

Peering into Agricultural Rebound Phenomenon Using a Global Sensitivity Analysis Approach

This chapter is a slightly modified version of the following paper to increase its consistency with the body of the Thesis. References are unified at the end of the dissertation.

Ghoreishi, M., Sheikholeslami, R., Elshorbagy, A., Razavi, S., & Belcher, K. (2021). Peering into agricultural rebound phenomenon using a global sensitivity analysis approach. *Journal of Hydrology*, *602*, 126739. https://doi.org/10.1016/j.jhydrol.2021.126739

Synopsis

Modernizing traditional irrigation systems has long been recognized as a means to reduce water losses. However, empirical evidence shows that this practice may not necessarily reduce water use in the long run; in fact, in many cases, the converse is true—a concept known as the rebound phenomenon. This phenomenon is at the heart of a fundamental research gap in the explicit evaluation of co-evolutionary dynamics and interactions among socio-economic and hydrologic factors in agricultural systems. This gap calls for the application of systems-based methods to evaluate such dynamics. To address this gap, we use a previously developed Agent-Based Agricultural Water Demand (ABAD) model, applied to the Bow River Basin (BRB) in Canada. We perform a time-varying variance-based global sensitivity analysis (GSA) on the ABAD model to examine the individual effect of factors, as well as their joint effect, that may give rise to the rebound phenomenon in the BRB. Our results show that economic factors dominantly control possible rebounds. Although social interaction among farmers is found to be less influential than the irrigation expansion factor, its interaction effect with other factors becomes more important, indicating the highly interactive nature of the underlying socio-hydrological system. Based on the insights gained via GSA, we discuss several strategies, including community participation and water restrictions, that can be adopted to avoid the rebound phenomenon in irrigation systems. This study demonstrates that a time-varying variance-based GSA can provide a better understanding of the co-evolutionary dynamics of the socio-hydrological systems and can pave the way for better management of water resources.

3.1 Introduction

For many decades, switching to efficient irrigation systems (e.g., sprinklers) has attracted attention as a management option to make better use of water than traditional irrigation systems. However, empirical evidence shows that this reduction may motivate farmers to expand irrigated areas, which may in turn lead to an increase in water use (Berbel & Mateos, 2014; Berbel et al., 2014; Food and Agriculture Organization (FAO), 2017). In complex coupled human-natural systems, this concept is known as the *rebound phenomenon*. This phenomenon occurs when increasing technological efficiency, counter intuitively, leads to an overall increase in water use in the long term, a concept first observed in the field of energy as the *Jevons' paradox* (Jevons, 1866).

The agricultural rebound phenomenon has attracted significant attention, with three general types of methods for its assessment: analytical models (e.g., Gómez & Pérez-Blanco, 2014; Huffaker, 2008), hydro-economic models (e.g., Dagnino & Ward, 2012; Ward & Pulido-Velazquez, 2008), and statistical analyses (e.g., Lecina et al., 2010; Pfeiffer & Lin, 2014). However, little attention has been paid to the feedback loops between the human and hydrological systems, which can explain the agricultural rebound phenomenon. In understanding this phenomenon, socio-hydrological models are useful because they focus on the co-evolutionary dynamics of social and hydrological systems, in which processes interact over different time scales (Sivapalan et al., 2012a; Sivapalan & Blöschl, 2015). The coevolution of slow processes (e.g., upgrading irrigation systems) and fast processes (e.g., runoff) in a socio-hydrological system can result in emergent phenomena (e.g., the rebound phenomenon) in the long run (Sivapalan & Blöschl, 2015). Socio-hydrological models capture the complexity of coevolving human-hydrological systems by updating both socio-economic and hydrological variables based on interactions between the human and the natural systems, using modeling approaches such as system dynamics (e.g., Di Baldassarre et al., 2013) and agent-based modeling (Ghoreishi et al., 2021). Understanding the co-evolutionary dynamics of social-hydrological systems can provide critical insights needed in policy-making to achieve sustainability (Iwanaga et al., 2021; Razavi et al., 2020).

Ghoreishi et al. (2021) developed a socio-hydrological agent-based model (ABM), applied in the Bow River Basin (BRB) in Canada to examine the agricultural rebound phenomenon. Their model, called the agent-based agricultural water demand (ABAD) model, captures the dynamic behaviors of individual farmers in upgrading on-farm irrigation systems and/or changing crop patterns. The BRB is an important sub-basin of the Saskatchewan River Basin (SaskRB) which has faced water security issues in recent years (P Gober & Wheater, 2014; Wheater & Gober, 2013). According to the literature of Jevons' paradox in agriculture (e.g., Berbel et al., 2014; Sears et al., 2018), when efficient irrigation systems reduce the marginal cost of irrigation and water use, a profit-maximizing farmer may increase water use mainly by (1) expanding the irrigated area and/or (2) switching to high-value crops that are also more water-intensive. The ABAD model in the BRB embeds this mechanism to reproduce the rebound phenomenon (Ghoreishi et al., 2021). In addition, compared to the models that demonstrate the agricultural rebound phenomenon based on decisions driven by strictly economic incentives (e.g., Gómez & Pérez-Blanco, 2014), the ABAD model adopts an alternative structure in three ways (Ghoreishi et al., 2021). First, unlike models that are based on the assumption that humans maximize their benefits, or producers maximize profit, ABAD uses a "bounded rationality" decision structure whereby agents have imperfect knowledge of system relationships and values and are only able to seek satisficing solutions rather than optimal ones (Epstein, 1999; Gigerenzer & Selten, 2001; Simon, 1955). Second, most models in the literature have been constructed with economic decision-making rules driven by market-based price incentives (e.g., Gómez & Pérez-Blanco, 2014; Huffaker, 2008), whereas the ABAD model includes economic and social factors (e.g., social interaction among farmers) influencing farmers' decision-making. Third, as opposed to the conceptual or theoretical nature of many of the available models (e.g., Huffaker, 2008), the ABAD model represented an empirical application and was tested in the BRB.

Ghoreishi et al. (2021) investigated the essential socio-economic factors in farmers' decision-making for water demand, as well as the relationship between these factors and water demand dynamics. However, a major research question was unanswered in that work: how can we avoid the agricultural rebound phenomenon? Socio-hydrological modeling of different complex phenomena has advanced our understanding of coupled human-natural systems (Di Baldassarre et al., 2019). However, an explicit evaluation of the co-evolutionary dynamics and interactions among socioeconomic factors that would prevent problematic behavior, including the agricultural rebound phenomenon, is a fundamental research gap. This gap calls for the application of systems-based methodologies that can attribute the systems-scale effect of individual factors and their interaction over the entire factor space.

In this paper, we argue that time-varying global sensitivity analysis (GSA) (Razavi & Gupta, 2019), as a powerful method for systems analysis, can unravel the extent to which different time-varying dimensions of co-evolutionary dynamics influence the rebound phenomenon. Furthermore, this method identifies interactions among model factors (parameter interaction) and can reveal hidden behaviors of models and the underlying systems (Razavi et al., 2021; Saltelli et al., 2008; Sheikholeslami & Razavi, 2020). The concept of parameter interaction implies that independent factors influence the model response in a non-additive manner. It is noteworthy that computation and interpretation of the interactions among factors are nontrivial and challenging (Razavi & Gupta, 2015). As well, although various GSA methods (e.g., derivative-based and variance-based methods) use different philosophies to estimate parameter interactions, the variance-based method can provide a meaningful global estimation of interactions among model factors.

Considerable literature has been published on the application of GSA to coupled human-natural systems with ABMs (e.g., Becu et al., 2003; Brown & Robinson, 2006; Burke et al., 2006; Li & Liu, 2007; Ligmann-Zielinska & Sun, 2010; Schlüter & Pahl-Wostl, 2007). Most of the previous studies used a time-invariant model output or an aggregated model output as a system response for sensitivity analysis (An et al., 2005; Becu et al., 2003; Schlüter & Pahl-Wostl, 2007). These aggregate system responses can lead to a loss of valuable information about the time-varying nature of the model behavior and cannot provide comprehensive insight into the co-evolutionary dynamics of the underlying system (Ligmann-Zielinska & Sun, 2010; Richiardi et al., 2006; Wagener et al., 2001). Alternatively, a time-varying GSA offers detailed information on how variability in model factors affects the dynamics of the model outputs (Gupta & Razavi, 2018; Ligmann-Zielinska & Sun, 2010; Razavi & Gupta, 2019). This type of analysis can deepen the understanding of the co-evolutionary dynamics of complex phenomena in water management, thus, providing insights into future water planning. However, interpretations of GSA results are constrained by the adopted models, which usually represent interactions between human and natural systems simply and imperfectly, although this simplicity is essential to model such complex systems (Yasmina Elshafei et al., 2016). Thus, findings based on any model should be treated with caution before being generalized to the underlying real-world system for sustainable water management.

The objective of this study is twofold: (1) to assess time-varying socio-economic factors that influence the agricultural rebound phenomenon; and (2) to explore ways to avoid the agricultural rebound phenomenon to support sustainable water management. For the first objective, we perform a time-varying GSA on the ABAD model, which can adequately represent the dynamics of agricultural water demand in response to farmers' adaptation to drought (i.e., adopting sprinkler irrigation systems and changing crop patterns) in the BRB. This time-varying GSA on the ABAD model provides valuable information about the dynamical nature of the model behavior and comprehensive insights into the co-evolutionary dynamics of the underlying system. For the second objective, we use the results of the time-varying GSA and the gained insights to explore strategies to control the agricultural rebound phenomenon with the support of literature.

3.2 Rebound Phenomenon in Agriculture

Recent studies have demonstrated that the rebound phenomenon can emerge in the context of agricultural water use, using empirical evidence (Pfeiffer & Lin, 2014; Song et al., 2018) or theoretical research (Qureshi et al., 2010; Scheierling et al., 2006; Ward & Pulido-Velazquez, 2008). Agricultural water use comprises (1) beneficial evapotranspiration, which improves crop production; (2) non-beneficial evaporation, in which water unnecessarily evaporates from wet bare soil or sprinkler system water; (3) non-recoverable runoff/percolation; and (4) recoverable runoff/percolation (Burt et al., 1997). Both recoverable and non-recoverable runoff/percolation, as well as part of the non-beneficial evaporation, can be reduced through improvements in irrigation systems. In this regard, the agricultural rebound phenomenon can be described as follows:

> Improving the efficiency of irrigation systems has generally been viewed as a means to reduce water losses. As a result, farmers adopt more efficient irrigation systems through government subsidies or self-financing, thus, decreasing water use. However, the saved water may, in turn, encourage farmers to increase their irrigated area or shift to more water-demanding crops, which in the long run can increase water use in a river basin.

Two approaches have been used to assess the agricultural rebound phenomenon. A few studies have used price elasticity as a proxy to represent the rebound phenomenon as they suggested a close relationship between price elasticity and the dynamics of water demand (Carlos Mario Gómez et al., 2011; Song et al., 2018). The second method directly compares the agricultural water use before and after shifting to efficient irrigation systems (Lecina et al., 2010; Pfeiffer & Lin, 2014; Song et al., 2018):

$$R = \frac{W_E - W_N}{W_E - W_I} \tag{3.1}$$

where R [-] is the agricultural rebound index, W_E [MCM] is the expected water use after irrigation efficiency improvement, W_N [MCM] is the new water use after irrigation efficiency improvement, and W_I [MCM] is the initial water use before irrigation efficiency improvement. The agricultural rebound index is calculated over a time window. For example, considering 2002 as the reference year, the agricultural rebound indices in 2006 and 2010 represent water demand dynamics in the periods 2002-2006 and 2002-2010, respectively. From Eq. 1, a rebound (R) of say 0.3 represents that 30% of the expected water saving is offset by increased water use. The denominator in Eq.1 is always negative in the sign. Inspired by the field of energy (Saunders, 2008), five conditions of interest can be realized in Eq.1:

- **Backfire** (R>1): The new water use after irrigation efficiency improvement exceeds the initial water use before irrigation efficiency improvement (see the empirical evidence by Lecina et al. (2010) and Pfeiffer and Lin (2014)).
- **Full Rebound** (R=1): The new water use after irrigation efficiency improvement equals the initial water use before irrigation efficiency improvement.
- **Partial Rebound** (0<R<1): The new water use after irrigation efficiency improvement exceeds the expected water use through irrigation efficiency improvement. However, the new water use is still less than the initial water use (see the empirical evidence by Song et al. (2018)).
- **Zero Rebound** (R=0): The new water use after irrigation efficiency improvement equals the expected water use through irrigation efficiency improvement.
- **Super-conservation** (R<0): The new water use after irrigation efficiency improvement is less than the expected water use through irrigation efficiency improvement (see the empirical evidence by López-Gunn et al. (2012)).

Figure 3.1 shows our conceptualization of the rebound phenomenon in agriculture by dividing it into four phases: (1) orientation phase, (2) ideal phase, (3) growth phase, and (4) backfire phase. In phase 1, governments generally introduce a conservation policy (e.g., technical assistance or financial incentives to adopt more efficient irrigation systems with a specific goal of water savings). In phase 2, the agricultural water use almost reaches the pre-determined purpose of the program (R~0). However, this ideal phase can be followed by the growth phase, an increase in agricultural water use due to several side effects (0≤R≤1). This pattern may finally lead to phase4; the backfire phase in which the new water use is even more than the initial water use (R≥1).

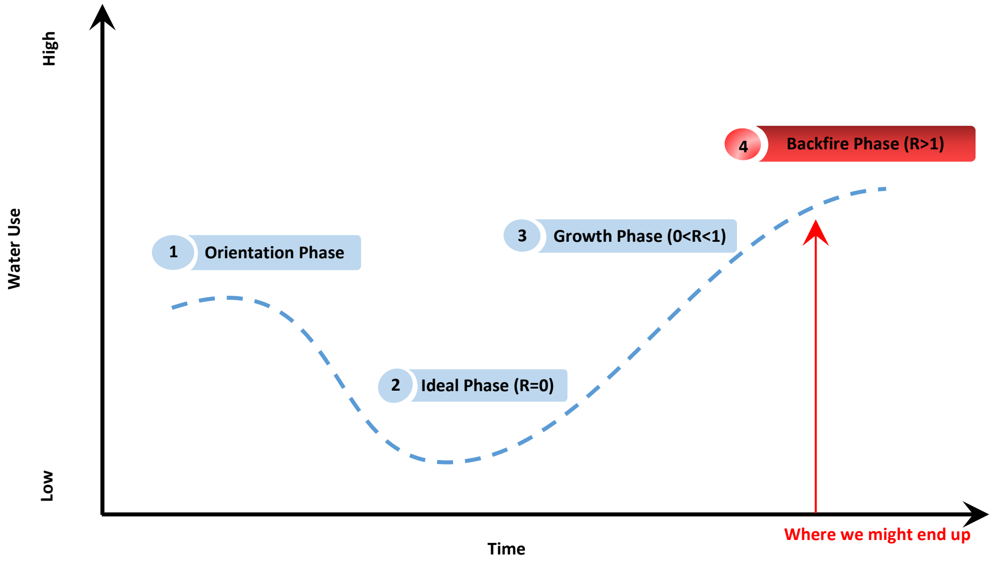

Figure 3.1 Different phases in the agricultural rebound phenomenon

3.3 Methodology

3.3.1 Description of the ABAD model in BRB

The BRB is located in semi-arid southern Alberta, Canada. While the annual precipitation in the headwaters of this basin ranges from 500 to 700 millimeters, the low land areas of the basin, which include the City of Calgary, have an annual precipitation of 412 millimeters (Bow River Basin Council, 2010). Around 80% of Bow River water is provided by snowmelt from the Rocky Mountains, and the rest of the water source is from rain, groundwater, and glacial melt (Bow River Basin Council, 2010). Alberta is required to pass 50% of the natural annual flow to downstream based on the Master Agreement on Apportionment (Prairie Provinces Water Board, 1969). In 2010, the agricultural sector accounted for 71% of total water allocation in the BRB (Bow River Basin Council, 2010). As the water source is fully allocated in the BRB, no new applications for water allocation are accepted (Alberta Queen's Printer, 2000).

The ABAD model consists of two submodels: the monthly water submodel and the yearly human submodel (see Table B.1 for a summary of the main equations, variables, and factors in the ABAD model). The water submodel of ABAD is a lumped monthly water demand model, which is based on the one developed by the United States Department of Agriculture (1970). This model accounts for the soil moisture and meteorological data. The human submodel simulates the individual farmers as agents (2000 agents based on the BRB population). These agents make three decisions: adopting sprinkler systems, changing crops, and expanding irrigated areas. Agents switch from the flood to sprinkler irrigation systems to conserve water. Their second conservation decision is to change from forages to other crops that require less water. When agents save water through their water conservation decisions, they may expand their irrigated area to benefit from the full amount of their water license.

The agents make their decisions based on several socio-economic factors: *conservation policy*, *future profits*, *past profits*, *risk-aversion*, *environmental protection*, *social interaction*, and willingness to *expand irrigation* (Ghoreishi et al., 2021). The government defines conservation policy according to a given government budget and economic considerations. With the case study of BRB, for example, a water conservation target of 30% means that the government plans to reduce the water demand by 30% over a given period with an assumed policy instrument of financial support of the adoption of water-efficient irrigation technology. The future profits represent the expected gross margin per hectare through conservation. In addition to variable costs, agents consider the subsidies provided by the government to improve irrigation systems. The past profits follow the same idea, but it represents the agents' memory from their past gross margins. Risk-aversion suggests the degree to which farmers deviate from their past decisions on water conservation. Environmental protection shows the extent to which agents conserve water in favor of the environment. Social interaction indicates the degree to which farmers' decisions are affected by their neighbors. A willingness to expand irrigation suggests the degree to which an agent uses the saved water to expand irrigation.

To make yearly decisions, agents use different weights for socio-economic factors. The weights show the relative importance of each factor for the agents' conservation decisions. In the ABAD model, these weights are sampled from specified probability distributions (i.e., normal distributions), which represent the heterogeneity in a farming society in terms of farmers' decision-making processes. Following Ghoreishi et al. (2021), we used the ranges of the ABAD model factors shown in Table 3.1. This table shows the lower and upper bounds of means and standard deviations of the normal distributions corresponding to the specified socio-economic factors. The upper bound of the mean for yearly conservation goal (μ_c) is assigned based on the target in the Water for Life Program (i.e., 2% of the total irrigated area was targeted to be under the water conservation program on average each year) (Alberta Irrigation Projects Association, 2015). The mean for irrigation expansion is based on the historical data, while individual farmers can expand their irrigation above or below the historical records. Besides, a large boundary for standard deviations is defined.

Table 3.1 The ranges of the ABAD model factors for sensitivity analysis

Factors	Description	Lower Bound	Upper Bound
μ_{ra}	Mean of a normal distribution for the risk-aversion factor	0	1
μ_{pp}	Mean of a normal distribution for the past profit factor	0	1
μ_{fp}	Mean of a normal distribution for the future profit factor	0	1
μ_e	Mean of a normal distribution for the environmental protection factor	0	1
μ_s	Mean of a normal distribution for the social interaction factor	0	1
μ_c	Mean of a normal distribution for the conservation policy factor	0	0.02

μ_{ie}	Mean of a normal distribution for the irrigation expansion factor	0	0.005
σ_{ra}	Standard deviations of a normal distribution for the risk-aversion factor	0	0.3
σ_{pp}	Standard deviations of a normal distribution for the past profit factor	0	0.3
σ_{fp}	Standard deviations of a normal distribution for the future profit factor	0	0.3
σ_{e}	Standard deviations of a normal distribution for the environmental protection factor	0	0.3
σ_{s}	Standard deviations of a normal distribution for the social interaction factor	0	0.3
σ_{c}	Standard deviations of a normal distribution for the conservation policy factor	0	0.01
σ_{ie}	Standard deviations of a normal distribution for the irrigation expansion factor	0	0.01

To test the ABAD model's performance, Ghoreishi et al. (2s021) used a multi-objective approach for the calibration and validation process. The ABAD model was calibrated on two of its three outputs (i.e., water demand and irrigation system area) and validated on the other output (i.e., cropping patterns). Ghoreishi et al. (2021) indicated that the ABAD model showed a good model performance in simulating agricultural water demand in the BRB. Thus, this model is a good candidate for further analysis of the water demand dynamics and the BRB rebound phenomenon.

3.3.2 Time-varying Variance-based GSA

To improve the understanding of the co-evolutionary dynamics of the rebound phenomenon, we conducted a time-varying variance-based GSA on the ABAD model's rebound index (R). While identifying the most influential model factors over time, we investigated the extent to which the interactions among the socio-economic factors are important in giving rise to the variability of the model response. The variance-based method is capable of exploring the interactions among model factors (Saltelli et al., 2008). For k model factors, the variance of the rebound index (V) can be decomposed by the following variance decomposition formula (Gómez-Delgado & Tarantola, 2006; Saisana et al., 2005):

$$V = \sum_{i} V_i + \sum_{i<j} V_{ij} + \sum_{i<j<m} V_{ijm} + \cdots + V_{12\ldots k} \qquad (3.2)$$

where V_i represents the portion of the rebound index variance that can be explained by varying an individual factor X_i. On the other hand, V_{ij} denotes the portion of the rebound index variance explained by the interaction between X_i and X_j, and so on for higher-order interactions (V_{ijm}, ...).

Using the aforementioned variance decomposition, the first-order (main effect) (S_i) and total-effect (interaction effect) (S_{Ti}) indices (Sobol indices) for all model factors can be calculated as follows (Saltelli et al., 2008):

$$S_i = \frac{V_i}{V} = \frac{V_{X_i}\left[E_{X_{-i}}(R|X_i)\right]}{V(R)} \tag{3.3}$$

$$S_{Ti} = 1 - \frac{V_{X_{-i}}\left[E_{X_i}(R|X_{-i})\right]}{V(R)} = S_i + S_{ij} + S_{im} + S_{ijm} + \cdots + S_{ij\ldots k} \tag{3.4}$$

where S_i is the fractional contribution of variability in factor *i* to *V*, independent of other model factors (*k-1*), S_{Ti} is the overall contribution of a given model factor *i*, including its interaction with other model factors, X_{-i} means all factors but X_i. Following the proposed formulations by Saltelli et al. (2008), we calculated the Sobol indices (S_i and S_{Ti}) and the interactions among model factors ($S_{Ti} - S_i$).

The variance-based sensitivity indices defined in Eq. 3 and 4 can be interpreted as follows: a relatively high S_i means that factor X_i is individually influential on the variability of the rebound index. Importantly, the sum of S_i (of all factors) represents the extent to which all model factors individually influence the rebound index, while the remaining one ($1 - \sum_{i=1}^{k} S_i$) implies the degree to which the interaction among model factors influences the rebound index variability. Thus, if the sum of the first-order indices (S_i) is close to one, it can be interpreted that the interaction effects likely play a limited role in the variability of the rebound index, and accordingly, the model response behaves in an additive manner. In other words, if the model response is additive, then the rebound index variation is the sum of the individual effects of factor variations. Conversely, quantifying a relatively high value of $S_{Ti} - S_i$ means that the interaction of factor *i* with other model factors is highly influential on the rebound index variability.

To conduct a time-varying variance-based GSA on the ABAD model's rebound index, we performed the following procedure:

- **Step 1.** Randomly generate *n* sample points from the feasible ranges of the model factors (Table 3.1).
- **Step 2.** Run the ABAD model *n* times for the sampled model factors over the study period.
- **Step 3.** Calculate the rebound index using Eq. 1 for every year of the ABAD model response.
- **Step 4.** Estimate the variance-based sensitivity indices using Eq. 3 and 4 and obtain the time series of S_i and S_{Ti}

- **Step 5.** Compute $S_{Ti} - S_i$ to represent the interaction of model factor i of any order with every other factor.

In this study, we used a pre-specified factor grouping strategy for the time-varying variance-based GSA (Table 3.2). This strategy helps reduce the dimensionality of the factor space to analyze the ABAD model and reduce the computational cost of the sensitivity analysis (Saltelli et al., 2008). Furthermore, it has been shown that grouping-enabled GSA can provide a better understanding of complex models by identifying dominant/influential groups of factors that significantly contribute to the variability in model outputs (e.g., Huo et al., 2019; Sheikholeslami et al., 2019). Therefore, because we intend to use the interpretations of the GSA results to explore the implications for sustainable water management, grouping model factors can possibly help policymakers to understand and use these factors to control the agricultural rebound phenomenon. In the present study, we defined the first group as the *economics group*, which includes all monetary factors. For example, since the conservation policy factor in the ABAD model is based on a governmental budget and economic considerations, we included this factor in the economics group. The risk-aversion factor can also be considered in the economics group based on past research (e.g., (Kulshreshtha & Brown, 1993)). Therefore, we classified the means of normal distributions corresponding to the past profits, future profits, risk-aversion, and conservation policy factors as the economics group. As well, we specified a *heterogeneity group* to represent the variability in the farmers' decision-making regarding different socio-economic values. If all farmers make a decision in the same manner, the value of this group factor becomes zero. Otherwise, the more the farmers behave differently in decision-making, the higher the heterogeneity group's value becomes. Therefore, standard deviations of all factors were included in the heterogeneity group. All other factors (i.e., social interaction, environmental protection, and irrigation expansion) were treated as individual factors for our analysis.

Table 3.2 Groups of factors, their components, and descriptions for a time-varying variance-based GSA on the ABAD model

Group of Factors	Description of Group	Group Components
Economics group	Monetary values of farmers' decision-making	Mean of a normal distribution for past profit (μ_{pp}) Mean of a normal distribution for future profit (μ_{fp}) Mean of a normal distribution for risk-aversion (μ_{ra}) Mean of a normal distribution for conservation policy (μ_c)
Heterogeneity Group	Variability in the farmers' decision-making	Standard deviations of a normal distribution for the risk-

	aversion factor (σ_{ra})
	Standard deviations of a normal distribution for the past profit factor (σ_{pp})
	Standard deviations of a normal distribution for the future profit factor (σ_{fp})
	Standard deviations of a normal distribution for the environmental protection factor (σ_{e})
	Standard deviations of a normal distribution for the social interaction factor (σ_{s})
	Standard deviations of a normal distribution for the conservation policy factor (σ_{c})
	Standard deviations of a normal distribution for the irrigation expansion factor (σ_{ie})

Following Ghoreishi et al. (2021), we used the feasible parameter ranges of Table 3.1 and the Progressive Latin Hypercube Sampling (PLHS) strategy proposed by Sheikholeslami and Razavi (2017) to draw sample points from those ranges randomly. The PLHS strategy samples the factor space progressively and as uniformly as possible, thereby facilitating the evaluation of the stability and convergence of the GSA at each iteration. In this study, we generated 10 sub-samples with 20,000 points (total sample size of 10*20,000 = 200,000). This multi-sampling sequential approach helped us monitor the convergence of the GSA results iteratively at each sub-sample and stop the algorithm when the desired level of stability was reached. To conduct the variance-based GSA, we considered the rebound index as the system response in the ABAD model, and we performed the analysis from 2002 to 2015, a period that includes multiple droughts in the BRB. The rebound index was dynamically calculated using an expanding window with the fixed initial water use (W_I) in 2002 and new water use (W_N) in each year. In this study, the expected water use (W_E) is assumed to reduce by 30% of the initial water use (W_I) from 2002 to 2015, based on Alberta Irrigation Projects Association (AIPA) (2015).

3.4 Results

Figure 3.2 shows the envelope of the simulated rebound index for the sampled model factors in the BRB by the ABAD model, along with the time-varying variance-based GSA of the rebound index. Figure 3.2.a indicates how variability in model factors affects the dynamics of the rebound index from 2002 to 2015. The highly reduced rebound index in wet years (e.g., 2004 and 2010) shows the decreased agricultural water demand, compared to 2002, with the adoption of more efficient irrigation technologies in the BRB. Our time-varying GSA results show that the economics group, most of the time, is the most influential group among all other factors (or groups of factors), affecting the rebound phenomenon in the BRB (Figure 3.2b). Furthermore, the importance of this group indicates an upward trend over the simulation period, meaning that the economics group plays an increasingly important role over time (from 2002 to 2015) in the variability of the rebound phenomenon, compared to the other factors or groups of factors. We argue that the adoption of more efficient irrigation technologies improves the value of water as an economic good for farmers in the BRB; thus, the economic value of water becomes more important with time in farmers' decision-making on water use.

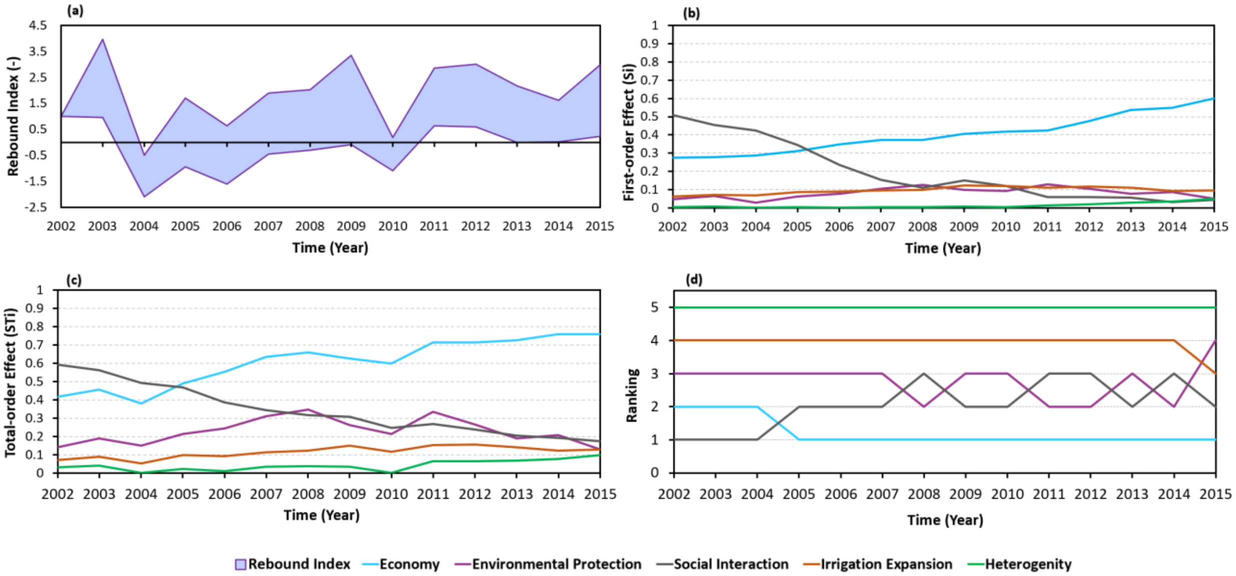

Figure 3.2 a) The envelope of the simulated rebound index for the sampled model factors by ABAD between 2002 and 2015, considering 2002 as the reference year, b) The first-order sensitivity indices (S_i), c) The total-order effect indices (S_{Ti}), and d) The factor rankings based on the total-order effect indices (1 is the most important factor, and 5 is the least important factor), and. These sensitivity indices were obtained using the time-varying variance-based GSA of the rebound index, considering the socio-economic factors and the pre-specified groups of factors in the BRB from 2002 to 2015.

The results of the first-order effect (Figure 3.2b) also show that social interaction is a crucial factor in the rebound index; however, its importance declines over time. The downward trend shows that the neighbors' conservation actions (i.e., adopting new irrigation systems and changing crop patterns) become less important in farmers' decision-making about water use over time.

Accordingly, we attribute this pattern to the fact that when agents adequately learn about adaptation to drought from their neighbors, the effect of their interactions decreases over time. Figure 3.2b indicates that the environmental protection and the irrigation expansion factors stay at around 10% of the rebound index variability. However, the contribution of the irrigation expansion factor slightly increases over time, which shows that the role of this factor in the rebound index becomes increasingly influential over the long term. This finding indicates that the growing contribution of irrigation expansion to the rebound phenomenon is revealed in the long term. The heterogeneity group does not show any significant role in the rebound index in the BRB (Figure 3.2b) and, thus, can be considered as the least influential factor. This result shows that farmers in the BRB make conservation decisions in the same manner; therefore, the heterogeneity of farmers' decision-making does not play a significant role in the rebound phenomenon.

Figures 3.2c and 3.2d depict the time-varying GSA results for the total-order effect sensitivity indices, as well as the associated factor ranking in the ABAD model. Compared to the results of the first-order effect (Figure 3.2b), the total-order effect shows the overall importance of the factors, including interactions with all other factors. Figure 3.2c shows that the contribution of the factor interactions does not change the overall trend in the results of the GSA. For example, the economics group remains the most important factor in the rebound phenomenon, considering its interactions with other factors over most of the simulation period (Figure 3.2d). In comparison to Figure 3.2b, what is interesting in Figures 3.2c and 3.2d is a decrease in the ranking of the irrigation expansion factor after including all factor interactions. However, the contribution of the social interaction factor increases, and this factor becomes more important in the rebound index with its parameter interaction (Figures 3.2c and 3.2d), compared to its individual effect (Figures 3.2b). We attribute this increasing role of social interaction to the fact that farmers are willing to learn more about their neighbors when they observe a considerable change in their neighbors' benefits. Therefore, given the factor interactions, our results indicate that the interaction of some socioeconomic factors can significantly change the perception of their contributions to the rebound phenomenon, compared to their individual contributions.

Moreover, our results of the time-varying GSA (Figure 3.2) demonstrate that conducting a GSA experiment based on an arbitrary snapshot of the (time-independent) model response is inadequate for factor prioritization and can contaminate the assessment of the sensitivities (Ligmann-Zielinska & Sun, 2010). For example, note how the ranking of socioeconomic factors changes over time in the ABAD model. As can be seen from Figure 3.2d, the ranking of the social interaction factor successively switches from one to three over the simulation time. This time-varying contribution of factors is a challenging issue for most ABMs due to the lack of adequate tools for the explicit evaluation of the ABM dynamics (Parker et al., 2003; Richiardi et al., 2006).

Based on the method of variance-based GSA (Saltelli et al., 2008), one minus the sum of all first-order sensitivity indices ($1 - \sum_{i=1}^{k} S_i$) quantifies the extent to which the impact of factors in the ABAD model behaves in an non-additive manner – the larger this difference, the more interaction the factors exert. Figure 3.3 shows the degree of interactions of the ABAD model factors. This result reveals that around 20% of the rebound index variability (averaged over time) cannot be explained solely by the individual effect of the model factors, and that this variability is due to the interactions among the socio-economic factors in the ABAD model. To further investigate the nature of the interactions, based on the Sobol method (Saltelli et al., 2008), Figure 3.4 shows the effect of factor interaction ($S_{Ti} - S_i$) on the rebound index. The factor interactions of the heterogeneity group and the irrigation expansion factor have limited contribution to the variability of the rebound phenomenon. On the other hand, the parameter interactions of the economics group, environmental protection, and the social interaction factors play a major role in the variability of the rebound index. The high parameter interaction of the economics group and social interaction suggests that the variability of the rebound index can increase through simultaneous changes on both the profits of irrigation and the social network.

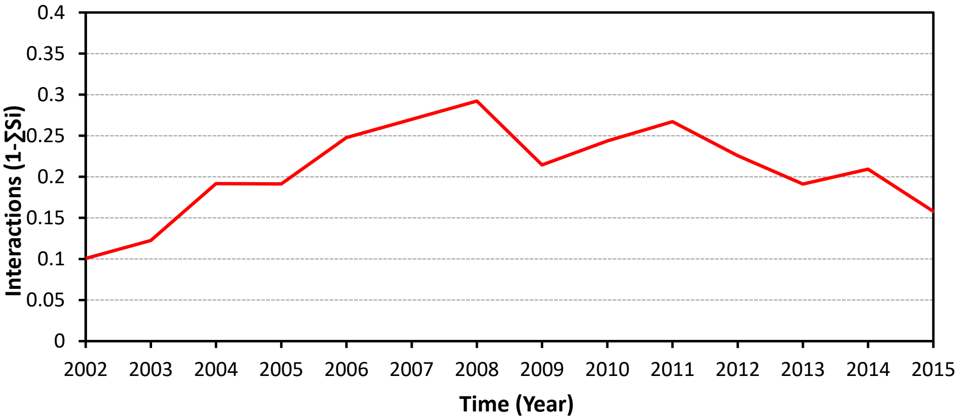

Figure 3.3 Interaction quantification of the ABAD model factors.

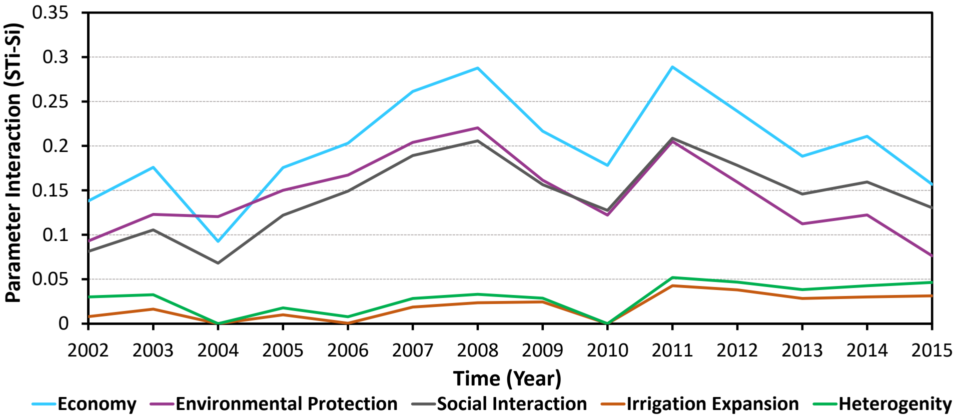

Figure 3.4 The time-varying GSA with the factor interaction ($S_{Ti} - S_i$) on the rebound index considering the socio-economic factors and the pre-specified groups of the factors in the BRB for a representative period (2002-2015).

As an alternative visualization tool, we plotted the trajectories of sensitivities for the ABAD model to better illustrate the relationship between first-order and total-order effects. Figure 3.5 shows the differences between the total-order effect and the first-order effect as a function of the first-order effect over the period 2002–2015, with the squares and circles on each curve representing the years 2002 and 2015, respectively. The 1:1 ratio between the parameter interaction and the first-order effect indicates that the contribution of the parameter interaction and the first-order effect to the total order-effect are equal. Therefore, factors with a large contribution of interaction effects would lie toward the top-left corner in Figure 3.5. For example, the environmental protection factor shows a large interaction effect in the rebound index, while the irrigation expansion factor shows only a small effect. Additionally, the social interaction factor shows a time-varying interaction effect in the rebound index.

Among all socio-economic factors, the trajectories of sensitivities for the social interaction factor and the economics group exhibit a large variability, as shown in Figure 3.5. This large variability indicates that the magnitude of sensitivity indices (i.e., factor importance) for these factors is highly changeable from 2002 to 2015, and, thus, time-varying GSA is highly beneficial for understanding the impact of these factors on the rebound index. In addition, as shown in Figure 3.5, the trajectories of sensitives for the social interaction factor and the economics group reveal regular patterns over time: the first-order effect increases for the economics group but decreases for the social interaction factor. However, there is no clear pattern for trajectories of sensitivities for other factors. In particular, the heterogeneity and irrigation expansion factors have a very irregular pattern. It is also noticeable that the trajectory of sensitivity for the environmental protection factor shows a nearly closed orbit, suggesting a somewhat circular pattern. This pattern occurs because the environmental protection factor makes the same contribution to the beginning of the simulation period (a square in Figure 3.5) and in the final year (a circle in Figure 3.5) of the analysis. In other words, the sensitivity indices in 2015 are approximately equal to the indices in 2002.

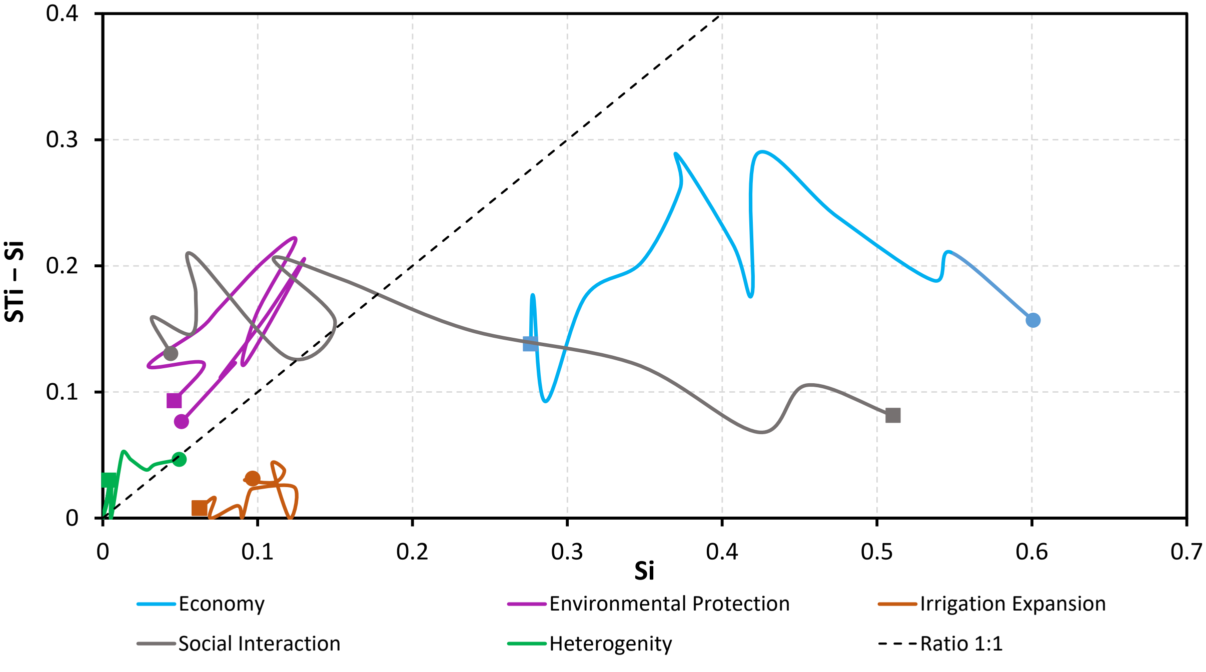

Figure 3.5 The difference between the total-order effect and the first-order effect ($S_{Ti} - S_i$) in the y-axis as a function of the first-order effect (S_i) in the x-axis, using the time-varying GSA on

the rebound index considering socio-economic factors and the pre-specified groups of the factors in the BRB for a representative period (2002–2015). Each curve corresponds to the time evolution of a factor's sensitivity index. The square and circle on each curve represent the years 2002 and 2015, respectively.

3.5 Discussion

3.5.1 Are the GSA Results consistent with empirical evidence?

We investigated the literature to support the GSA results, mainly from socio-economic data and previous studies on the rebound phenomenon. As shown in Figure 3.2, we argued that the growing economic value of water improves the economic group's contribution to the rebound phenomenon. Indeed, as farmers adopt efficient irrigation systems, they are able to irrigate more profitable crops, which are often more water-dependent (e.g., specialty crops). Therefore, economic productivity (i.e., gross margin per hectare) increases, leading to an increasing reliance on irrigation from an economic perspective. This issue is considered in the ABAD model as individual farmers adopt more profitable crops by comparing the economic productivity of forage and that of other crops.

The observed data in the Canadian province of Alberta can support our GSA findings and our argument about the economic value of water. According to past studies (Kulshreshtha & Brown, 1993, 1994; Nicol et al., 2008), from individual farmers' perspective, high-tech irrigation systems enable them to obtain higher yields, expand their irrigation, and switch to higher-value crops, all of which increase agricultural benefits and might motivate farmers to withdraw more water. As well, global evidence from the Food and Agriculture Organization (FAO, 2017) suggests that the availability of high-tech irrigation systems convinces farmers that irrigation secures higher profits over time; thus, this perception may result in an increase in water use in the long term. This local and global evidence supports the notion that the economics group increases in importance over time.

The GSA results show that irrigation expansion plays a less significant role in the short term compared to the long term. This finding is supported by both empirical evidence (Berbel et al., 2014; Food and Agriculture Organization (FAO), 2017) and theoretical research (Berbel & Mateos, 2014; Huffaker, 2008; Pfeiffer & Lin, 2014; Ward & Pulido-Velazquez, 2008), indicating that irrigation expansion is more influential in the long-term in the agricultural rebound phenomenon in response to improvements in irrigation systems. In other words, irrigation expansion is a gradual process as farmers want to ensure they have saved enough water to expand their irrigation. Also, the cost of irrigation expansion limits farmers from short-term responses to available water.

The GSA results reveal that the individual effect of social interaction in the rebound phenomenon is not as high as that of irrigation expansion, which aligns with the findings based on local interviews (Kulshreshtha & Brown, 1994). These interviews implied that the contribution of the irrigation expansion is more than that of the farmers' neighbors (social interaction) to the water use. However, the total effect of social interaction becomes more important than irrigation expansion due to the high factor interactions.

3.5.2 How Can the GSA Results Inspire Sustainable Water Management?

It is widely accepted that improving irrigation systems has certain benefits: the saving of labor, the more precise application of chemicals and fertilizers, and the potential to switch to higher-value crops (FAO, 2017). However, this improvement can conflict with sustainable development goals if it gives rise to an increase in water use (Di Baldassarre et al., 2019). Our GSA results reveal that the economics group is the most important factor in the rebound phenomenon, with an increasing role over time. Crop value has a direct influence on the economic functions of the ABAD model, motivating farmers to switch to high-value crops. The literature on agricultural rebound has shown that the rebound phenomenon is more likely to happen in areas where high-value crops are also more water-intensive crops with high-tech irrigation systems enabling farmers to make an economic decision to produce these higher-value crops (Berbel et al., 2014; Food and Agriculture Organization (FAO), 2017). Thus, the adoption of water-intensive crops will affect the water demand dynamics, which may lead to the rebound phenomenon.

Previous studies have indicated that farmers' interactions and the associated increase in social capital can be a means to achieve an effective collective action (the action taken by a group of people for shared interest) to mitigate the rebound phenomenon (Dessart et al., 2019; Ferraro et al., 2011). Effective collective actions could be enhanced by community participation and raising awareness through formal channels to inform an individual farmer of the average water use in their community. Collective actions can control the rebound phenomenon by enabling farmers to compare their water use with that of their neighbors, which may be an effective strategy in reducing water use (e.g., Dessart et al., 2019; Le Coent et al., 2017). Le Coent et al. (2017) showed that farmers with high water use could be motivated to reduce their water use when they compared their own water use with the average water use of their neighbors. Additionally, our analysis of the ABAD model identified social interaction as the second most important factor. In the ABAD model, the degree to which the farmers' network is connected influences the effectiveness of the collective action. Therefore, raising farmers' awareness through formal channels will affect this connectedness, leading to a change in the dynamics of the rebound phenomenon.

The literature on the agricultural rebound has shown the important influence of irrigation expansion on the rebound phenomenon (Berbel & Mateos, 2014; Berbel et al., 2014; FAO, 2017). Our GSA results also confirm that irrigation expansion increases the rebound phenomenon in the long term. Jurisdictions often support irrigation expansion because it can result in economic growth. For example, economic prosperity was a key goal of Alberta's Water for Life program (Alberta Irrigation Projects Association (AIPA), 2015). However, from a sustainable development perspective, improving irrigation efficiency along with irrigation expansion in the BRB is likely to result in the rebound phenomenon (i.e., the backfire phase in Figure 3.1), as the irrigation expansion is introduced as one cause of the rebound phenomenon in its literature (Berbel et al., 2014; Sears et al., 2018). To prevent the rebound phenomenon, improvements in irrigation systems could be accompanied by restrictions to irrigated areas. Using the ABAD model, it is possible to determine the effect of irrigation restrictions on the rebound phenomenon as it explicitly simulates the effects of farmers' decisions. Aligning with previous studies (Berbel & Mateos, 2014; Berbel et al., 2014), another strategy to avoid the rebound phenomenon could be to reassign water allocations to reduce farmers' water rights (Marston & Cai, 2016). As the ABAD model includes crop yields in the economic functions of individual farmers, any reassigned water allocations would affect the dynamics of water use and then the rebound phenomenon. It is worth mentioning that such regulatory controls should be carefully monitored as they may raise incentives to infringe the regulations.

Finally, what are the implications of the quantified interaction effects for decision-makers? Our results show that a few factors (e.g., irrigation expansion and heterogeneity) have a small interaction effect on the variability of the rebound index, while other factors (e.g., social interaction) have a relatively large interaction effect. From the decision-makers' point of view, a model parameter with a large interaction effect should not be individually considered in the decision-making process; thus, such a factor should be comprehensively considered along with the model's other socio-economic factors. On the other hand, factors with small interaction effects can be considered individually by decision-makers; one at a time. For example, policymakers could design a strategy related to irrigation expansion (e.g., introduce incentives to limit expansion) independently, as the interaction effect of this factor has a limited contribution to the rebound index. However, to control the rebound phenomenon, any strategies related to the social interaction factor (e.g., raising farmers' awareness through formal channels such as an extension or technical assistance measures) should be accompanied by strategies associated with economic factors (e.g., governmental support for irrigating crops with low water requirements), as the economic group and the social interaction factor have parameter interactions.

3.6 Conclusion

The improvement of irrigation systems has been traditionally identified as a means to enhance resilience to drought in agriculture. However, evidence from across the globe reveals that such improvements may not lead to the expected reduction in water use, which may, paradoxically, even increase—a concept known as the rebound phenomenon. Sustainable water management requires a good understanding of both the co-evolutionary dynamics of the coupled human-natural systems and the influential socio-economic factors in the agricultural rebound phenomenon. To achieve this purpose, we used a previously developed Agent-based Agricultural Water Demand (ABAD) model, which captures the rebound phenomenon in the Bow River Basin (BRB), Alberta, Canada. Based on the time-varying variance-based Global Sensitivity Analysis (GSA) that we performed on the ABAD model, the main conclusions of this study include the following:

- Time-varying GSA provides a better understanding of the co-evolutionary dynamics of the coupled human-natural systems, as opposed to most GSA applications on ABMs, which use the time-independent, final state of the model output.
- The economics group is the most influential factor in the agricultural rebound phenomenon in the BRB, with an upward trend over time (i.e., increasing importance).

This study suggests generating new breeds of high value-crops with relatively less water need.

- Our GSA results revealed that the social interaction factor had a high total-effect on the rebound phenomenon in the BRB. We highlighted the significant role of community participation as a strategy to improve community awareness and avoid the rebound phenomenon. Considering the high value of parameter interaction for the social interaction factor, this study suggests that any strategies related to the social interaction factor should be followed by other strategies associated with the economic group to control the rebound phenomenon.
- In the BRB, the irrigation expansion factor plays a vital role in the rebound phenomenon in the long term. We proposed and discussed how restrictions on irrigated areas and farmers' water rights could prevent individual farmers from over-using their saved water, thus, in turn, preventing the rebound phenomenon.

We acknowledge that these interpretations of the results are constrained by the structure, assumptions, and simplifications of the ABAD model. While the ABAD model simulates the agricultural water demand dynamics over a relatively short time period, the length of this period is comparable to most previous studies on the rebound phenomenon, and it captures the years before and after several droughts in a river basin (Berbel et al., 2014). The ABAD model uses a lumped water submodel, which is a limitation of this study. Despite the limitation, the primary findings of this study are broadly consistent with the literature on the rebound phenomenon and water management (e.g., Berbel & Mateos, 2014; Berbel et al., 2014; Food and Agriculture Organization, 2017). This study shows that the time-varying variance-based GSA analysis can pave the way for developing a method that explicitly evaluates co-evolutionary dynamics in a socio-hydrological model for better management of water resources.

Author Contributions

Mohammad Ghoreishi developed the methodology with Razi Sheikholeslami under supervision of Amin Elshorbagy and Saman Razavi. Mohammad Ghoreishi wrote the computer codes, conducted all the experiments, and analyzed the results under supervision of Amin Elshorbagy and Saman Razavi. Mohammad Ghoreishi prepared the manuscript, and all the co-authors contributed to the editing of the paper and critically reviewed the manuscript.

Chapter 4

Cooperation in a Transboundary River Basin: a Large Scale Socio-hydrological Model of the Eastern Nile

This chapter has been written in manuscript style. References are unified at the end of the dissertation. A slightly modified version of this chapter will be submitted to an international peer-reviewed journal for possible publication.

Synopsis

Managing transboundary rivers is a complex issue due to the coevolutionary behavior of hydrological and human systems that may lead to conflict and cooperation among riparian countries. The conflict-and-cooperation phenomena in transboundary rivers have been widely studied in different contexts (e.g., resolving conflicts, analyzing C&C, and investigating influential factors in C&C). However, an important issue is to investigate the feedback mechanisms that explain how conflict and cooperation co-evolve with the water resources and socio-economic conditions in a transboundary river. This study develops a model to quantify and simulate the riparian countries' willingness to cooperate in the Eastern Nile River Basin, where Ethiopia, Sudan, and Egypt are located, from 1983 to 2016. Our results show that relative political stability and foreign direct investment can explain Ethiopia's decreasing willingness to cooperate within the basin between 2009 and 2016. Our modeling results suggest that a very low value of willingness to cooperate can lead to "free rider" behavior, where riparian countries focus more on unilateral projects than on multilateral ones. Further, we show that the 2008 food crisis may account for Sudan recovering its willingness to cooperate with Ethiopia. Our results also show that a long-term lack of trust among the riparian countries may have reduced basin-wide cooperation. This research ultimately proposes a socio-hydrological framework, indicating how fully coupling the developed model with a water resources model can enable future research to explore the evolution of cooperation pathways among the riparian countries affected by changing dam operation in the future and reveal the actions that may fuel conflict in the basin.

4.1 Introduction

There exist more than 250 international transboundary rivers worldwide, accounting for about 60% of the world's freshwater (United Nations Environment Programme, 2002). Managing transboundary rivers is a complex issue as riparian countries with different socio-economic statuses and interests share water resources; their decisions about water affect other countries. The contested use of these shared water resources can lead to fierce disputes and even water wars (Wolf et al., 2003; Zeitoun & Mirumachi, 2008).

The complexity of transboundary rivers partly arises from the coevolutionary behavior of hydrological and human systems (Lu et al., 2021; Sivapalan & Blöschl, 2015; Wei et al., 2019). To depict socio-hydrological factors involved with a transboundary river system, Zeitoun and Warner (2006) developed a qualitative conceptual framework of hydro-hegemony (i.e., hegemony at a river basin as a result of either a riparian's position or historical water rights). In general, upstream countries have superior power over water due to their riparian position. In upstream countries, water management decisions (e.g., operating rules and dam construction) affect streamflow, resulting in socio-economic benefits for different sectors, such as agriculture and industry. However, these water management decisions might influence the streamflow downstream, which can motivate downstream countries to negotiate with upstream countries to increase socio-economic benefits (Nicol & Cascão, 2011). The negotiations between countries can lead to different levels of cooperation (e.g., a treaty signed by riparian countries) (Zeitoun & Mirumachi, 2008), which in turn can change water use and/or dam operating rules or result in dam construction along the river basin (Cascão, 2009).

Conflict and cooperation (C&C) in transboundary water resources have been widely investigated in different contexts. Studies include those focused on resolving conflicts (e.g., Madani et al., 2014; Rogers, 1969; Zarezadeh et al., 2012), analyzing C&C (e.g., Mirumachi & Van Wyk, 2010; Wolf, 2007; Wolf et al., 2003), and investigating influential factors in C&C (e.g., Dinar et al., 2010; Zeitoun et al., 2011). However, most previous studies on transboundary rivers have treated C&C as scenarios (i.e., external variables of an underlying system): investigating how C&C as boundary conditions influence the water resources and socio-economic conditions of riparian countries. Recently, socio-hydrology researchers have paid increasing attention to the C&C dynamics in transboundary rivers due to co-evolution of social and hydrological systems (Di Baldassarre et al., 2019; Lu et al., 2021; Wei et al., 2019). Unlike most previous research, studies based on socio-hydrological models treat cooperation as an internal variable that can co-evolve with hydrological and socio-economic variables in a transboundary river system (Lu et al., 2021). From this perspective, an important question in socio-hydrology research arises about why C&C dynamics emerge in a socio-hydrological system and how these dynamics evolve over time because of complex interactions of hydrological, socio-economic, and political factors (Di Baldassarre et al., 2019). The ambitious goal of transboundary socio-hydrology research is to provide opportunities to avoid conflicts in transboundary rivers (Wei et al., 2019).

As a transboundary river, the Nile River Basin has a long history of cooperation and conflict (Cascão, 2009; Nicol & Cascão, 2011). Water conflicts are more severe in the Eastern Nile Basin (ENB), where Ethiopia, Sudan, and Egypt are located, due to the water scarcity and disagreements over the use of the Eastern Nile water. A recent dispute arose when Ethiopia announced the Grand Ethiopian Renaissance Dam (GERD) construction in 2011, which would impact the hydrological regime in the ENB. Because Sudan lacks any multi-year water storage facility, a regular pattern of monthly flow is important for the water requirements of its municipalities, industry, and agriculture (Abdul Latif Jameel Water and Food Systems Lab, 2014). However, Egypt is more concerned about the annual inflow volume to the Aswan High Dam (AHD), as the AHD has a large storage capacity and can buffer seasonal fluctuations (Abdul Latif Jameel Water and Food Systems Lab, 2014). Thus, Egypt and Sudan, as the downstream countries, have several concerns about the impacts of GERD that might occur during both the filling and the operation phases of the dam.

Many studies on the Nile River Basin have addressed the trade-offs among riparian interests and analyzed potential developments in the basin (Arjoon et al., 2014; Block & Strzepek, 2010; Digna et al., 2018; Geressu & Harou, 2015; Jeuland & Whittington, 2014; Kahsay et al., 2015; Nigatu & Dinar, 2016; Sangiorgio & Guariso, 2018; Strzepek et al., 2008; Wheeler et al., 2018, 2020, 2016). In general, these studies are either based on multi-objective optimization (Geressu & Harou, 2015; Wheeler et al., 2018), which seeks to quantify trade-offs among a variety of interests in an optimal setting, or scenario analyses (Mulat & Moges, 2014a; Wheeler et al., 2016), which assess potential alternatives for basin management. These studies have provided valuable insights into the Nile River Basin; however, like many other studies of transboundary rivers (e.g., Gandolfi & Togni, 1997; Giuliani & Castelletti, 2013), they treated C&C as boundary conditions. An important issue is to assess how dam operations/constructions affect the downstream countries from a socio-hydrology modeling perspective. Treating cooperation as an internal variable that can co-evolve with hydrological and socio-economic variables, this assessment is complex because as the impacts of water management decisions become more severe, riparian countries become more alert to react. In other words, the severity of the impacts and riparian behavior co-evolve. Socio-hydrological modeling of co-evolutionary behavior can be used to reveal how C&C dynamics emerge in the Eastern Nile River Basin as the behavior of hydrological and socio-political systems co-evolve. Socio-hydrological models can be used to investigate basin-wide cooperation opportunities and highlight actions and events leading to conflict. However, unlike the validation process in hydrological models in which good sources of data might be available, validating transboundary socio-hydrological models is complicated because quantitative data on cooperative events are sparse (Lu et al., 2021).

This study aims to quantify and simulate the riparian countries' willingness to cooperate in the ENB and thus, to view the basin-wide cooperation dynamics as a problem that is hypothesized to arise due to the interaction of hydrological and socio-political factors. By developing a socio-hydrological model, we provide an explanation of how hydrological and socio-political factors led to cooperation in the ENB from 1983 to 2016. This simulation is followed by model validation based on qualitative data and narratives in the basin. However, we acknowledge that our results and interpretations are constrained by the model's conceptualization and assumptions. We ultimately propose a transboundary framework that indicates how our developed model can be fully coupled with a water resources model, in future work, to provide a comprehensive socio-hydrological decision aid tool for the ENB. This framework can highlight actions leading to potential conflict in the ENB (i.e., when the riparian countries are not willing to cooperate and act independently to maximize their benefits), enabling policymakers to explore the evolution of cooperation pathways among the riparian countries affected by the GERD operation.

4.2 Historical Events of Conflict and Cooperation in the Nile River Basin – Case study

With a main stem of 6,695 km, the Nile River is the longest transboundary river in the world. This river basin is shared among 11 countries: Tanzania, Uganda, Rwanda, Burundi, The Democratic Republic of the Congo, Kenya, Ethiopia, Eritrea, South Sudan, Sudan, and Egypt. The river has two main tributaries, the White Nile and the Blue Nile (Abay) (Figure 4.1), each with distinct hydrologic regimes. These tributaries join at Khartoum, whose annual rainfall is under 300 millimeters (Nile Basin Initiative (NBI), 2012). The ENB (Figure 4.1), covering the Blue Nile, Atbara (Tekezze), and the Baro Rivers, contributes 85–90% of the Nile River water flowing into Egypt with high seasonality; the White Nile contributes 10–15% of the water with a steady streamflow.

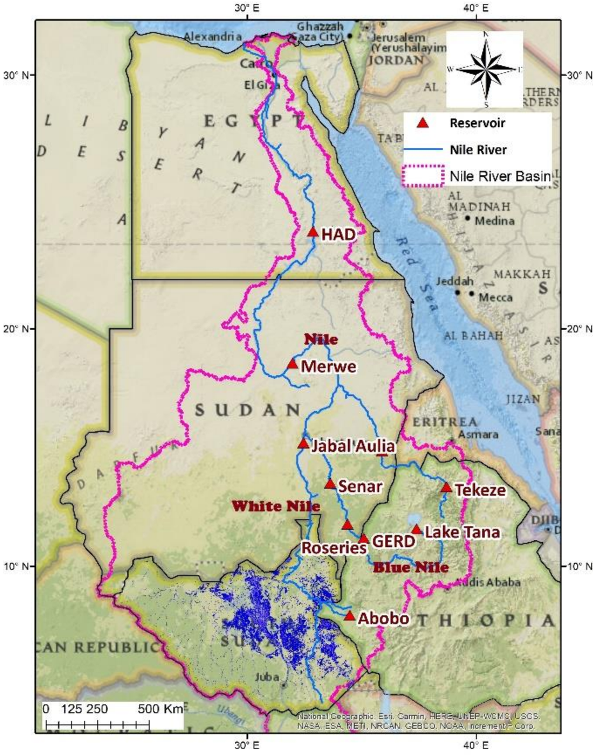

Figure 4.1 The Nile River Basin with a particular focus on the three riparian countries of Egypt, Sudan, and Ethiopia

Figure 4.2 indicates the main cooperation and conflict events from 1959 to 2020 among the riparian countries in the Nile River Basin. Under the 1959 treaty, Egypt and Sudan agreed on the use of the Nile River—an agreement that excluded Ethiopia (Food and Agriculture Organization, 1959) and other riparian countries. This agreement was followed by the construction of the Roseires Dam and the AHD in 1966 and 1970, respectively (Food and Agriculture Organization, 1959) (Figure 4.1). The 1968–1973 drought and food security issue in Ethiopia heightened awareness among Ethiopians of the importance of the Nile water and the need to negotiate with the other riparian countries (Nicol & Cascão, 2011). In 1983, several countries in the basin formed the Undugu group to achieve regional cooperation, but Kenya, Tanzania, and Ethiopia joined only as observers (Kagwanja, 2007; Seide, 2014). In addition to the Undugu project, the riparian countries formed the Technical Cooperation Commission for the Promotion and Development of the Nile

(TECCONILE) in December 1992 to pave the way for the guidelines for the Nile Basin Initiative (NBI) (Kagwanja, 2007; Seide, 2014). Signed in 1999 by nine countries—Egypt, Sudan, Ethiopia, Uganda, Kenya, Tanzania, Burundi, Rwanda, and the Democratic Republic of Congo—the NBI was intended "to achieve sustainable socio-economic development through the equitable utilization of and benefits from the shared Nile Basin water resources" (NBI, 2019). This partnership was followed by an agreement named the Joint Multipurpose Project (JMP) in 2003 for widespread economic improvements along the river basin.

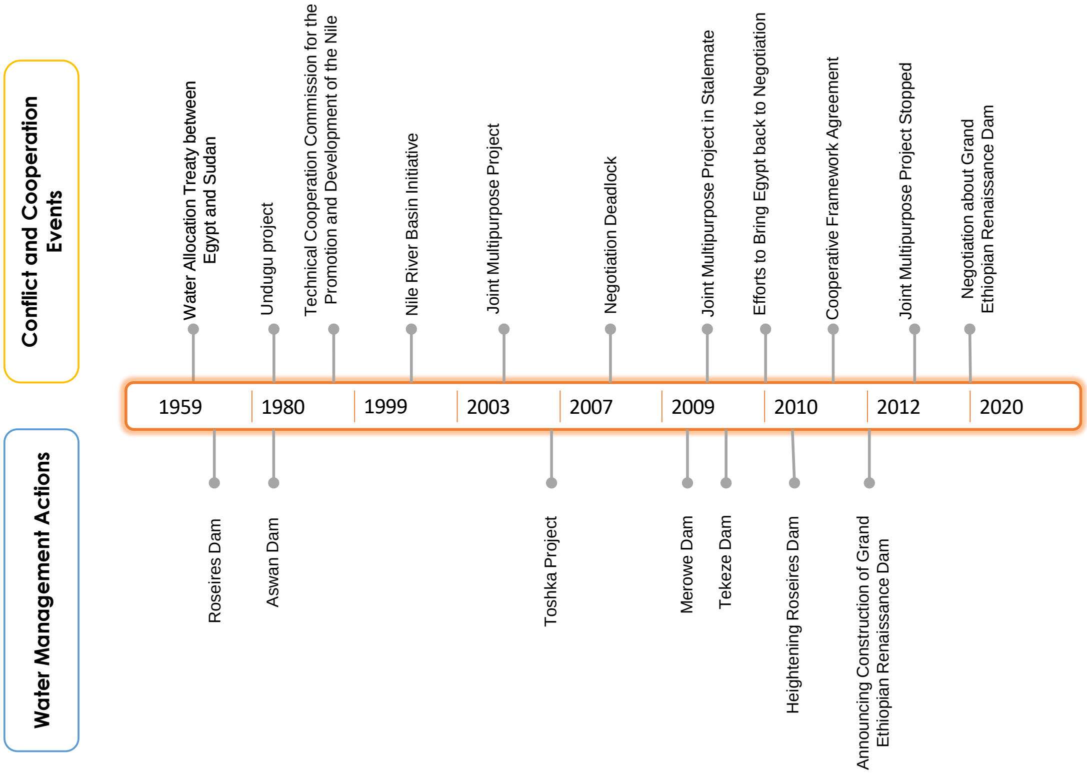

Figure 4.2 Timeline of conflict and cooperation events and water management actions in the Nile River Basin, with a particular focus on the three riparian countries of Egypt, Sudan, and Ethiopia

However, the cooperative agreements did not prevent countries from making unilateral developments (Cascão, 2009; Nicol & Cascão, 2011). The irrigated areas extended rapidly in Egypt with significant foreign investments. In 2005, Egypt also launched an important part of the Toshka project (Nicol & Cascão, 2011), transferring water to irrigate a part of the Western Desert of Egypt to expand the agricultural area. Ethiopia launched the Tekeze Dam, with a capacity of 9. $3x10^9$ m^3, on the Atbara River in 2009 (Figure 4.1), improving its hydropower generation (Cascão, 2009). Sudan completed and opened the Merowe Dam, with a capacity of $12.5x10^9$ m^3, on the main Nile River (Figure 4.1), increasing the country's hydropower capacity (Cascão, 2009). It is worth mentioning that the Tekeze Dam and the Merowe Dam were built for single-purpose hydropower generation, as opposed to the Roseires Dam and the AHD that were designed as multi-purpose reservoirs.

Although the countries' negotiations on several agreements passed through many different stages, and a Cooperative Framework Agreement (CFA) was going to be reached, representatives from Sudan and Egypt expressed strong disagreement about a part of this agreement because they were concerned about possible negative impacts on their historical water rights. Their objections led to a negotiation deadlock in 2007 (See Article 14b in the Annex of CFA (2010)). This impasse weakened the high expectations for the JMP and resulted in a stalemate in 2009. Despite attempts to bring Egypt back to the negotiation table, efforts were unsuccessful. Afterward, the upstream countries without Burundi, the Democratic Republic of Congo, Sudan, and Egypt reached a CFA in 2010 for further cooperation. However, as a two-thirds majority of all riparian countries was required, the agreement was not ratified. As a reaction to CFA, Sudan and Egypt froze all their participation in the NBI (Nicol & Cascão, 2011). Also, Egypt convinced Burundi and the Democratic Republic of Congo not to sign the agreement (Nicol & Cascão, 2011).

Between 2010 and 2012, the Arab Spring became a game changer, creating political upheaval in Egypt (Knaepen & Byiers, 2017; Salman, 2013). Meanwhile, the global food crisis of 2008 and South Sudan's independence from Sudan in 2011 convinced Sudan to refocus on the agricultural sector, for which it received foreign investments between 2008 and 2012. To proceed with an ambitious agricultural improvement plan, Sudan started raising the height of the Roseires Dam in 2010, and the country rejoined the NBI in 2012 (Cascão & Nicol, 2016; Nicol & Cascão, 2011). Given the new situation in the basin, as well as the substantial foreign investments and improved political stability in Ethiopia, this country announced the construction of GERD, with a total storage capacity of 74 km^3, which could pose a potential water threat to Egypt and possibly to Sudan (Cascão & Nicol, 2016). Although the JMP did not continue because financial support was reduced, the negotiations were ongoing among Egypt, Sudan, and Ethiopia, as Egypt considers GERD an existential water threat. These ongoing negotiations convinced Egypt, Sudan, and Ethiopia to sign a declaration in 2015 on GERD (Agreement on Declaration of Principles between Egypt, Ethiopia, and Sudan, 2015). According to this agreement, Ethiopia, Sudan, and Egypt will agree on a guideline of GERD operation and filling phases; however, the dam owner may adjust the rules from time to time while informing downstream countries of the situation leading to this adjustment. Since then, growing concerns about the negative impacts of GERD filling and operation phases on the downstream countries have heightened disagreements among Egypt, Sudan, and Ethiopia (Abdul Latif Jameel Water and Food Systems Lab, 2014; Kahsay et al., 2017; Mulat & Moges, 2014b; Wheeler, 2017).

However, there is strong belief in the region that the riparian countries can overcome any problems if they agree on cooperation policies for filling and operating GERD (e.g., Whittington et al., 2014). For designing these cooperation policies, each country's strengths in water availability, agriculture, and hydropower will be of interest. Ethiopia's strengths lie mainly in its position. The country contains the headwaters of the ENB, covering the Blue Nile, Atbara (Tekezze), and Baro, with a contribution of 85–90% to the Nile River water flowing into Egypt (NBI, 2012). According to NBI (2012), Ethiopia is also strong when it comes to hydropower potential, with 1,946 MW of existing capacity and 15,409 MW of potential capacity compared with Sudan's 3,280 MW potential capacity, and Egypt's 2,800 MW potential capacity. Sudan's strengths lie mainly with its agriculture. Of the 33.2 million ha of rainfed agriculture in the Nile Basin, 45% (14.7 million ha) is located in Sudan (NBI, 2016). Although low rainfall prevents Egypt from rainfed farming (NBI, 2016), the country's strengths lie with irrigation. The country has the largest irrigated crop area in the Nile Basin, with 3.45 million ha. Crop yields in Egypt are therefore much higher than those in the other Nile countries, including Sudan and Ethiopia: yields in the Nile countries are generally only one-sixth to one-half of the yields in Egypt (NBI, 2012). Also, the average annual potential evapotranspiration of Ethiopia is around one-half of that of Egypt; thus, hydrologically, Ethiopia is a better location for dam constructions than Egypt (NBI, 2012).

4.3 Method

We first identify the contributing socio-hydrological factors in the C&C dynamics in the ENB. This identification is verified by the qualitative and quantitative literature on the ENB as well as the literature on transboundary rivers. Based on these socio-hydrological factors, we conceptualize the key feedback loops between the hydrological and social systems in the ENB, using systems thinking to reveal the causes, effects, and relations in a system (Ford & Ford, 1999). Finally, using the conceptualized model, we develop a socio-hydrological model to quantify and simulate the riparian countries' willingness to cooperate in the ENB and thus, to simulate the basin-wide cooperation dynamics.

4.3.1 Contributing socio-hydrological factors in the conflict and cooperation phenomenon

Based on the literature on the Nile River Basin and other international transboundary rivers, we proposed a list of the contributory factors in the riparian countries' willingness to cooperate in the ENB, as our ENB system conceptualization. In this study, the countries' willingness to cooperate is proposed as an indicator of how likely they are to change their dam operations or build a reservoir for multilateral projects. The countries' willingness to cooperate ultimately creates the dynamics of the basin-wide C&C.

4.3.1.1 Political stability

Political stability has been recognized as an important factor in countries' willingness to cooperate in decisions about transboundary rivers (Zeitoun & Warner, 2006; Zeitoun et al., 2017) and the Nile River Basin (Cascão, 2009; Di Nunzio, 2013). A country's political stability index represents indicators of political stability, such as government stability and the presence of protest or civil war (Worldwide Governance Indicators, 2021). The annual political stability index is calculated by Worldwide Governance Indicators (2021) with a composite measure of several representative factors (See Table C.1 in the appendix for more information).

The importance of political stability in the Nile River Basin can also be reflected in quantitative data. Figure 4.3 shows the effect of the Arab Spring on Egypt's political stability in 2011 and in the years following. After 2010, Egypt's political stability dramatically declined, paving the way for Ethiopia's GERD announcement (Nasr & Neef, 2016). Figure 4.3 also indicates the low values of Sudan's political stability, with fluctuations after South Sudan's independence from Sudan in 2011. It was reported that the unstable nature of its politics motivated Sudan to return to the NBI, so it could proceed with its ambitious water development plans (Nicol & Cascão, 2011). Given the deteriorating political stability in Sudan and Egypt and the increasing political stability in Ethiopia after 2010, it was reported that Ethiopia announced the GERD construction, potentially threatening the downstream countries (Tawfik, 2016).

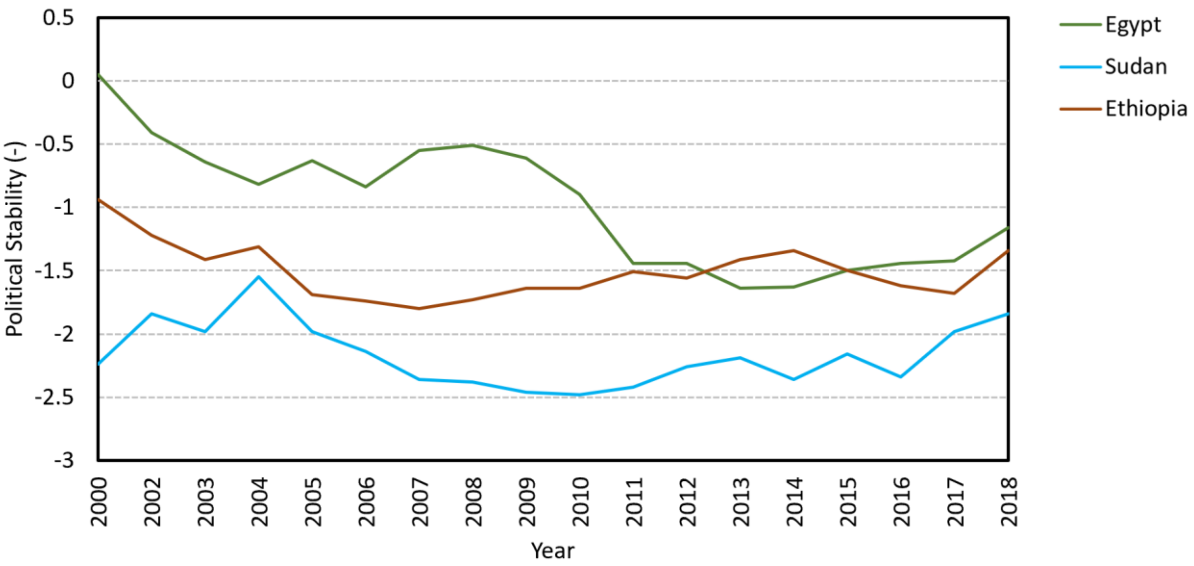

Figure 4.3 The political stability from 2000 to 2018 of Egypt, Sudan, and Ethiopia (-2.5 weak; 2.5 strong) (Food and Agriculture Organization Data, 2020b)

4.3.1.2 Foreign direct investment

Foreign direct investment (FDI) is an investment in a country by another country (World Bank, 2021). Several qualitative studies have found that FDI influences C&C in transboundary rivers, including the Nile Basin (Cascão, 2009; Waterbury, 2008; Whittington et al., 2014; Zeitoun & Mirumachi, 2008; Zeitoun & Warner, 2006; Zeitoun et al., 2011, 2017). Figure 4.4 shows that, after 2003, FDI in Sudan remained almost stable with minor changes. However, in Egypt and Ethiopia, FDI substantially fluctuated in some periods (i.e., Egypt between 2003 and 2018; Ethiopia between 2012 and 2018). It was proposed as a hypothesis that low FDI motivated Ethiopia to embrace the NBI in the 1990s (Zeitoun et al., 2011). However, with increasing FDI after 2011 (Figure 4.4), Ethiopia's willingness to cooperate with Sudan and Egypt declined (Cascão & Nicol, 2016). Figure 4.4 also reveals Egypt's changing FDI, which is connected to cooperative events in the basin in 2007 and 2015. It was reported that, in 2007, a year in which Egypt enjoyed high level of foreign investments, the country had disagreements with other riparian countries, but in 2015, when Egypt's foreign investments were relatively low, it was more likely to cooperate (Cascão & Nicol, 2016). Thus, we hypothesize that an increase in riparian countries' foreign investments reduce their willingness to cooperate.

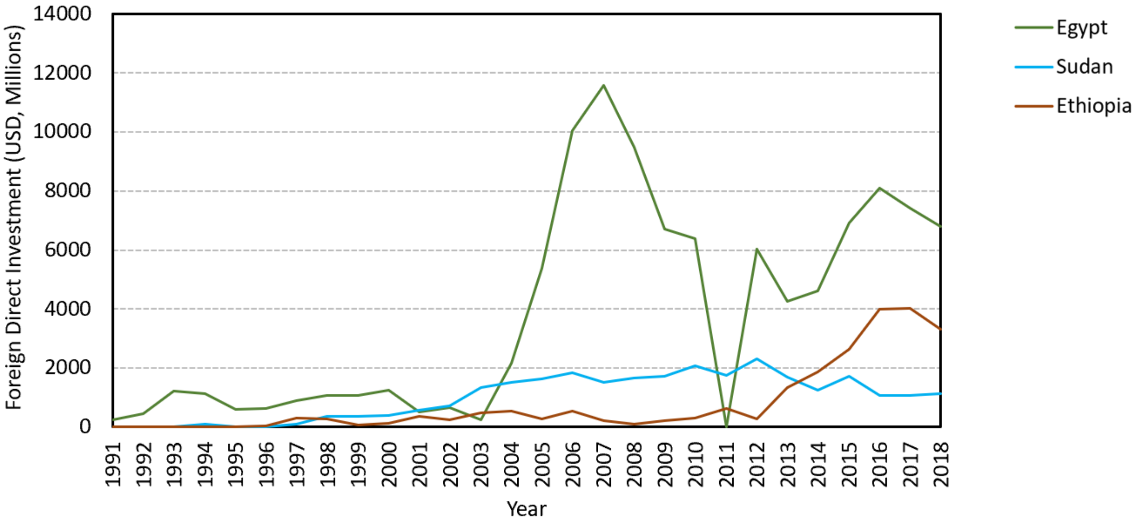

Figure 4.4 The foreign direct investments from 1991 to 2018 (Food and Agriculture Organization Data, 2020a) in Egypt, Sudan, and Ethiopia

4.3.1.3 Countries' memory of cooperation

Countries' memory of cooperation is proposed to indicate the effect of the historical basin cooperation on countries' willingness to cooperate. Past studies have suggested the important role of memory and trust in C&C in transboundary rivers, including the Nile River Basin (Cascão, 2009; Metawie, 2004; Tafesse, 2001; Whittington et al., 2014; Zeitoun & Mirumachi, 2008). In general, positive memories of basin cooperation can lead to trust and an improved environment in the basin (Whittington et al., 2014). In this research, the memory is defined as a weighted average of countries' historical willingness to cooperate over their memory span. Also, the 1959 treaty between Egypt and Sudan, for example, triggered feelings of profound mistrust among other riparian countries in the Basin (Whittington et al., 2014). However, the NBI provided a unique opportunity for the riparian countries to improve their cooperative plans and build trust in the basin (Metawie, 2004).

4.3.1.4 Future water storage capacity

The existing Nile plans show a considerable potential to increase the future water storage capacity in the basin, particularly in Ethiopia and Sudan, by 2050 (NBI, 2016). For hydropower generation, the installed capacities are planned to increase to 26,000 MW in the basin by 2050 (NBI, 2016). Reservoirs and dams have been constructed in the Nile River Basin as a result of unilateral or multilateral projects undertaken by the riparian countries (Nicol & Cascão, 2011). For example, the Roseires and the Aswan High Dams were built as a result of the 1959 treaty in Sudan and Egypt, respectively (Food and Agriculture Organization, 1959). Thus, the desire to increase reservoir storage in Sudan and Ethiopia through multilateral projects, like the Roseires Dam and the AHD, can be an important factor in the countries' willingness to cooperate in the basin (Food and Agriculture Organization, 1959).

4.3.1.5 Food gap

The food gap shows the difference between food consumption and the produced food from rainfed and irrigated areas. The food gap has been recognized as an important factor in the C&C within the Nile River Basin (Kagwanja, 2007; Nicol & Cascão, 2011). This factor can motivate riparian countries to cooperate on agricultural developments. For example, Ethiopia's population growth and food security issues have convinced Ethiopia to negotiate with other countries to achieve water development plans that increase the country's food production (Nicol & Cascão, 2011). In another example, although Sudan stopped participating in the NBI in 2007, the 2008 food crisis in Sudan and its agricultural development plans later convinced this country to return to the NBI (Cascão & Nicol, 2016; Nicol & Cascão, 2011).

4.3.1.6 Energy gap

The energy gap represents the difference between actual hydropower generation and potential hydropower capacity. Because the Nile River Basin has a high potential power capacity, several hydropower plants have been proposed under unilateral/multilateral agreements, in addition to existing hydropower plants (NBI, 2016). To fill its energy gap, Ethiopia has proposed the GERD hydropower plant, fueling concerns in the basin and indicating the role of the energy gap in conflicts among countries (Cascão & Nicol, 2016). However, the energy gap can also be a motivation for cooperation among the riparian countries in the Nile Basin (Basheer et al., 2018; Wheeler et al., 2018). In fact, energy gap can increase or decrease by changing reservoir operation rules. Cooperation relates to the fact that generated hydropower in a country can be exported to other countries in the basin.

4.3.2 Key feedback loops between the hydrological and social systems

Figure 4.5 shows our Eastern Nile Basin Socio-hydrological (ENSH) model conceptualization with a specific structure for each country. As mentioned in Section 4.2, GERD construction started for hydropower generation to decrease Ethiopia's energy gap. However, the growth in the energy gap may reduce Ethiopia's willingness to cooperate within the ENB. Ethiopia reduces the water released to Sudan and Egypt in the recurring filling period (Whittington et al., 2014). Also, GERD operation is anticipated to smooth the peaks of the Blue Nile flow and increase the low flows of the spring period (Abdul Latif Jameel Water and Food Systems Lab, 2014).

To meet the transboundary requirements (i.e., historical water rights of the riparian countries) after the construction of GERD (GERD transboundary flow), we conceptualize two separate amounts of transboundary water released to Sudan and Egypt: (1) water used for hydropower generation in

Ethiopia (water for hydropower) and (2) water released during the GERD filling period. Ethiopia's available surface water is affected by the climate and other water uses in Ethiopia (i.e., the water supply for agriculture). It is proposed that the food gap problem motivates countries to adopt technology in agriculture (Gebrehiwot & van der Veen, 2015; Juana et al., 2013; Tadesse et al., 2009), thus, increasing irrigated areas and crop yields, which boost food production, and decrease the food gap. Like the energy gap problem, an increase in Ethiopia's food gap may reduce Ethiopia's willingness to cooperate (Basheer et al., 2018; Kagwanja, 2007; Nicol & Cascão, 2011; Wheeler et al., 2018). As mentioned in Section 4.3.1, the increase in relative political stability and foreign investments, as external socio-political factors, can negatively affect willingness to cooperate.

Sudan has available surface water that consists of the transboundary flow from Ethiopia and the Equatorial Lakes, and rainfall. Part of this available surface water flows into Egypt as transboundary flow. The food and energy components are similar to the ones explained above for Ethiopia. Egypt's available surface water depends mostly on the transboundary flow, which is positively impacted by cooperation in the ENB. As for hydropower production in Egypt, our ENSH model ignores it because it makes only a small contribution to Egypt's energy production (NBI, 2016). The main two water uses considered for Egypt in the model are for agriculture, with a similar structure to the Ethiopian and Sudanese components, and for municipalities, which are impacted by Egypt's investments in desalination and wastewater treatment.

In contrast to Ethiopia, Sudan and Egypt may become more willing to cooperate with other countries in the basin when their food/energy gaps increase (Nicol & Cascão, 2011). Decreasing transboundary flow from Ethiopia reduces energy/food production downstream, thereby, increasing Sudan's and Egypt's willingness to cooperate within the ENB to increase their shares of surface water. Through negotiation, downstream countries can encourage upstream countries to release more water by proposing multilateral projects and helping to conserve water flows upstream. In principle, increasing upstream reservoir storage capacity can increase available surface water, which in turn can increase transboundary flow. This future reservoir storage would enable the riparian countries both to decrease food and energy gaps (Abtew & Melesse, 2014; Blackmore & Whittington, 2008) and to address the projected changes in interannual variability of the Nile flow by 50% due to climate change (Siam & Eltahir, 2017). Therefore, Sudan and Egypt can be generally interested in increasing Ethiopia's future reservoir capacities, provided that agreements are reached regarding the filling and operation of such reservoirs. Intuitively, the riparian countries' willingness to cooperate increases cooperation in the ENB, which creates a positive environment and trust in the basin. Thus, creating a history of basin cooperation can increase the riparian countries' willingness to cooperate.

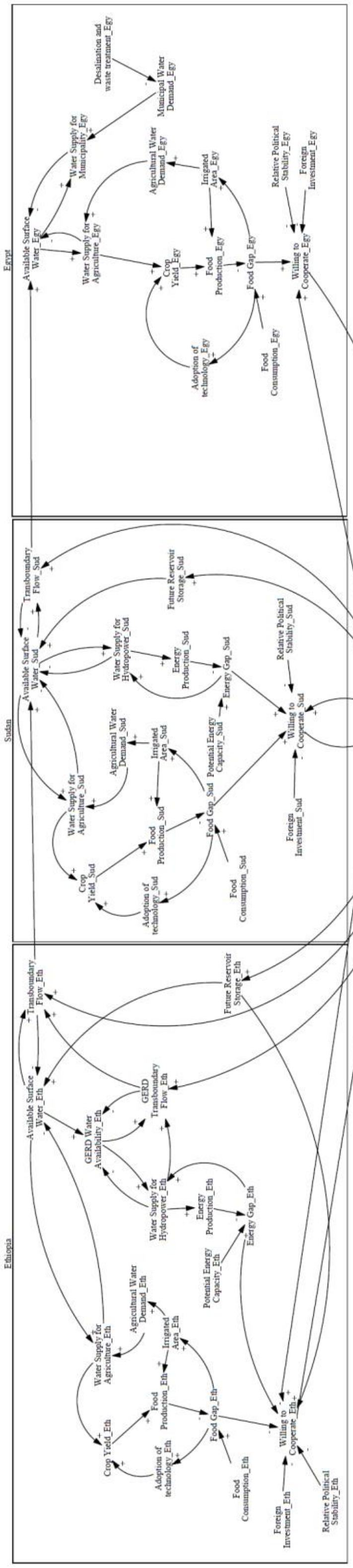

Figure 4.5 Conceptualization of the Eastern Nile Basin socio-hydrological (ENSH) model, showing feedback mechanisms in the Basin.

4.3.3 Model overview

The yearly ENSH model quantifies and simulates the willingness of Ethiopia, Sudan, and Egypt to cooperate from 1984 to 2016. The riparian countries' willingness to cooperate likely encourages cooperation throughout the basin. The ENSH model is a model of human behavior that takes inputs from the external water resources model developed by Abdelkader & Elshorbagy (2021). In past research, the collective memory in human-water systems has been mostly simulated by pre-specified and deterministic differential equations following the common top-down approach in the literature of socio-hydrology (e.g., Di Baldassarre et al., 2013; Viglione et al., 2014). In this research, we adopted a bottom-up approach using agent-based modeling that accounts for stochasticity in social behaviors (by introducing random variables to the model) in the simulation of each country's memory to represent both uncertainty and heterogeneity in countries' decision making.

The water resources model simulates monthly streamflow, food production, food consumption, and energy production (Abdelkader & Elshorbagy, 2021). Using simulated food production, food consumption, and energy production, the human model quantitatively simulates the willingness of countries to cooperate by year. We determined three agents based on the number of riparian countries in the ENB that are policymaker agents. As mentioned in our model conceptualization, we determined several socio-political variables: energy gap, food gap, relative political stability, foreign direct investments, countries' memory of cooperation, and future reservoir storage. Following the study by Ghoreishi et al. (2021), we assumed different weights for socio-political and hydrological factors. Each of these weights shows the extent to which the riparian countries emphasize any of the socio-political and hydrological factors. Assigning these weights for each country enables us to capture the heterogeneity among the various policymakers within the ENB. In this study, we made assumptions, based on the literature of the Nile, for choosing these weights (more details are given in Section 4.3.6).

4.3.4 Model Inputs

The inputs to the human model are based on yearly socio-political data for each riparian country (Table 4.1). The annual political stability index is collected from Worldwide Governance Indicators (2021). The potential dam and energy capacities were defined for each country based on proposed dams and potential hydropower generation in the ENB (NBI, 2012, 2016). Table 4.1 shows all model inputs with their time and spatial resolutions.

Table 4.1 Description of the data, their time/spatial resolutions, and sources (dash means that the data are fixed in the model over time)

Data	**Time Resolution**	**Spatial Resolution**	**Source**
Political stability index	Annual	Country	(Food and Agriculture Organization Data, 2020b)

Foreign direct investment	Annual	Country	(Food and Agriculture Organization Data, 2020a)
Potential energy capacity	-	Country	(NBI, 2012)
Potential dam capacity	-	Country	(NBI, 2016)

4.3.5 Water resources model

The water resources model has been previously calibrated and validated by Abdelkader & Elshorbagy (2021) and simulates daily water, hydropower, and agricultural crop growing and consumption dynamics in the ENB from 1981 to 2016. This water resources model constitutes a hydrological model using the soil water assessment tool (SWAT), which is a spatially semi-distributed model. The first two years (i.e., 1981 to 1982) were used as a spin-up period. Using the dynamically dimensioned search (DDS) calibration algorithm (Tolson & Shoemaker, 2007), the hydrological model was calibrated and validated to daily and monthly streamflow data.

The water resources model simulates water demand/supply for municipal, industrial, and irrigation use in the basin. Using the simulated water demand/supply, this model simulates the food/energy production and food consumption of each riparian country. Water is supplied from each dam to different demand sites based on the priority rules from the highest priority to the lowest one: municipal, industrial, and agricultural sites. The sources of water supply for Sudan and Ethiopia are river flows and rainfall; however, due to surface water scarcity in Egypt, this country uses more diverse water sources, including deep and shallow groundwater, wastewater reuse, and desalination (more details in Abdelkader et al. (2018)). For each agricultural, municipal, and industrial site, daily water demand is calculated. The municipal water demand is calculated by multiplying the per capita water demand by the population at a particular municipal site. According to Allen et al. (1998), the agricultural water demand is simulated by calculating crop evapotranspiration with the effect of soil moisture shortage and an irrigation efficiency factor. Also, the industrial water demand is defined by the input data series for each site.

After simulating demand for each water demand sector, the water resources model simulates daily hydropower generation for each dam based on dam release and a headwater reservoir. Food production is simulated for both irrigated and rainfed areas in the ENB by multiplying crop yields and agricultural areas for 20 crop groups (Abdelkader & Elshorbagy, 2021). To calculate crop yields, Abdelkader & Elshorbagy (2021) simulated the adjusted crop yields due to water shortage according to Doorenbos and Kassam (1979). In addition, food consumption is simulated by multiplying per capita food consumption by the national population for each country.

4.3.6 Human model

We define the “willingness to cooperate” (WC) of a riparian country as a variable in the range zero (i.e., no cooperation) to one (i.e., perfect cooperation) and propose Equations 4.1 through 4.6 for its estimation, based on the theory of reference dependence (Schmidt, 2003). This theory suggests that the benefits and losses are evaluated relative to a reference point in human decision making (Schmidt, 2003). This reference point can be the status quo (Tversky & Kahneman, 1991) or an aspiration level (Siegel, 1957). In this study, for the agricultural sector, food production (FP) is evaluated relative to food consumption (FC). For hydropower, energy production (HP) is evaluated relative to potential HP energy capacity (PEC). For future reservoir storage, as a result of basin cooperation, the reservoir storage under construction (S) is evaluated relative to a country's potential dam capacity (PDC). Political stability (PS) and foreign direct investment (FDI) are evaluated relative to their maximum historical values.

To develop our proposed formulations (Equations 4.1, 4.3, 4.5), we used the concept of additive and multiplicative effects in decision making (Anderson, 1965; Keeney, 1974). The additive effect implies that an effect of an extreme variable moderately decreases by another more neutral variable; however, through the multiplicative effect, an extreme variable can produce an exaggerated effect (Hensley & Levin, 1976). We assumed that the energy gap, the food gap, and future reservoir storage have additive effects on willingness to cooperate, while the other factors (i.e., relative political stability, foreign direct investment, and countries' memory from past cooperation at the basin) have multiplicative effects. This assumption means that the effects of a riparian's energy gap, food gap, and future reservoir storage are moderately impacted by each other, and the effects of other variables can significantly affect a country's willingness to cooperate. Thus, near zero values of multiplicative factors (e.g., a very bitter memory of past cooperation) can make willingness to cooperate near zero even if the other multiplicative variables have considerable values.

Ethiopia's willingness to cooperate (Equation 4.1) is the sum of the food gap, the energy gap, and future reservoir storage multiplied by relative political stability, foreign direct investment, and the country's memory. Based on our model conceptualization for Ethiopia, to consider the inverse effect of the food gap, willingness to cooperate includes food production (i.e., irrigated and rainfed areas multiplied by the corresponding crop yields (Equation 4.2)) divided by food consumption in Ethiopia. Also, the inverse effect of the energy gap is considered by the division of energy production by potential energy capacity. As relative political stability and foreign direct investment vary from 0 to 1 (i.e., low to high values), subtracting them from 1 produces an inverse effect between these variables and a willingness to cooperate. Unlike these variables, the country's memory positively affects its willingness to cooperate. In contrast to Ethiopia's conceptualization, the food gap has a direct effect on the willingness of both Sudan and Egypt to cooperate (Equations 4.3 and 4.5) through the division of food consumption by food production. The direct effect of the energy gap on Sudan is also captured by the division of potential energy capacity by energy production. Thus, willingness to cooperate can be written for Ethiopia ($\mathrm{WC_{Eth}}$), Sudan ($\mathrm{WC_{Sud}}$), and Egypt ($\mathrm{WC_{Egy}}$) as follows:

$$WC_{Eth,t} = \left(\beta_{1,Eth}.\frac{FP_{Eth,t}}{FC_{Eth,t}} + \beta_{2,Eth}.\frac{HP_{Eth,t}}{PEC_{Eth}} + \beta_{3,Eth}.\frac{S_{Eth,t}}{PDC_{Eth}}\right)^{\alpha_{1,Eth}}.\left(1 - PS_{Eth,t}\right)^{\alpha_{2,Eth}}.\left(1 - FDI_{Eth,t}\right)^{\alpha_{3,Eth}}.\left(\frac{CS_{Eth,t}}{n}\right)^{\alpha_{4,Eth}} \qquad 4.1$$

$$FP_{Eth,t} = \mathrm{A}_{\mathrm{ig},Eth,t}.CY_{ig,Eth,t} + \mathrm{A}_{\mathrm{rf},Eth,t}.CY_{rf,Eth,t} \tag{4.2}$$

$$WC_{Sud,t} = \left(\beta_{1,Sud}.\frac{FC_{Sud,t}}{FP_{Sud,t}} + \beta_{2,Sud}.\frac{PEC_{Sud}}{HP_{Sud,t}} + \beta_{3,Sud}.\frac{S_{Sud,t}}{PDC_{Sud}}\right)^{\alpha_{1,Sud}}.\left(1 - PS_{Sud,t}\right)^{\alpha_{2,Sud}}.\left(1 - FDI_{Sud,t}\right)^{\alpha_{3,Sud}}.\left(\frac{CS_{Sud,t}}{n}\right)^{\alpha_{4,Sud}} \tag{4.3}$$

$$FP_{Sud,t} = \mathrm{A}_{\mathrm{ig},Sud,t}.CY_{ig,Sud,t} + \mathrm{A}_{\mathrm{rf},Sud,t}.CY_{rf,Sud,t} \tag{4.4}$$

$$WC_{Egy,t} = \left(\beta_{1,Egy}.\frac{FC_{Egy,t}}{FP_{Egy,t}}\right)^{\alpha_{1,Egy}}.\left(1 - PS_{Egy,t}\right)^{\alpha_{2,Egy}}.\left(1 - FDI_{Egy,t}\right)^{\alpha_{3,Egy}}.\left(\frac{CS_{Egy,t}}{n}\right)^{\alpha_{4,Egy}} \tag{4.5}$$

$$FP_{Egy,t} = \mathrm{A}_{\mathrm{ig},Egy,t}.CY_{ig,Egy,t} \tag{4.6}$$

β_1 , β_2, and β_3 are countries' weights or emphasis on the food gap, the energy gap, and future reservoir storage, respectively. These weights, which add up to one, represent the policymakers' preference structure. t represents the time. The countries' relative political stability (PS) is normalized between 0.1 and 0.9 (0.1 and 0.9 represent the least and the most powerful riparian country in the ENB). To make FDI unitless like other parts in the formulation of willingness to cooperate, FDI is the normalized countries' foreign direct investment over all countries between 0.1 and 0.9 (0.1 and 0.9 represent the least and the most countries' FDI relative to their maximum historical values.) CS indicates a country's prediction of cooperation status of two other countries based on its memory from past cooperation in the basin. For example, $CS_{Eth,t}$ indicates Ethiopia's prediction of an aggregated cooperation status of Sudan and Egypt of time t (the quantification of CS is discussed in Equations 4.7-4.10). n is the total number of riparian countries (i.e., three). α_1, α_2, α_3, and α_4 represent the countries' weights or emphasis on multiplicative variables of policymaker decision making, and they all sum to one. A_{ig} and A_{rf} indicate the actual irrigated and rainfed areas in riparian countries. CY_{ig} and CY_{rf} represent the corresponding crop yields in irrigated and rainfed areas. Following a previous study by Lu et al. (2021), in this study, we assumed all socio-hydrological factors are treated equally. Thus, all multiplicative weights are assumed to be 0.25. The additive weights of Ethiopia and Sudan are assumed to be 0.33, but Egypt's additive weight is 1, as, based on model conceptualization, Egypt has only one additive factor (i.e., the agricultural sector).

To account for the riparian countries' memories of past cooperation, we used the El Farol model (Wilensky & Rand, 2015). With a memory of past cooperation in the basin, each country predicts if other countries are in a status of cooperation (1) or non-cooperation (0). Thus, the prediction of a riparian's cooperation status in the basin (CS) can vary from 0 (i.e., when two other countries have non-cooperation status) to 2 (i.e., when two other countries have cooperation status). Following the El Farol model, each country has a limited memory of cooperation status. The memory size (memory span) represents the number of years in which one country remembers the ENB cooperation events. Using the El Farol model, we used " a bag of strategies" for each riparian (Equation 4.7) to predict the river basin cooperation status (Wilensky & Rand, 2015). Based on an agent's memory, each strategy is a rule of thumb about the cooperation status in the river basin (e.g., twice last year's river basin cooperation, half the river basin cooperation of the last three years, or the average of the river basin cooperation over the last three years). In this study, each strategy is a weighted average of countries' willingness to cooperate over their memory size with random weights. "A bag of strategies" for an agent can be written as follows (Equation 4.7):

$$S_{\mathrm{k,t}} = \begin{cases} S_{\mathrm{k,1,t}} = A_{\mathrm{k,1,1}} \times \overline{\mathrm{WC}}_{-k,t-1} + A_{\mathrm{k,1,2}} \times \overline{\mathrm{WC}}_{-k,t-2} + \cdots + A_{\mathrm{k,1,m}} \times \overline{\mathrm{WC}}_{-k,t-m} \\ S_{\mathrm{k,2,t}} = A_{\mathrm{k,2,1}} \times \overline{\mathrm{WC}}_{-k,t-1} + A_{\mathrm{k,2,2}} \times \overline{\mathrm{WC}}_{-k,t-2} + \cdots + A_{\mathrm{k,2,m}} \times \overline{\mathrm{WC}}_{-k,t-m} \\ \vdots \\ S_{k,i,t} = A_{\mathrm{k,i,1}} \times \overline{\mathrm{WC}}_{-k,t-1} + A_{\mathrm{k,i,2}} \times \overline{\mathrm{WC}}_{-k,t-2} + \cdots + A_{\mathrm{k,i,m}} \times \overline{\mathrm{WC}}_{-k,t-m} \end{cases} \tag{4.7}$$

where $S_{\mathrm{k,1,t}}$ is the ith strategy of agent k included in an agent's bag of strategies in time t, $A_{\mathrm{k,i,m}}$ is the agent k's weight for the ith strategy in time $t-m$, $\overline{\mathrm{WC}}_{-k,t-m}$ means the average of countries' willingness to cooperate but agent k in time $t-m$, and t is the current year. The memory size (m) and the number of strategies (i) for agents are model parameters. In this study, the memory size and the number of strategies are assumed to be 10. This assumption, based on the ENB's narratives and common assumptions in agent-based modeling for cooperation and conflict models (Cascão & Nicol, 2016; Wilensky & Rand, 2015), means that the riparian countries have good memory from the past events in the basin.

Assuming a group of these strategies for each policymaker (agent), the agent investigates how well each strategy worked in previous years. Thus, the best strategy will be used by an agent to predict the riparian countries' cooperation status. In other words, the best strategy is the one that provides the best prediction based on the previous years (Equation 4.10), which can be written as follows:

$$\varepsilon_{k,i,t} = \left|S_{k,i,t-1} - \overline{\mathrm{WC}}_{-k,t-1}\right| + \left|S_{k,i,t-2} - \overline{\mathrm{WC}}_{-k,t-2}\right| + \cdots + \left|S_{k,i,t-\mathrm{m}} - \overline{\mathrm{WC}}_{-k,t-m}\right| \tag{4.8}$$

$$\widehat{\phi}_{k,t} = \min\left\{\varepsilon_{k,1,t}, \varepsilon_{k,2,t}, \dots, \varepsilon_{k,i,t}\right\} \tag{4.9}$$

$$CS_{k,t} = \mathrm{CS}\left(S_{k,i,t} | \widehat{\Phi}_{k,t}\right) \tag{4.10}$$

where $\varepsilon_{k,i,t}$ is the residual of the ith strategy for agent k in time t, and $\widehat{\Phi}_{k,t}$ is the minimum residual of different strategies included in a bag of strategies for agent k in time t. For initial values of the riparian countries' cooperation status, we assumed that Ethiopia had a bitter memory of the past cooperation (i.e., $CS_{-1:t-m} = 0$) but that both Egypt and Sudan have a positive memory of past events (i.e., $CS_{-1:t-m} = 2$), based on their bilateral projects in the basin (Cascão & Nicol, 2016).

After calculating countries' willingness to cooperate (WC), the basin-wide cooperation (BC) is proposed as an average of countries' willingness to cooperate (Equation 4.11).

$$BC_t = \frac{1}{3} \times (\mathrm{WC}_{\mathrm{Eth},t} + \mathrm{WC}_{\mathrm{Sud,t}} + \mathrm{WC}_{\mathrm{Egy,t}}) \tag{4.11}$$

As mentioned, the simulation time window starts in 1983 when the Undugu project was completed (Kagwanja, 2007; Seide, 2014). Based on this cooperative project, we assumed 0.6 for all countries' willingness to cooperate as an initial value.

4.4 Results

According to the ENSH model, Figure 4.6 shows the simulation of the dynamics of riparian countries' willingness to cooperate (WC) from 1983 to 2016 based on the historical basin water system (without GERD in Ethiopia). According to the model, Ethiopia's willingness to cooperate remained high in the first years, verified by the Undugu project in 1983 (Kagwanja, 2007; Seide, 2014). The country's willingness to cooperate further increased after 1990, which can be explained by the TECCONILE. Ethiopia's willingness to cooperate fell in 2001 due to a high value of political stability; however, Ethiopia's willingness to cooperate increased after 2001. This increasing value can be qualitatively verified by the JMP, bringing the riparian countries together in 2003 for wide economic improvements along the river basin.

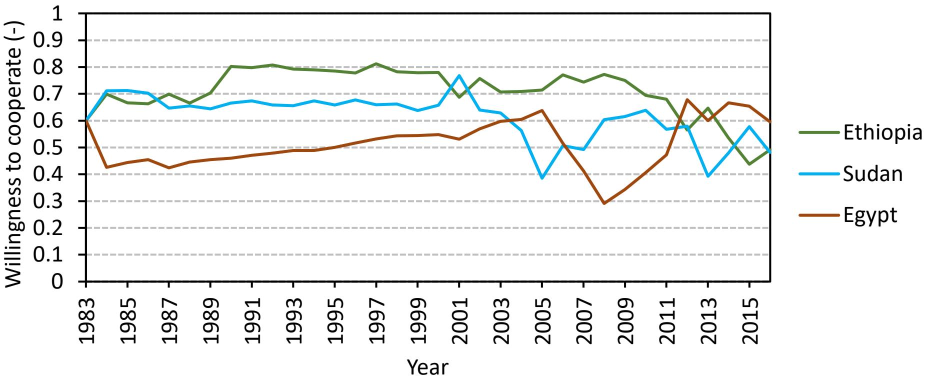

Figure 4.6 Simulated riparian countries' willingness to cooperate (WC) from 1983 to 2016.

After 2009, with Ethiopia's unsuccessful attempt to make Egypt return to the negotiation, Ethiopia's willingness greatly decreased, due in part to large foreign direct investment. In 2010, the reduction of Ethiopia's willingness to cooperate with Sudan and Egypt is highlighted by the CFA through which Ethiopia reached a cooperation agreement with the upstream countries in the absence of Sudan and Egypt (Cascão, 2009; Nicol & Cascão, 2011). The willingness of Ethiopia to cooperate continued to decrease in 2011 when the country announced the construction of the GERD dam (Cascão & Nicol, 2016). Our model suggests that this decreasing value after 2010 is explained by Egypt's weakened political stability after the Arab Spring, Ethiopia's increased political stability, higher foreign direct investment, and widening food and energy gaps. The dynamics of Ethiopia's willingness to cooperate can also explain the country's "free rider" behavior (i.e., focusing on water use through unilateral projects rather than multilateral projects (Cascão, 2009)) in announcing the construction of the GERD. In other words, using this socio-hydrological model, we argue that a very low value of Ethiopia's willingness to cooperate can lead to "the free rider" behavior, which can change the hydrological regime in the basin.

Although Sudan's willingness to cooperate declined after 1986, according to the model, it slightly increased after 1989 with fluctuations until 2003, except for 2001 when the willingness temporarily jumped due in part to relatively low political stability. While the high values of the first years can be justified by the Undugu project, the TECCONILE can qualitatively validate the slight increase after 1989 (Kagwanja, 2007; Seide, 2014). After 2003, Sudan's willingness dropped before bouncing back by 2008. The 2003–2008 pattern can be highlighted by the 2008 food crisis and Sudan's conflict with Ethiopia due to a threat to its historical water rights (Nicol & Cascão, 2011). Sudan's conflict with Ethiopia can qualitatively explain the decreasing value of Sudan's willingness, while the 2008 food crisis can explain the country's increasing willingness to cooperate. Sudan's willingness slightly rose between 2008 and 2010, which can be explained by Sudan's ambition to improve its agriculture (Cascão, 2009; Nasr & Neef, 2016). Sudan's willingness to cooperate dramatically declined between 2010 and 2013, which can be highlighted by Sudan's reaction to CFA and GERD's construction. Also, after 2013, the upward trend likely reflects Sudan's position change and its support for GERD (Barnes, 2017; Swain, 2011).

Egypt's willingness to cooperate gradually rose with fluctuations between 1984 and 2005. This gradual increase can be explained by the food gap, political instability to some extent, and declining foreign direct investment. This upward trend can also reflect Egypt's participation in the Undugu project, TECCONILE, NBI, and JMP (Kagwanja, 2007; Seide, 2014). After 2005, Egypt's willingness dropped to its lowest point in 2008. The negotiation deadlock can verify this decreasing value in 2007 and Egypt's conflict with Ethiopia about Egypt's historical water rights (Nicol & Cascão, 2011). Egypt's willingness increased from 2008 to 2012. This increasing value can be explained by the decreasing political stability of Egypt during this period, eventually leading to the Arab Spring in 2011 (Knaepen & Byiers, 2017; Salman, 2013). Afterward, Egypt's willingness fluctuated from 2012 to 2016, which can be attributed to Egypt's change of political regime, mixed reaction to GERD, and willingness to keep negotiating with the riparian countries (Tawfik, 2016).

The average of the riparian countries' willingness to cooperate leads to the ENB cooperation dynamics (Figure 4.7). The overall trend shows a slightly decreasing pattern from 1983 to 2016. This simulated basin-wide cooperation (BC) shows how mistrust and bitter memory from the past in the basin can reduce cooperation events (Whittington et al., 2014). The basin cooperation remained high in the first years after the riparian countries reached the Undugu project. We argue that the increase in cooperation after 1990 brought the riparian countries together for TECCONILE in 1992. Afterward, TECCONILE as guidelines for NBI, led to an increase in basin cooperation until NBI happened in 1999 (Kagwanja, 2007). Although the riparian countries reached these wide basin agreements, the basin cooperation decreased and dropped by 2007. This sharp downward trend can significantly show the negotiation deadlock and serious conflicts among the riparian countries between 2005 and 2008 (Paisley & Henshaw, 2013). After 2008, the Arab spring in 2011 and the importance of Sudan's agriculture projects motivated the riparian countries to return to negotiations, which is illustrated by an upward trend in Figure 4.7 (Cascão & Nicol, 2016). The basin cooperation went into a sharp decline in 2013, reflecting the riparian countries' conflict over the GERD construction (Nasr & Neef, 2016). We argue that the increased cooperation in 2014 led the riparian countries to sign a declaration on the GERD's first filling and operation in 2015 (Tawfik, 2016). However, the basin cooperation decreased shortly afterward, indicating that the declaration did not resolve the conflict (Cascão & Nicol, 2016).

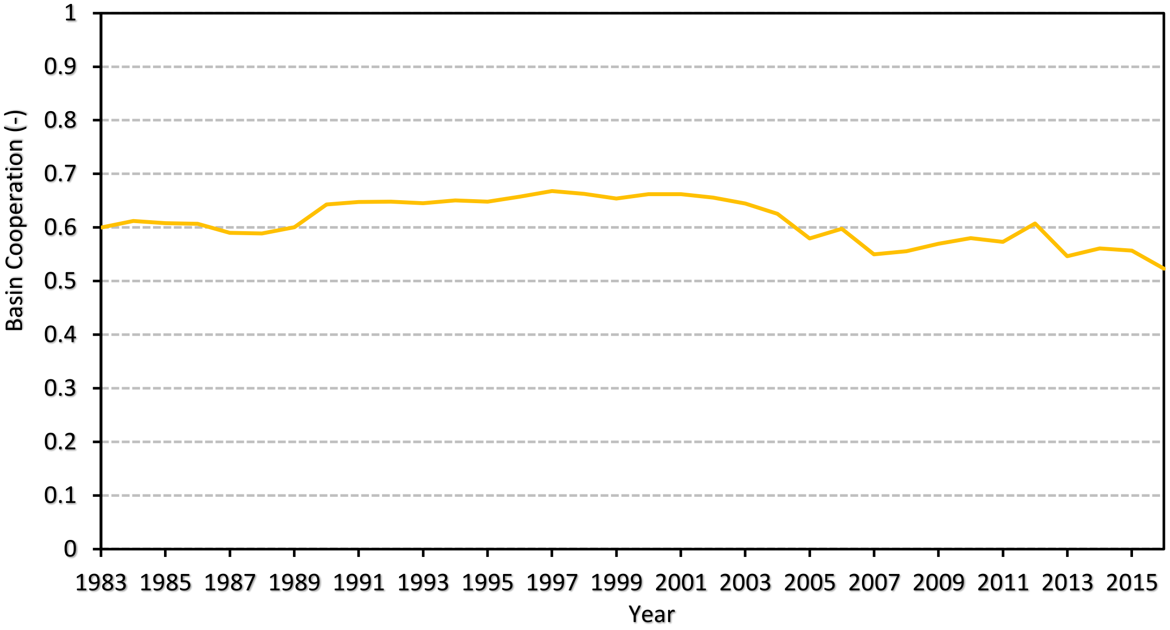

Figure 4.7 Simulated basin-wide cooperation (BC) at the ENB from 1983 to 2016.

4.5 Exploring the Evolution of Potential cooperation Pathways with the GERD Operation

The ENSH model quantifies the dynamic behavior of the cooperation phenomenon in the ENB, which paves the way for predicting cooperation pathways. Here, we propose how our ENSH model can be fully coupled with a water resource systems model, instead of using the outputs of an external model, to explore the evolution of cooperation pathways for GERD operations among the riparian countries. Figure 4.8 shows our proposed socio-hydrological modeling framework. The ENSH human submodel simulates the basin cooperation (BC) based on the countries' willingness to cooperate (WC). The BC value goes through if-then rule statements, with pre-determined thresholds, which allow transitions between different cooperation statuses. In fact, with assumed model thresholds (i.e., α_1, α_2, and α_3), in each model time step (i.e., year), the socio-hydrological model can transition from one to another cooperation status. For example, if the basin cooperation shows a very low value, defined by an assumed threshold, the "unilateralism scenario" will be predicted. Based on the "unilateralism scenario," the water submodel simulates the countries' food and energy productions through maximizing Ethiopia's energy production by the GERD operation and increasing Sudan's withdrawals from the Blue Nile for irrigation. These simulated food and energy productions, in turn, drive the ENSH model to predict new cooperation status. We have defined potential incremental cooperative arrangements that can exchange water, food, and energy among the riparian countries considering their strength under three settings: (1) unilateralism, where the riparian countries act independently to minimize their food and energy gaps; (2) and (3) semi cooperation (i.e., low and medium cooperation), where the riparian countries partially cooperate through exchanging water, food, and energy; and (4) full cooperation, where the riparian countries completely cooperate. However, it is noteworthy that these cooperative arrangements can be replaced by other available options. Their potential cooperation status can include, but are not limited to, the following:

Unilateralism: The GERD operation is set to maximize Ethiopia's energy production, and Sudan increases withdrawals from the Blue Nile for irrigation.

Low Cooperation: The GERD operation is set to maximize energy production while helping Egypt to manage drought. This policy resembles unilateralism, but Ethiopia releases the required water (rescue flow) to Egypt to ensure that the AHD level is not less than a threshold reservoir level intended to prevent severe water shortages in Egypt. Sudan does not use this rescue flow that goes to Egypt. In return, Egypt makes up for any hydroelectric power shortages in Ethiopia due to the supply rescue flow by investing in improving crop yields in Ethiopia.

Medium Cooperation: Here, the GERD operation policy is more balanced. We assume that Ethiopia does not fully maximize the energy production from GERD and releases a portion of water to Egypt and Sudan so that these countries can minimize any water shortages. Also, we assume that Sudan does not withdraw any additional water. In return, Egypt invests in Sudan to enhance the crop yields of rainfed areas to minimize the Sudanese food gap, and any food surplus is exported to Egypt then to Ethiopia to reduce their food gaps. Ethiopia's energy shortages are alleviated by Egypt.

Full Cooperation: This policy is similar to the medium cooperation policy, but here Ethiopia does not allow any water shortages to develop in Egypt or Sudan. In return, more food and energy are supplied from Egypt and Sudan, respectively, to Ethiopia. Additionally, more investments from Egypt are directed to improve irrigation efficiency, crop yields, and dam construction in Sudan and Ethiopia.

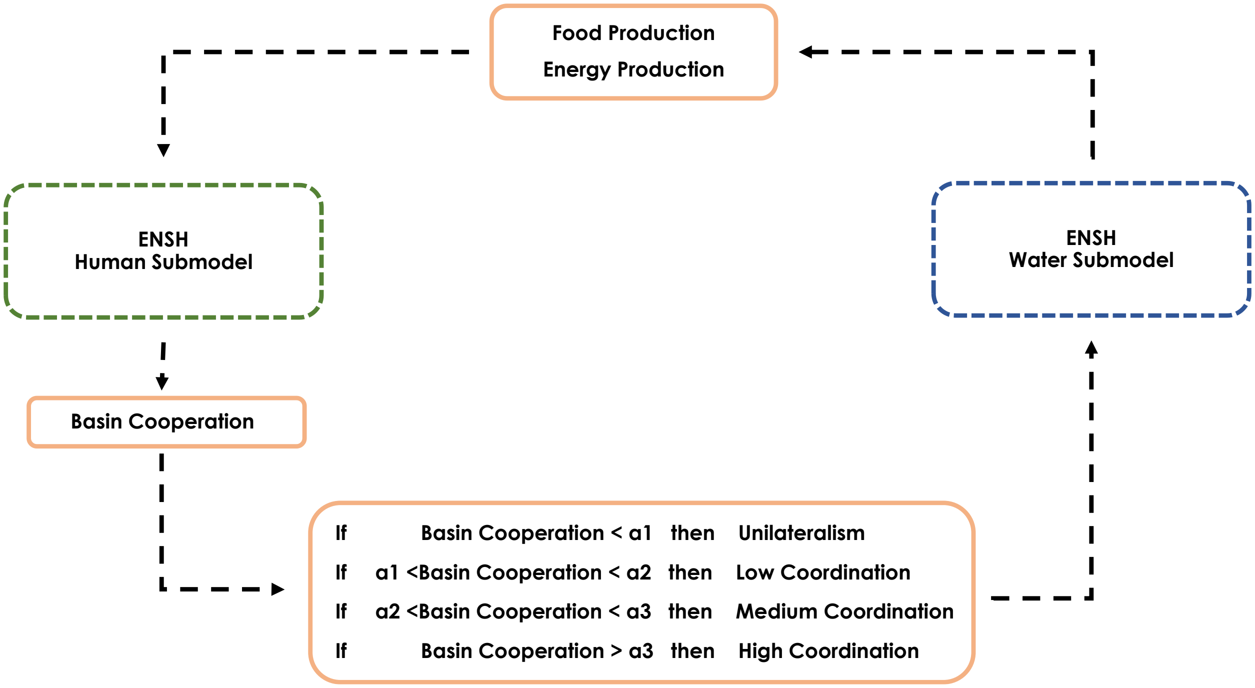

Figure 4.8 A proposed socio-hydrology transboundary framework to explore the evolution of cooperation pathways among the riparian countries affected by the GERD operation and to reveal how the GERD operation will affect agricultural sectors and hydropower in the riparian countries. α_1, α_2, and α_3 are the model thresholds for the transition between cooperation policies.

This exploratory framework can reveal how the GERD operation will affect agricultural sectors and hydropower in the riparian countries, and thus, how these effects will impact and co-evolve with potential cooperation pathways among the riparian countries. This framework may ultimately enable policymakers to understand and mitigate actions leading to conflict in the ENB. It is noteworthy that the cooperative arrangements in our proposed framework assume that the total flows of the ENB are open for negotiation and reassessment, which may not be the same as the historical water rights. However, this assumption may be unrealistic in light of the historical water rights of Egypt and Sudan.

4.6 Conclusion

When shared water resources are contested in transboundary rivers, conflict and cooperation phenomena can emerge. Unlike most studies using exogenous scenarios to analyze water resource developments in transboundary rivers, socio-hydrology treats cooperation as an internal variable in a socio-hydrological system that can co-evolve with hydrological variables.

This study has focused on the Eastern Nile Basin (ENB) including Ethiopia, Sudan, and Egypt, countries with a long history of conflict and cooperation. To provide a better understanding of the ENB conflict and cooperation phenomenon, we developed an agent-based socio-hydrological model that quantifies and simulates both the riparian countries' willingness to cooperate and basin-wide cooperation in the ENB from 1983 to 2016. By developing this model, we explained how hydrological and socio-political factors can lead to cooperation in this basin. The main findings of this study are as follows:

- Ethiopia experienced two general trends in cooperation dynamics: (1) fluctuations in its willingness to cooperate between 1983 and 2009 and (2) a decreasing willingness to cooperate between 2009 and 2016. The ENSH model showed that the socio-political factors (i.e., relative political stability and foreign direct investment) can explain these two different trends, along with Ethiopia's food and energy gaps. Also, learning from the simulation of Ethiopia's past behavior, we argued that a very low value of willingness to cooperate can lead to "free rider" behavior, where riparian countries focus more on unilateral projects rather than on multilateral ones.
- The ENSH model shows an important pattern in Sudan's willingness to cooperate between 2003 and 2008, which dropped to its lowest value before recovering by 2008. Our model indicated that the 2008 food crisis (i.e., Sudan's food gap) may account for Sudan recovering its willingness to cooperate.
- The ENSH model shows the role of Egypt's political (in)stability in its willingness to cooperate. A negotiation deadlock occurred in 2007, but because Egypt later entered a politically unstable phase, it returned to the negotiations years later.
- The ENSH model can be coupled with a water resources model to explore the evolution of cooperation pathways among the riparian countries affected by the GERD operation. This framework can help future studies by revealing the actions that may fuel conflict in the basin.

The ENSH model was an initial attempt to quantify and simulate riparian countries' willingness to cooperate and basin-wide cooperation for a complex hydrological and socio-political system of the ENB. In this regard, we acknowledge that our results and interpretations are constrained by the model's conceptualization and assumptions. Although we built our ENSH model using social theories, future studies could employ other social theories and hypotheses, thus, assessing the validity of the model structure. Our model conceptualization required several model parameters and assumptions, which can impose large uncertainty on the model outputs due to socio-hydrological data limitations. These assumed parameters include multiplicative and additive weights for riparian countries' decision making, the memory size, the number of strategies, and past countries' memory of basin cooperation. Although these assumptions were grounded in the literature on the Nile Basin and socio-hydrology studies, future studies need to carefully enhance the model parameterization through data collection. A large number of our model parameters can also pose a challenge to any calibration process, which was out of the scope of this research. In fact, future research needs to conduct a global sensitivity analysis on the ENSH model to indicate the most and least sensitive parameters for over-fitting issues in the calibration process.

Chapter 5

Summary, Conclusions and Future Directions

5.1 Summary and Conclusions

This thesis was an attempt to provide a better understanding of coupled human and hydrological systems in different regions and at different scales by investigating feedback mechanisms and important socio-hydrological factors for two phenomena: (1) the agricultural rebound phenomenon and (2) cooperation and conflict phenomena. The understanding of these phenomena can pave the way for proposing practical water management strategies and a socio-hydrological framework that policymakers can use to avoid unintended water management consequences in future water planning. To gain this improved understanding, two case studies were chosen: (1) The Bow River Basin (BRB) in Alberta, Canada and (2) the Eastern Nile Basin (ENB) in Africa, which includes Ethiopia, Sudan, and Egypt. These two case studies with completely different environments enabled this research to conceptualize socio-hydrological systems at different scales, which would enable future research to search for potential generic social processes that dominate in various hydrological systems. Also, the specific findings of each case study might be transferable to other similar case studies.

In **Chapter 2**, an agricultural water demand model was developed to capture a feedback mechanism influencing potential rebound phenomenon in the BRB. In this chapter, to assess the effects of modernizing irrigation systems and changing cropping patterns on agricultural water demands, an agent-based agricultural water demand (ABAD) model was developed, followed by a calibration and validation process with a satisfactory performance. This model showed how farmers' attitudes toward profits, risk aversion, environmental protection, social interaction, and irrigation expansion explain the dynamics of the water demand. In fact, the ABAD model showed that water conservation through modernizing irrigation systems may paradoxically increase agricultural water demand after an initial decrease (i.e., the agricultural rebound phenomenon) because the saved water can motivate farmers to expand their irrigation to increase their profits.

Using the developed ABAD model, in **Chapter 3,** the influential socio-economic factors in the long-term agricultural water demand dynamics and potential rebound phenomenon were presented. A time-varying variance-based Global Sensitivity Analysis (GSA) was used with the ABAD model to examine the individual effects of the factors, as well as their joint effects on the potential rebound phenomenon in the BRB. Based on the results of the time-varying GSA, different strategies were explored to avoid the agricultural rebound phenomenon. The GSA analysis revealed that a set of the model parameters (i.e., the economics group: means of normal distributions of past profit, future profit, risk aversion, and conservation policy), social interaction among farmers, and irrigation expansion play a significant role in the rebound phenomenon. Due to the role of the economics group, generating new breeds of high-value crops with relatively less water demand was suggested as a strategy to avoid the rebound phenomenon. The importance of the social interaction factor calls for heightening community awareness about their water use to control rebound phenomenon. Also, the large long-term effect of the irrigation expansion highlights the importance of restrictions on irrigated areas and farmers' water rights to discourage the overuse of saved water by farmers, thus, in turn, preventing the rebound phenomenon.

Switching from a local scale and agricultural context to a large scale and an international transboundary river, in **Chapter 4,** a socio-hydrological model was developed to represent feedback mechanisms that might lead to the emergence of conflict and cooperation phenomena for the ENB. This model, called the Eastern Nile Socio-Hydrological (ENSH) model, quantified and simulated the riparian countries' willingness to cooperate in the ENB and the basin-wide cooperation dynamics. The ENSH model was verified by qualitative data and narratives in the basin. The ENSH model explained a high level of Ethiopia's willingness to cooperate between 1983 and 2009 by its relatively low political stability, low foreign direct investments, and high food and energy gaps. The ENSH model indicated that the 2008 food crisis in Sudan may account for Sudan's increasing willingness to cooperate. Also, the ENSH model shows the role of Egypt's relative political instability during the Arab Spring in its increasing willingness to cooperate. By simulating basin-wide cooperation, this model depicts that the long-standing mistrust among the riparian countries may reduce basin-wide cooperation. A framework was ultimately proposed to show how the ENSH model can be fully coupled with a water resources model to explore the evolution of cooperation pathways among the ENB countries as affected by the Grand Ethiopian Renaissance Dam (GERD) operation.

5.2 Research Contributions

This thesis contributed toward filling an important research gap in socio-hydrology on a tenuous connection of socio-hydrology to broader research on social, economic, and policy aspects of water resources in two regions at different scales. In addition to a contribution to socio-hydrological modeling in general, this thesis was an attempt to contribute to agent-based modeling in particular. The detailed contributions associated with each study within the thesis can be written as follows:

- In **Chapter 2**, unlike traditional water demand modeling with exogenous factors as scenarios, socio-economic factors were endogenized in the ABAD model, and feedback loops between human and hydrological systems were investigated to simulate long-term agricultural water demand and capture a potential rebound phenomenon in the BRB. In particular, to model agricultural water demand, the effects of water conservation policies (i.e., changing crop patterns and improving irrigation systems) were included in the ABAD model for irrigation water use.
- In **Chapter 3**, it was demonstrated that a time-varying variance-based GSA can provide valuable information about the dynamical nature of the model behavior and comprehensive insights into the coevolutionary dynamics of a socio-hydrological system. This thesis showed how the results of GSA can be used to explore ways to avoid unintended

consequences of water management decisions (e.g., the agricultural rebound phenomenon) to support sustainable water management and communicate with policymakers.

- In **Chapter 4**, a socio-hydrological model was developed to treat cooperation as an internal variable in the ENB. This was a novel approach because in most previous research studies on transboundary rivers, a set of scenarios for cooperation was prescribed as boundary conditions in the problem framing. In this thesis, cooperation and conflict were considered as dynamic phenomena that were hypothesized to arise due to the interaction of hydrological and socio-political factors. A socio-hydrological framework was ultimately proposed toward filling a gap in capturing the evolution of cooperation pathways among the riparian countries affected by the GERD operation.
- This research showed the important role of qualitative data and narratives in validating the general dynamics of cooperation in the ENB with limited quantitative data (**Chapter 4**).
- Using the Sobol method to conduct a GSA on ABAD, this thesis filled a gap in the explicit evaluation of interactions among socio-economic and hydrological factors in the complex socio-hydrological system of the BRB over time (**Chapter 3**).
- This thesis showed how Agent-based modeling accounts for the uncertainty associated with human decision making in a socio-hydrological system in various contexts and at different scales (**Chapters 2 and 4**). In fact, given a limited understanding of human decision making, ABAD and ENSH simulated and captured two phenomena (i.e., rebound phenomenon and cooperation and conflict phenomena) through stochastic processes. Instead of using deterministic differential equations, the application of Agent-based modeling filled a gap associated with the uncertainty of human decision making in socio-hydrology.

Finally, by developing socio-hydrological models with two case studies representing various scales, this thesis was also an attempt to shed light on the similarities and differences in socio-hydrological systems in different contexts and scales:

- The model conceptualizations in **Chapters 2** and **4** showed that similar socio-hydrological factors can be found in the BRB and ENB models with different scales. In fact, social memory was found as an important social factor in decision-making processes in both agricultural water use in the BRB and willingness to cooperate in the ENB.
- The BRB and ENB models showed how interactions between agents (i.e., farmers in the BRB and countries in the ENB) can highlight a similar property in complex socio-hydrological systems at different scales (**Chapters 2 and 4**). ABAD model showed that farmers in the BRB learn from each other to conserve water through social interactions, which affect their decisions regarding water conservation (i.e., changing crop patterns and improving irrigation systems). At a large scale, the interaction of agents was reflected in a

riparian country's trust in other countries. In fact, countries' willingness to cooperate was affected by their memory of other countries' cooperation status in the past.

5.3 Limitations

The results of this thesis are constrained by the structure, assumptions, and simplifications of the ABAD and ENSH models. The limitations of these models can be summarized as follows:

- Although both ABAD and ENSH models used general social theories to capture human decision making, translating these theories into mathematical equations required assumptions and subjective considerations, leading to uncertainty of the model outputs.
- While the ABAD model reasonably covered the years before and after several droughts in the BRB, this model's calibration and validation were limited to a relatively short simulation period due to insufficient data.
- The interpretations of the GSA results in the BRB are constrained by the structure, assumptions, and simplifications of the ABAD model, however, the interpretations are broadly consistent with the literature of the rebound phenomenon.
- The interpretation of the rebound phenomenon in this research focused on the issue of water scarcity. However, from the economic perspective, this phenomenon may not always be a negative consequence as the irrigation expansion can lead to increased job opportunities and economic development.
- The ENSH model suffers from limited calibration and validation. Quantitative data on cooperative events are sparse in transboundary rivers, therefore, the ENSH model was validated by narratives and qualitative data in the literature of the Nile River Basin.
- The ENSH model conceptualization required several model parameters and assumptions, which can impose large uncertainty on the model outputs due to socio-hydrological data limitations. Having a large number of parameters in this model can also pose a challenge to any calibration process (e.g., over-fitting issues).
- Although this research made the best use of previous studies, it is constrained by the scarcity of empirical evidence. This issue can pose a considerable uncertainty in investigating and parameterizing the socio-political factors in human decision-making processes of the agricultural rebound phenomenon and the cooperation phenomenon.

5.4 Future Research

This thesis has raised a few questions worthy of further future research:

- Future studies could use other social theories (e.g., rational choice) and hypotheses in ENSH and ABAD models, thus, assessing which theories and model structures provide a better model performance to capture the observed human behavior.

- This research designed and discussed water management strategies to avoid rebound phenomenon from the perspective of water scarcity. However, when the rebound phenomenon is associated with increased water productivity, there can be trade-offs between increased water use and economic gains, which need to be investigated in future studies.
- As the ENSH model has a large number of parameters, future research needs to conduct a global sensitivity analysis on this model to indicate the most and least sensitive parameters to contribute to two interesting areas: (1) diagnostic testing and (2) the design of water management strategies to mitigate conflicts in the ENB. When the results of the time-varying sensitivity analysis are consistent with modelers' perceptions of how the system works, this understanding could be used as a qualitative model validation. For the second area, the understanding of the time-varying hydrological and socio-political factors can provide insights to explore long-term water management strategies to mitigate potential conflicts at the ENB. In this regard, future research could use the proposed socio-hydrological framework to explore these water management strategies with the effect of the GERD operation.
- Due to the lack of quantitative data on cooperation status in the ENB, future studies need to investigate a way to quantify the observed cooperation events for further calibration and validation of the ENSH model. Also, future research needs to conduct community surveys and direct stakeholder engagement to identify and measure the socio-economic and political factors in the agricultural rebound phenomenon and the cooperation phenomenon.
- This thesis was a preliminary attempt to provide common principles and unique considerations in socio-hydrological modeling. Future studies need to further synthesize and compare different case studies at different scales to better identify common ground in socio-hydrological modeling.

Appendix A: Supplementary materials for Chapter 2

A.1 Past Profit Calculation

Following Dziubanski (2018) and Dziubanski et al. (2019), the past profit is formulated by a quadratic function as follows:

$$\Delta IS\_PP_{\mathrm{t}} = (A * NITech_t^2 + B * NITech_t + C) * W_c * (IS_{f,t}) \tag{A.1}$$

$$\Delta A\_PP_{\mathrm{t}} = (A' * NICrop_t^2 + B' * NICrop_t + C') * W_c * (A_{tot,t}) \tag{A.2}$$

where $NITech_t$ (Can$/ha) is the net income from adopting 1 ha of sprinklers at the current year, W_c is the degree to which an agent is following the conservation target of the program (Water for Life program in Alberta), and $NICrop_t$ (Can$/ha) is the net income from irrigating 1 ha of forage crops versus the other crops (oil seeds, cereals, and specialty) at the current year.

The first terms in Equations A.1-A.2 are quadratic functions ($Ax^2+Bx+C=y$). To find the coefficients (A, B, and C), we need to solve three equations simultaneously. Following Dziubanski (2018) and Dziubanski et al. (2019), these three equations are based on statistics (the first, the second, and the third quartile) of historical $NITech_t$. Based on the historical $NITech_t$, Equations S3-S8 show how to calculate the coefficients, namely A', B', and C'. The other coefficients can be calculated in a similar way.

If an agent observes a positive net income at the current year, the coefficients are calculated as follows:

$$A'(PNI_3)^2 + B'(PNI_3) + C' = 1 \tag{A.3}$$

$$A'(PNI_2)^2 + B'(PNI_2) + C' = 0.5 \tag{A.4}$$

$$A'(PNI_1)^2 + B'(PNI_1) + C' = 0 \tag{A.5}$$

where PNI_3, PNI_2 and PNI_1 (Can$/ha) are the third, the second, and the first quartile of the positive historic income from the start to the past year in the model.

If an agent observes a negative net income at the current year, the coefficients are calculated as follows:

$$A'(NNI_3)^2 + B'(NNI_3) + C' = 0 \tag{A.6}$$

$$A'(NNI_2)^2 + B'(NNI_2) + C' = -0.5 \tag{A.7}$$

$$A'(NNI_1)^2 + B'(NNI_1) + C' = -1 \tag{A.8}$$

where NNI_3, NNI_2 and NNI_1 (Can\$/ha) are the third, the second, and the first quartile of the negative historic income from the start to the past year in the model.

A.2 Design of Analysis, Data, and Result

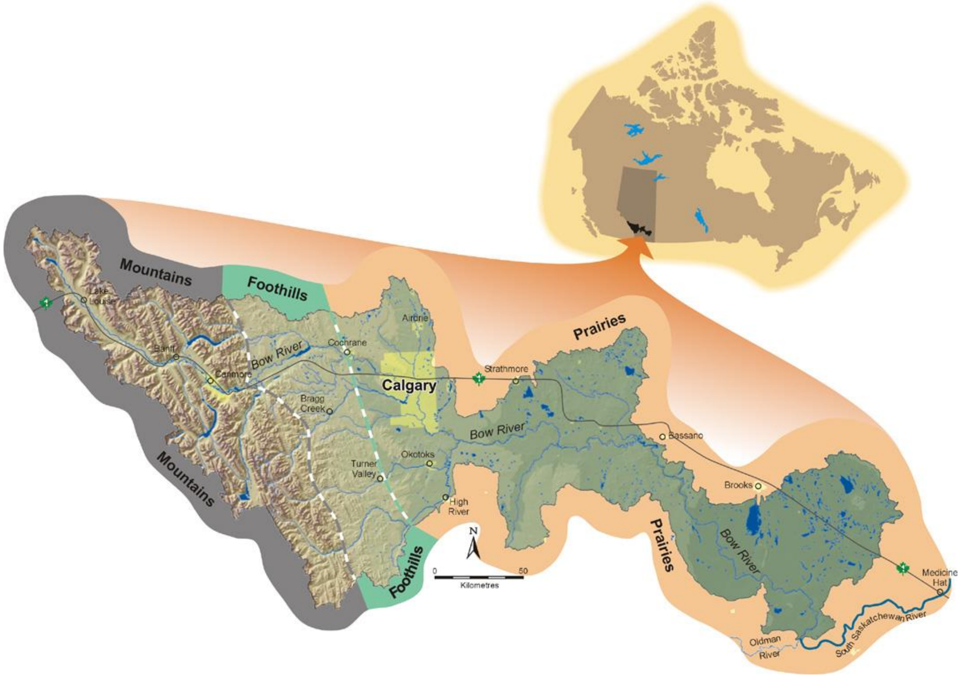

Figure A.1 Bow River Basin, Alberta, Canada (Reprinted from (Turner et al., 2005))

Table A.1 The items of production costs for forage and other crops based on the Government of Alberta (Source: https://open.alberta.ca/publications/agriprofit-cost-and-return-benchmarks-for-crops-and-forages-irrigated-soil-zone)

Total production costs

Cost Items	Seed Fertilizer Chemical Hail/Crop Insurance Premium Trucking and Marketing Fuel Irrigation Fuel and Electricity Repairs - Machinery Repairs - Buildings Utilities and Miscellaneous Custom Work Operating Interest Paid Paid Labour Unpaid Labour
Variable Costs	Cash/ Share Land Rent Taxes, Water Rates, License & Ins Equipment and Building (Depreciation and Lease Payments)

Table A.2 The ranges of the ABAD model parameters for sensitivity analysis

Parameters	**Lower Bound**	**Upper Bound**
μ_{ra}	0	1
μ_{pp}	0	1
μ_{fp}	0	1
μ_{e}	0	1
μ_{s}	0	1
μ_{c}	0	0.02
μ_{ie}	0	0.005
σ_{ra}	0	0.3
σ_{pp}	0	0.3
σ_{fp}	0	0.3
σ_{e}	0	0.3
σ_{s}	0	0.3
σ_{c}	0	0.01
σ_{ie}	0	0.01

Table A.3 The ranges of the ABAD model parameters for the sensitivity analysis

Parameters	**Lower Bound**	**Upper Bound**
μ_{ra}	0	1
μ_{pp}	0	1
μ_{fp}	0	1
μ_{e}	0	1

μ_s	0	1
μ_c	0	0.02
μ_{ie}	0	0.005
σ_{ra}	0	0.1
σ_{pp}	0	0.1
σ_{fp}	0	0.1
σ_e	0	0.1
σ_s	0	0.1
σ_c	0	0.01
σ_{ie}	0	0.01

Table A.4 The new setting for parameter sensitivity analysis of the ABAD model with seven parameters

Parameters	**Lower Bound**	**Upper Bound**
μ_{ra}	0	1
μ_{pp}	0	1
μ_{fp}	0	1
μ_e	0	1
μ_s	0	1
μ_c	0	0.02
μ_{ie}	0	0.005

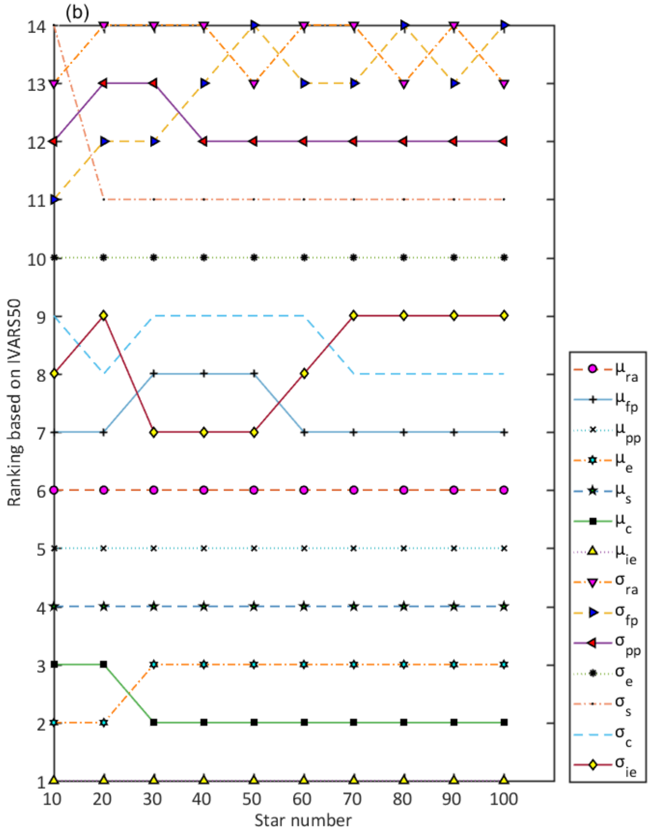

Figure A.2 Parameter sensitivity analysis of the ABAD model versus star number based on IVARS50 with new ranges for standard deviations: Rank 1 represents the most influential parameter, while rank 14 represents the least influential parameter. Here, the global sensitivity of NSE (Water Demand) to the model parameters is assessed.

Appendix B: Supplementary materials for Chapter 3

B.1 ABAD Model Components

Table B.1 Summary of the main equations, variables, and factors in the ABAD model

Model Component	Equation		Variables/Factors
Farmer's decision on adopting sprinkler	$\Delta IS_{s,t} = W_{ra}(\Delta IS_{s,t-1}) + W_{pp}(\Delta IS_{s,t-1} + \Delta IS\_PP_{\mathrm{t}}) + W_{fp}(\Delta IS_{s,t-1} + \Delta IS\_FP_{\mathrm{t}}) + W_{e}(\Delta IS_{s,t-1} + \Delta IS\_E_{\mathrm{t}}) + W_{s}(\Delta IS\_S_{\mathrm{t}})$	(1)	$\Delta IS_{s,t}$ (ha): the change in a farmer's land area that is switched to sprinklers W_{ra} $(-)$: the weight for risk aversion factor W_{pp} $(-)$: the weight for past profit factor $\Delta IS\_PP_{\mathrm{t}}$ (ha): the change in a farmer's land area that is intended to switch to sprinklers given an individual's past gross margin W_{fp} $(-)$: the weight for future profit factor $\Delta IS\_FP_{\mathrm{t}}$ (ha): the change in a farmer's land area that is intended to switch to sprinklers given the expected gross margin W_{e} $(-)$: the weight for environmental protection factor ΔIS_E_{t}: (ha) is the change in a farmer's land area that is intended to switch to sprinklers given the environmental protection factor W_{s} $(-)$: the weight for social interaction factor ΔIS_S_{t} (ha): the change in a farmer's land area that is intended to switch to sprinklers given the social interaction $IS_{tot,t}$ (ha): the total farmer's irrigated area under irrigation system $IS_{s,t}$ (ha): the total farmer's irrigated area under sprinkler irrigation system $IS_{f,t}$ (ha): the total farmer's irrigated area under flood irrigation system
	$IS_{s,t} = \sum_{\mathrm{t}=\mathrm{t}_0}^{\mathrm{t}} \Delta IS_{s,t}$	(2)	
	$IS_{tot,t} = IS_{s,t} + IS_{f,t}$	(3)	
Farmer's decision on changing crop patterns	$\Delta A_{o,t} = W_{ra}(\Delta A_{o,t-1}) + W_{pp}(\Delta A_{o,t-1} + \Delta A\_PP_{t}) + W_{fp}(\Delta A_{o,t-1} + \Delta A\_FP_{t}) + W_{e}(\Delta A_{o,t-1} + \Delta A\_E_{t}) + W_{s}(\Delta A\_S_{t}) + W_{ie}(\Delta IS_{s,t-1})$	(4)	$\Delta A_{o,t}$ (ha): the change in a farmer's land area that is intended to switch to other crops ΔA_PP_{t} (ha): the change in a farmer's land area that is intended to switch to other crops given an individual's past gross margin ΔA_FP_{t} (ha): the change in a farmer's land area that is intended to switch to other crops given the expected gross margin
	$A_{o,t} = \sum_{t=t_0}^{t} \Delta A_{o,t}$	(5)	

	$A_{tot,t} = A_{o,t} + A_{f,t}$	(6)	ΔA_E_{t} (ha): the change in a farmer's land area that is intended to switch to other crops given the environmental protection factor ΔA_S_{t} (ha): the change in a farmer's land area that is intended to switch to other crops given the social interaction W_{ie} $(-)$: the percentage of the increase in annual irrigation for each agent $A_{tot,t}$ (ha): the total farmer's irrigated area $A_{o,t}$ (ha): the total farmer's irrigated area under other crops $A_{f,t}$ (ha): the total farmer's irrigated area under forage
Farmer's decision given the past gross margin	$NITech_t = Incentive_t + Subsidy - CostTech$ $Incentive_t = U(0,1) \times (Price_{t-1,specialty} * Yield_{t-1,specialty} - Cost_{t-1,specialty})$ $NICrop_t = GrossMargin_{t-1,OtherCrops} - GrossMargin_{t-1,forage}$ $GrossMargin_{t-1,OtherCrops} = \frac{1}{3}(Price_{t-1,specialty} * Yield_{t-1,specialty} - Cost_{t-1,specialty} + Price_{t-1,cereals} * Yield_{t-1,cereals} - Cost_{t-1,cereals} + Price_{t-1,oilseeds} * Yield_{t-1,oilseeds} - Cost_{t-1,oilseeds})$ $GrossMargin_{t-1,forage} = Price_{t-1,forage} * Yield_{t-1,forage} - Cost_{t-1,forage}$	(7) (8) (9) (10) (11)	$NITech_t$ (Can\$/ha): the net gain in income from adopting 1 ha of sprinklers at the current year (i.e., opportunity cost) $Incentive_t$ (Can\$/ha): the incentive to an individual farmer for adopting sprinklers (i.e., the opportunity for irrigating specialty) $Subsidy$ (Can\$/ha): the financial support of the adoption of sprinklers by the government $CostTech$ (Can\$/ha): the installed cost for adopting sprinklers $U()$: a uniform distribution $Price_{t-1,specialty}$ (Can\$/Ton): the price for cereals at the previous year $Yield_{t-1,specialty}$ (Ton/ ha): the crop yield for the cereals at the previous year $Cost_{t-1,specialty}$ (Can\$/ha): the production cost for the cereals at the previous year $NICrop_t$ (Can\$/ha): the net gain in income from irrigating 1 ha of forage crops versus the other crops (oil seeds, cereals, and specialty) at the current year (i.e., opportunity cost) $GrossMargin_{t-1,forage}$ (Can\$/ha): the gross margin of 1 ha of forage $GrossMargin_{t-1,OtherCrops}$ (Can\$/ha): the gross margin of 1 ha of the crops, namely specialty, cereals and oil seeds at the previous year $Price_{t-1,cereals}$ (Can\$/Ton): the price for cereals at the previous year $Yield_{t-1,cereals}$ (Ton/ ha): the crop yield for the cereals at the previous year

			$Cost_{t-1,cereals}$ (Can\$/ha): the production cost for the cereals at the previous year $Price_{t-1,oilseeds}$ (Can\$/Ton): the price for oilseeds at the previous year $Yield_{t-1,oilseeds}$ (Ton/ ha): the crop yield for the oilseeds at the previous year $Cost_{t-1,oilseeds}$ (Can\$/ha): the production cost for the oilseeds at the previous year $Price_{t-1,forage}$ (Can\$/Ton): the price for forage at the previous year $Yield_{t-1,forage}$ (Ton/ ha): the crop yield for the forage at the previous year $Cost_{t-1,forage}$ (Can\$/ha): the production cost for the forage at the previous year
Farmer's decision given the environmental protection	$\Delta IS\_C_t = W_c * (IS_{tot,t})$ $\Delta A\_C_t = W_c * (A_{tot,t})$	(12) (13)	W_c $(-)$: the degree to which an agent is following the conservation target of the program
Farmer's decision given the social interaction	$\Delta IS\_S_t = \left(\frac{\sum_{k=1}^{m} \Delta IS_{s,t-1,k}}{\sum_{j=1}^{n} \Delta IS_{s,t-1,j}}\right) * IS_{tot,t}$ $\Delta A\_S_t = \left(\frac{\sum_{k=1}^{m} \Delta A_{o,t-1,k}}{\sum_{j=1}^{n} \Delta A_{o,t-1,j}}\right) * A_{tot,t}$	(14) (15)	k and j: the neighbors and agents, respectively $\left(\frac{\sum_{k=1}^{m}}{\sum_{j=1}^{n}}\right)$ stands for the ratio of an individual's decision (on changing crops or adopting sprinklers) to all other individuals' decisions.
Agricultural water demand	$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$ $ET_c = K_c \times ET_0$ $WD_{c,t} = ET_{c,t} - P_{eff,t}$ $TotalWD_t = \beta \times \frac{\sum_{c=1}^{2} WD_{c,t} \times A_{c,t}}{IE_t}$ $IE_t = \left(\frac{IE_f \times IS_{f,t} + IE_s \times IS_{s,t}}{IS_{tot,t}}\right)$	(16) (17) (18) (19) (20)	R_n (MJ/m2.day): net radiation at the crop surface G (MJ/m2.day): soil heat flux density γ (kPa/°C): psychometric constant T (°C): mean daily air temperature at 2 m height U_2 (m/s): the wind speed at 2 m height e_s (kPa): saturation vapor pressure e_a (kPa): actual vapor pressure Δ (kPa/°C): the slope of the vapor pressure curve K_c $(-)$: the crop coefficient

			$TotalWD_t$ (MCM/month): the simulated total agricultural water demand of the river basin in a million m3 $A_{c,t}$ (ha): the crop area (i.e., forage or other crops) IE_f $(-)$: the flood irrigation system efficiency IE_s $(-)$: the sprinkler system efficiency IE_t $(-)$: the total efficiency, with β is the conversion factor $10^{-5}\,\frac{MCM}{mm.Hectare}$

B.2 Stability and Convergence of GSA Results

Because the accuracy of the estimated variance-based GSA indices varies by changing the number of model evaluations (or sample size), it is crucial to monitor the stability and convergence of the GSA results. To achieve an optimal performance of the GSA analysis, we performed the estimation of the Sobol indices using progressively increasing numbers of model evaluations (from 20,000 to 200,000 sample size). Figure B.1 shows the convergence of the GSA results versus the number of model executions in the year 2010, as an example. Figure B.1 indicates the high stability for the total-order effect in the year 2010 over the different number of model executions; however, the relative importance of rankings become stable after 840,000 model executions (Figure B.1). Therefore, Figure B.1 demonstrates that reliable results were achieved with 1,400,000 model executions for our analysis. We used the results of the last experiment, with 1,400,000 model executions in this study.

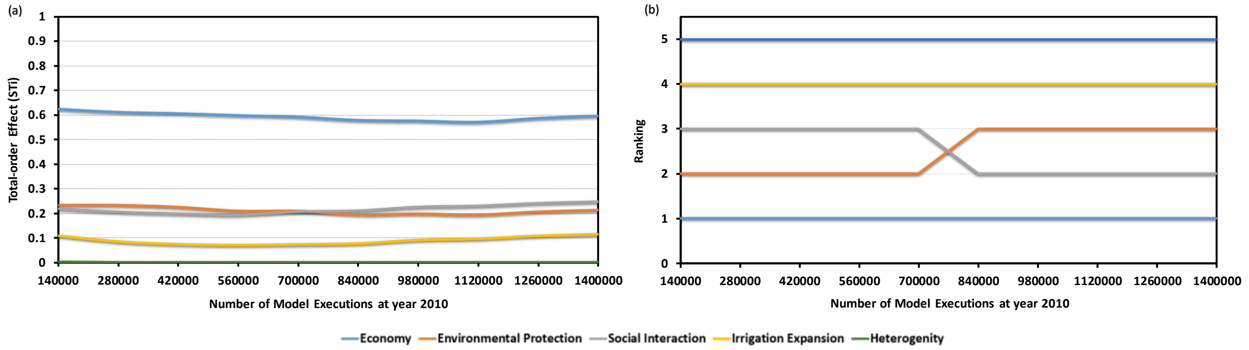

Figure B.1. a) The convergence of the estimated total-order effect (S_{Ti}) b) the convergence of the factor rankings (1 is the most important factor, and 5 is the least important factor) versus the number of model executions in 2010 on the rebound index to the socio-economic factors and the pre-specified groups of the factors in the BRB, by sampling across the potential ranges of the ABAD model's factors

Table B.2. A summary of the main findings, implications for sustainable water management, and comparisons with the literature

Factor (or a group of factors)	**Main Findings**	**Implications for Sustainable Water Management**	**Comparisons with Findings in the Literature**
Economics group	- This group is the most important element in the rebound phenomenon. - This group has considerable interactions with other factors. - The importance of the economics group increases over time.	- Switching to crops needing less water after improving irrigation systems.	- Previous studies have indicated that planting crops requiring less water would avoid the rebound phenomenon (Food and Agriculture Organization (FAO), 2017; Huffaker, 2008; Pfeiffer & Lin, 2014).
Social Interaction	- The social interaction factor has a critical role in the rebound phenomenon, with high interactions with other factors.	- Fostering farmers' knowledge about the average water use in their community could be a means to avoiding the rebound phenomenon through community participation.	- Ramirez (2013) showed the strong influence of social networks on agricultural technology adoption. - Community-based solutions attract attention in less developed countries (Wutich et al., 2014). - Improving community awareness is key for community involvement and prosperity (Portes, 2000; Putnam, 1993). - Improving farmers' knowledge of the average water use in their community can reduce water use (Le Coent et al., 2017).

Irrigation Expansion	- Irrigation expansion is one of the influential long-term elements in the rebound phenomenon. - This factor becomes increasingly important over the long term.	- Reducing farmers’ water rights and irrigating crops at a deficit: after improvements in irrigation systems, the water allocation should be reassigned to achieve environmental goals. - Restricting irrigated areas: no irrigation expansion should be allowed after improvements in irrigation systems.	- Studies have shown that irrigation expansion is one of the main reasons for the rebound phenomenon and proposed restrictions on water rights and land area as solutions (Berbel & Mateos, 2014; Berbel et al., 2014; Food and Agriculture Organization (FAO), 2017; Huffaker, 2008; Pfeiffer & Lin, 2014; Ward & Pulido-Velazquez, 2008).

Appendix C: Supplementary materials for Chapter 4

C.1 Political Stability

Table C.1 Individual variables and corresponding data sources to measure political stability index (Worldwide Governance Indicators, 2021)

Variables	Sources
Orderly transfers	Economist Intelligence Unit Risk Wire & Democracy Index
Armed conflict	
Violent demonstrations	
Social unrest	
International tensions / terrorist threat	
Political terror scale	Cingranelli Richards Human Rights Database and Political Terror Scale
Security risk rating	iJET Country Security Risk Ratings
Intensity of internal conflicts: ethnic, religious or regional	Institutional Profiles Database
Intensity of violent activities of underground political organizations	
Intensity of social conflicts (excluding conflicts relating to land)	
Government stability	Political Risk Services International Country Risk Guide
Internal conflict	
External conflict	
Ethnic tensions	
Protests and riots	Global Insight Business Conditions and Risk Indicators
Terrorism	
Interstate war	

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