ROLE OF ECONOMIC DIVERSIFICATION IN SUSTAINABLE WATER MANAGEMENT: A SOCIO-HYDROLOGICAL ANALYSIS

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A Thesis submitted in fulfillment for the degree of
Doctor of Philosophy

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August 2017

CERTIFICATE OF AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for any degree nor has it been submitted as part of requirements for a degree except as fully acknowledge within the text. I also certify that this report has been written by me. Any help that I have received in my research work and the preparation of the report itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Mahendran Roobavannan
August 2017.

ACKNOWLEDGMENTS

I like to thank the people who guided me and supported throughout this academic research. It was not possible to complete this without their help. First of all, I would like to express my sincere gratitude to my principal supervisor, Associate Professor Jaya Kandasamy at UTS for his supervision, continuous guidance, encouragement, support and valuable advice. I would also like to thank Professor Murugesu Sivapalan at the University of Illinois, Urbana Champaign for his continuous guidance, encouragement, and advice. I am also very much thankful to Assistant Professor Saket Pande at Delft University of Technology for his tremendous support, guidance, and motivation. As well, I thank Professor Saravanamuthu Vigneswaran at UTS for his support and guidance. All of these great teachers influenced me in my academic and personal life through sharing their valuable time and ideas, and providing thoughtful and critical comments. It would never have been possible without their contributions.

I am very thankful to Dr. Matthew Gaston, system administrator at ARCLab, and Mr. Michael Lake, Research Computing Officer, at UTS eResearch HPCC for providing great support for this research by making high performing computers available to me. I also like to thank Dr. Prabu Sivapalan for helping me in the initial stages of my work. I also appreciate the help given by and discussions with Dr. Amit Chanan, Dr. Nandakumar, Mr. Gurmeet Singh at NSW State Water Corporation. I am also thankful for the academic and technical support of the University of Technology Sydney and its staff. Especially, I cannot forget the support given by UTS International, GRS and School of Civil and Environmental Engineering, FEIT at UTS. I appreciate the support of my friends Danious Pratheep, Kalaruban, and Kireesan at CTWW, friends from SESYNC and all my friends in Sydney. It was always fun being with you guys.

Any of my achievements are the result of dreams and sacrifices made by my parents, and my lovely sister Dushande, who sacrificed her education for me. I would not have been where I am today if it was not for my family. I would like to thank my wife for her support in the latter stages of my PhD. Finally, I want to express my gratitude to the UTS and Australian Federal government for the financial support it offered through a scholarship that allowed me to undertake this research.

DEDICATION

To my lovely parents

Mahendran & Thanaluxmy

RESEARCH OUTCOMES

Journal publications.

- Roobavannan, M., Kandasamy, J., Pande, S., Vigneswaran, S., Sivapalan, M. 2017. Allocating environmental water and impact on basin unemployment: Role of a diversified economy. *Ecological Economics*, 136, 178-188, http://dx.doi.org/10.10 16/j.ecolecon.2017.02.006.
- Roobavannan, M., Kandasamy, J., Pande, S., Vigneswaran, S., Sivapalan, M., 2017b. Role of Sectoral Transformation in the Evolution of Water Management Norms in Agricultural Catchments: A Socio-hydrologic Modeling Analysis. Water Resour. Res. 1–22. doi:10.1002/2017WR020671
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- Mahendran Roobavannan, Jaya Kandasamy, Saket Pande, Saravanamuthu Vigneswaran, Murugesu Sivapalan, Allocating environmental water and impact on basin unemployment: Role of a diversified economy, Joint meeting of Japan Geoscience Union and American Geophysical Union, Chiba, Japan, May 2017.
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- Danielle Baker, Michael Blumenstein, Jinyan Li, Richard Beecham, Jon Sayer, Roshan Iyadurai, Shameek Gosh, Roobavannan Mahendran, Yi Zheng, Shoshana Fogelman, Christobel Ferguson, A novel data driven approach to ensuring water security, via deep analytics and data visualization, Ozwater17, Sydney, Australia, May, 2017.

Workshop attended

- Participated the Socio-hydrology workshop conducted at National Socio-Environmental Synthesis Center (SESYNC), Annapolis, Maryland, USA, August 4-7, 2014
- Participated the Socio-hydrology workshop conducted at National Socio-Environmental Synthesis Center (SESYNC), Annapolis, Maryland, USA, May 11-13, 2015

TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

NOMENCLATURE /ABBREVIATION

ABM	Agent based models
ABS	Australian Bureau of Statistics
ACF	Auto correlation function
AIC	Akaike information criterion
ARMA	Auto regressive moving average
BCC	Basin community committees
BIC	Bayesian information criterion
BSDI	Basin sustainable development index
CCM	Coupled-component modelling
CHANS	Coupled human and natural systems
CIA	Coleambally irrigation area
CPI	Commodity price index
CSR	Community sensitivity and response
EKC	Environmental kuznets curve
EWH	Environmental water holder
FPE	Final prediction error
FSR	Fish species richness
GDPc	Gross domestic product per capita for Australia
HDI	Human development index
HQIC	Hannan-Quinn information criterion
HSDI	Human sustainable development index
IWRM	Integrated water resource management
MBDA	Murry darling basin authority
MBDC	Murry darling basin commission
MDB	Murry darling basin
MHI	Median household income
MIA	Murrumbidgee irrigation area
MRB	Murrumbidgee river basin
NSE	Nash-Sutcliffe efficiency
NSW	New south wales
R^2	Coefficient of determination

RMSE	Root mean squared error
SD	System dynamics
SDL	Sustainable diversion limits
TFP	Total factor of productivity
UNDP	United nations development program
VAR	Vector auto regressive
WSP	Water-sharing plans
WSR	Water storage resilience

ABSTRACT

Water-human systems are closely linked and display co-evolutionary dynamics influenced by society's values and preferences. This has been observed in the Murrumbidgee River Basin, Australia where water usage initially focused on agriculture. After more than 100 years of agricultural development the Murrumbidgee Basin experienced a "pendulum swing" in terms of water allocation, initially exclusively for agriculture but changed in recent times to being reallocated to the environment. People became more concerned about the degradation of ecosystems, the amount of water left in the system and how much should be returned to the natural environment. However, water diversion for environmental purposes threatens many agricultural communities and their livelihoods. This thesis focuses on the human-water-environment nexus in the Murrumbidgee River Basin, and attempts to explain how and why changes in the management of water have impacted on the local economy and the community, but also with wider ramifications.

Predictably reduced water allocation to agriculture saw declines in that agricultural employment levels. Despite this, paradoxically, the basin unemployment rate declined and basin median household income increased. To understand and interpret this, in Chapter 3 we first analyze available labor, economic and hydrology data, and then develop a simple dynamic model to interpret the observed patterns of basin employment and unemployment. Data analysis revealed the likely causes behind the paradox as: (a) migration of people from the basin; and (b) absorption of the labor force in the fast-growing non-agricultural sectors of the basin's diversified economy. The model simulations reinforced this interpretation. Further model simulations under alternative scenarios of out-migration and sectoral transformation indicated that *basins embedded in faster growing national economies*, and are *more diversified* to begin with, are likely to be more conducive to agriculture industry reform (e.g., reduced water allocation) and environmental regeneration. This is a sobering message for other regions experiencing environmental degradation due to extensive agricultural development.

Chapter 4 hypothesizes that in the competition for water between economic livelihood and environmental wellbeing, economic diversification is the key to changing community sentiment in favor of environmental protection, and triggering policy actions that resulted in more water allocation to the environment. To test this hypothesis, we develop a socio-hydrological model to link the dynamics of the whole economy (both

agriculture and manufacturing and services industries) to the community's sensitivity regarding the environment. Changing community sensitivity influenced how water was allocated and governed and how the agricultural sector declined relative to manufacturing and services. In this way, we show that *economic diversification played a key role* in influencing the community's values and preferences with respect to the environment and economic growth. Without economic diversification, model simulations show that the community would not have been sufficiently sensitive and willing enough to act to restore the environment, highlighting the key role of sectoral transformation in achieving sustainable agricultural development.

Chapter 5 attempts to foresee future developments in the basin with a focus on how water managers could be informed and prepare for un-foreseen issues arising from climate change and the economy. The study uses a coupled socio-hydrological dynamical system model with endogenous social values and preferences. The exogenous drivers were economic and climatic-based. The dynamical system is represented by a suite of differential equations that can evolve over time. The study revealed possible basin development and exogeneous forcing conditions which could lead to sustainable basin development. In terms of sustainability the modelling and analysis revealed the importance of a diversified basin economy and how this is enhanced by moderate growth (or near current observed levels) of the national economy. An analysis was also carried out on the reliability of the system to meet water demand. Apart from an obvious relationship with available basin inflows, the reliability of meeting water demands from communities in the basin is low when the national economy is weak. The reverse was also found to be true.

Even though the changes in water management adversely impacted on the agriculture sector and created economic stress in the basin, its communities were able to adapt to and cope with water allocations favoring the environment through industry changes facilitated by movement of capital in a free economy, supported by appropriate strategies and government funding. This was helped by the adaptive capacity of people through reemployment in other economic sectors of the basin economy, experiencing unemployment for a period of time, migrating from the basin, and engaging in crop diversification. It is found that for given climate conditions, a higher level of diversification in the basin's economy increases its sustainability. Therefore, policy-makers and resource managers need to focus on measures to diversify the economy when it is thriving, but also recognize capacity of society to adapt to unpredictable shocks in the system.

CHAPTER 1

INTRODUCTION

1. Introduction

1.1 Research background

Attention to the world's water scarcity and food security is becoming more focused due to rising populations and their demands (Gleick and Palaniappan, 2010), evidence of climate change (IPCC, 2014) and unevenly distributed resources (IPCC, 2007; van Emmerik et al., 2014). From the beginnings of civilization water resources have been managed to effectively support socio-economic development utilizing various frameworks. As our knowledge of water systems has increased, water scientists have used different conceptual frameworks that have evolved from hydrology, to eco-hydrology, through to the integrated water resource management framework (IWRM). Many studies using IWRM have been carried out to solve water scarcity issues and project future levels of water stress (Gain et al., 2016; Hanasaki et al., 2012; IPCC, 2014; Koirala et al., 2014; Nsubuga et al., 2014) and food security (Misra, 2014). At present, water resource assessments are being carried out by including human activity as a boundary condition to a water system without considering the feedback on how water systems impact on human society. The human-water system is dynamically linked (Savenije et al., 2014; Sivapalan et al., 2012) and an improved understanding of the complex interactions of social and water systems is required in a rapidly changing world. Both of them interact with each other and co-evolve in different space and time resolution (Sivapalan and Blöschl, 2015). In rapidly changing systems or where prediction over a longer time scale is required, the IWRM approach has inherent inaccuracies preventing reasonable prediction of future water scarcity. Therefore, understanding and incorporating the interaction and feedback in human-water systems improves the ability to predict system behavior and then subsequently to devise and measure the impact of adaption measures.

In view of the fundamental character of the water cycle as the main driver of the biosphere, hydrology constitutes a key discipline in regard to world environmental problems (Falkenmark, 1997). Falkenmark (1999) illustrates four main functions (i.e. health, habitat, carrier, production) of water which interconnect socio-economic and ecological systems. As the world's population rises, unbalanced use of water in the above-mentioned four functions generates undesired stresses on water, economic, ecology and human systems. It is envisioned that these stresses can be reasonably managed by government and business policies that consider the priority of developing socio-economic and political conditions that recognize environmental constraints.

In previous water resource management and water scarcity studies, human interactions with the water system were considered as an external driver. Although there is a good understanding of hydrology and climate, the prediction of future water security is poor because the dynamics of interaction and feedback regarding the human-water system have not been defined and incorporated. Furthermore, it is not possible to properly understand or evaluate the effect of an adaptation strategy or policy implementation if feedback of the system is not well defined. In order to overcome this issue, Sivapalan et al. (2012) proposed a scientific framework called "socio-hydrology" which calls for a new inherent bi-directional feedback in human-water systems.

Socio-hydrology by incorporating feedback loops integrates socio-economic, environmental, technological, human behavior, decision-making and governance systems in a holistic manner (Elshafei et al., 2014; Savenije et al., 2014; van Emmerik et al., 2014). It is observed that individuals in all parts of world voluntarily organize themselves to gain the benefits of trade, to provide mutual protection against risk, and to create and enforce rules that protect natural resources (Ostrom, 2000). Human decisions on water resource management are made from collective choice and actions of society and change as society's values and preferences of how water is used evolve (Ostrom, 2000; Sivapalan and Blöschl, 2015). Since society is generally heterogenous in terms of economy and social status, it is important to understand the heterogeneity of society and how and why values and preferences change. When a decision is made on resource management, acceptance depends on how society's wellbeing is affected by the decision, i.e. if a society is more dependent on agriculture, there will be more resistance to water reform that favors the environment. The important question in effectively managing water resources is how values and preferences change in a heterogeneous society.

In the Murrumbidgee River basin, Australia, water usage initially focused on agriculture and until the mid-1990s favored this industry. This turned around as society became more concerned about the increasingly degraded ecosystems and ultimately led to water being reallocated back to the environment. Water diversion for environmental purposes threatens many agricultural communities but in the Murrumbidgee River basin, communities have adapted to changes in water management. It is important to understand factors such as economic diversification and migration which increase the adaptive capacity of society and can reduce the impact when water management changes.

Economic diversification and dependence on water for production also play a major role in changing society's values in a heterogeneous society and how water is managed (Kandasamy et al., 2014). Therefore, the human-water dynamics and how it is influenced by technology and sectoral transformation due to industrialization, migration dynamics needs to be deeply understood. This also applies to how society's values and preferences change on the issue of water management. These form major challenges to the growth of socio-hydrology as a science underpinning sustainable water management, and at the same time provide the motivation for this research study.

1.2 Objectives of this study

This research aims to contribute a novel conceptualized model that employs a more holistic framework useful for improving our understanding of the dynamics of human-water systems and reducing the uncertainties in predicting future water scarcity. This conceptualization is based on improving the interface between human-water systems and actors who influence this relationship. As well, this research aims at applying this model to human-water interactions using a case study of an agricultural basin with a diversified economy. The objectives of this study are to:

- improve the understanding of current river and catchment hydrology and human co-evolution (loops and feedbacks) and the drivers of co-evolution in an agricultural basin with a diversified economy.
- understand the impact of changing water management on the basin's economy and how communities in the basin adapted to changing water management.
- explain how societal values and preferences change with the co-evolution of the human-water system and understand the influence of sectoral transformation on the values and preferences of society.
- develop a coupled socio-hydrology model that can explain the coupled dynamics.
- improve the ability to predict water stress under a non-stationary climate and economic conditions in a basin which humans have significantly influenced.
- analyze socio-economic drought in the basin using a bottom-up approach in which humans and water systems co-evolve.

This research aims at building on the strengths of previous socio-hydrological modelling. Additional complexity is added to previous approaches by analyzing historical data of human-water systems invoking an established set of underpinning principles.

1.3 Organization of the thesis

The thesis is organized as follows:

Chapter 1: This chapter provides the general introduction to the research topic.

Chapter 2: This chapter summarizes the context of socio-hydrology, theories underpinning the concept of socio-hydrology and recent progress or advances being made in socio-hydrology.

Chapter 3: This chapter analyzes the role of a diversified economy on basin unemployment when allocating water to environment.

Chapter 4: This chapter analyzes the role of sectoral transformation in the evolution of water management norms in agricultural catchments using a socio-hydrological modelling approach.

Chapter 5: This chapter examines the sustainability of a socio-hydrological system with changing values and preferences where future climate and economic conditions may well be uncertain. It also analyzes the reliability of a socio-hydrological system to meet water requirements from a socio-economic perspective.

Chapter 6: This chapter presents the overall conclusions and recommendations for future study.

CHAPTER 2

Literature review

This chapter includes the significant part of

Roobavannan, M., van Emmerik, T. H. M., Elshafei, Y. , Kandasamy, J., Sanderson, M., Vigneswaran, S., Pande, S., Sivapalan, M., norms and values in socio-hydrological models, Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-432.

2. Literature review

2.1 Water security challenges

One-fifth of the global population suffers from water scarcity, and it is projected that 1.8 billion people will be living under conditions of absolute water scarcity in 2050 (FAO, 2014). In many places, water resources are being affected in terms of the quantity and quality due to changes in the planet's precipitation patterns or melting snow or ice (IPCC, 2014). These are being exacerbated by the impacts of climate change and compounded by the rapidly growing population. This in turn exerts pressure on finite resources as suitable freshwater supplies deplete. The demand for water for human consumption has now grown to a point where humans are in intense competition with the ecosystem, whose functioning depends on water (Pande and Sivapalan, 2016; Savenije et al., 2014). Humans also depend on what the ecosystem can provide.

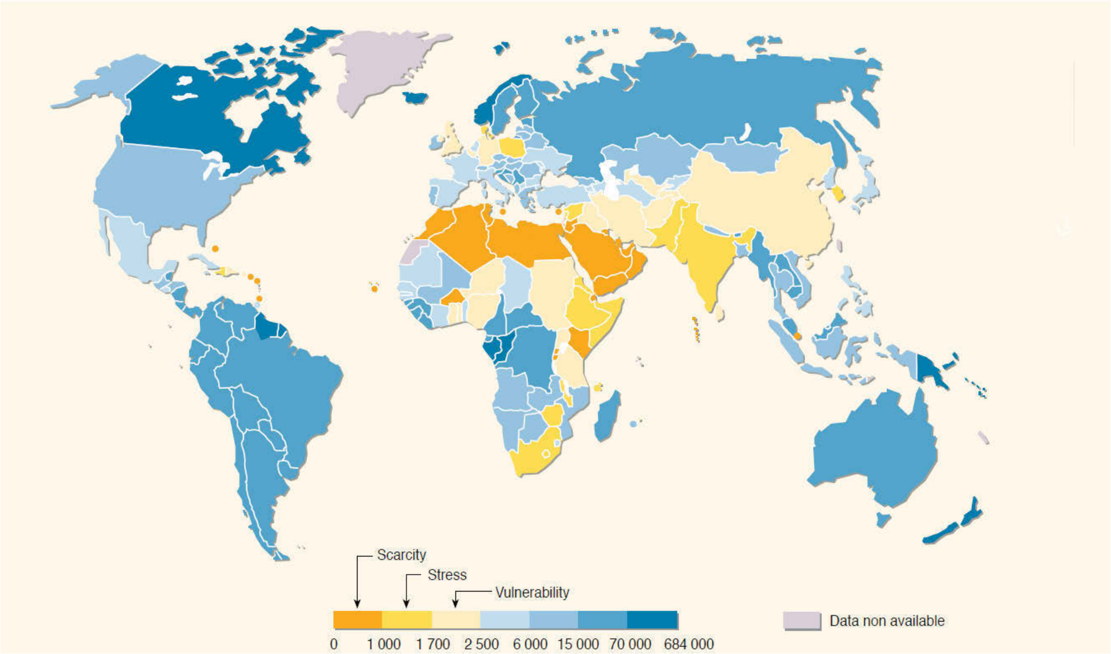


Figure 2.1: Freshwater availability (m^3 per person per year, 2007) (adapted from WWAP, 2012)

Humans have for millennia exerted a significant geophysical force (Savenije et al., 2014; Steffen et al., 2007) and have altered the hydrological cycle in myriad different ways to improve their socio-economic wellbeing or advantage (Oki and Kanae, 2006; Falkenmark, 1997; Pande and Sivapalan, 2016; Troy et al., 2015). At the same time, they have significantly modified several biogeochemical or element (such as carbon, nitrogen, phosphorus, and sulfur) cycles that are fundamental to life on Earth (Savenije et al., 2014). In turn, changes to these cycles influence people's behavior and decision-making (Kandasamy et al., 2014; Troy et al., 2015; van Emmerik et al., 2014).

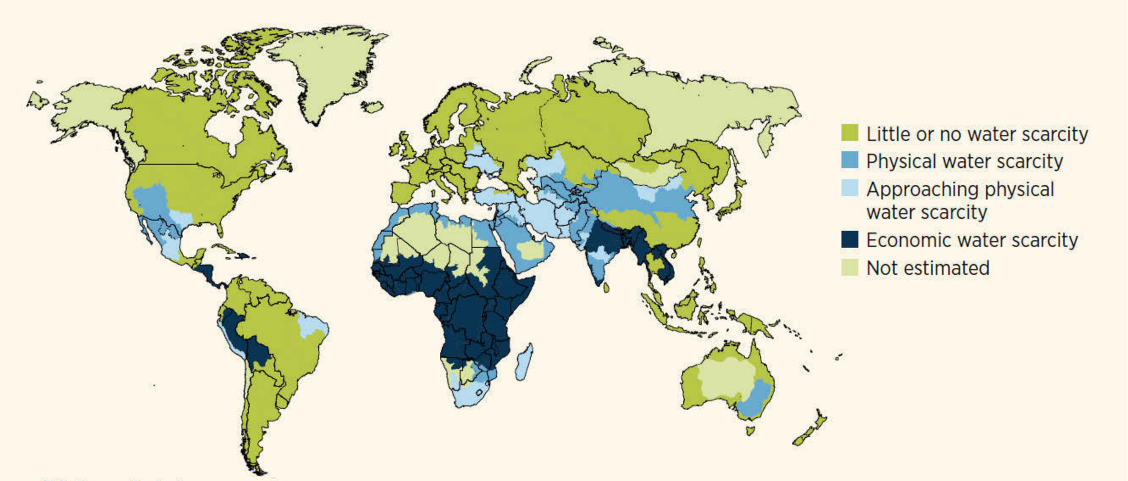
Water security studies focus on the availability of an acceptable quantity and quality of water for human health and livelihood, economic productive purposes, ecosystem health, etc. coupled within an acceptable level of water-related risks to people, environments and economies. Ensuring water security is important for society's wellbeing, and also for industry such as agriculture, energy and manufacturing, etc. Therefore it is one of the major contemporary challenges for the scientific community, society, and policy-makers (Gain et al., 2016).

Water is a freely accessible, common pool resource, and as a result, it is potentially exposed to overexploitation (Elshafei et al., 2014) as individuals look to maximize their use for different purposes, which is sometimes referred to as the "tragedy of the commons" (Hardin, 1968). Its use has always been constrained in terms of availability, quantity, and quality. Since water is a core of human development, more has been invested in scientific research to understand the hydrological processes and effective management of finite water resources. Beginning from understanding observed hydrological components, a deeper investigation was begun. Hydrology and the science of managing water resources have played key roles in human and economic development throughout history, although its role has often been marginalized (Savenije et al., 2014).

Given the recent rapid advances in technology such as supercomputing, the Internet, and satellites to monitor the earth, collect and analyze the data, etc., our understanding of the planet's hydrological cycle has deepened. Different components of the system have been included in such studies (i.e. precipitation, evapotranspiration, groundwater, ecology, geology, society) to explain the observed signatures in the water cycle. It has led to related fields of study such as basin hydrology, ecohydrology, hydrogeology, and socio-hydrology (Savenije et al., 2014; Sivapalan and Blöschl, 2015).

The availability of fresh water in terms of quality and quantity on the planet has changed as a result of direct human efforts to manage water and also as a consequence of alterations in urban and rural land use that influence flow and storage of water (Savenije et al., 2014). Humans have modified the hydrological response of many catchments through one or more of the following means: (a) direct diversion of water flows, including inter-basin transfers for water supplies to cities, industries and agriculture, (b) transformation of stream networks, for example through the construction of dams and reservoirs or the canalization of rivers, (c) changes in drainage basin characteristics, for example through deforestation, urbanization, drainage of wetlands and agricultural practices, and (d) activities that alter the regional or global climate, for instance by enhancing greenhouse gas emissions, land-cover changes, and consumptive water use (Falkenmark, 1997; Savenije et al., 2014). Humans have strongly influenced the physical, chemical and biological quality of streams, lakes and groundwater bodies through various sorts of diffuse and point sources of pollution (Meybeck, 2002). As a consequence, freshwater availability and water quality currently influence and constrain the possibilities and potential for human development, food production and economic growth (Pande and Sivapalan, 2016; Savenije and van der Zaag, 2002). An increasing number of signals, from depleting groundwater and decreasing lake levels to disappearing wetlands, collectively and comprehensively indicate that the current use of water systems is not sustainable (Kingsford and Thomas, 2004; Mensing et al., 1998; Savenije et al., 2014).

How to manage a common pool water resource effectively has become a major question and the science community has taken up the challenge of how to move forward to effectively manage the limited water resources utilizing a fundamental understanding of hydrology (Falkenmark, 1997). Science is expected to provide critical knowledge to help guide plausible, desirable and novel futures paths in the Anthropocene epoch (Bai et al., 2016). In recent decades, however, the prediction of collective over-exploitation of the resource under the rational agent paradigm has been called into question (Ostrom et al., 2002). It has become increasingly apparent that such individual optimization is not always the case (Sivapalan, 2015), and that in fact the degree of collective co-operation in the "commons dilemmas" is influenced by micro-situational variables (Elshafei et al., 2014). Falkenmark (2003) emphasizes that "to support the growing world population, balancing will be needed between emerging societal needs and long-term protection of the life-support system upon which social and economic development ultimately depends."



Definitions and indicators

- Little or no water scarcity. Abundant water resources relative to use, with less than 25% of water from rivers withdrawn for human purposes.
- Physical water scarcity (water resources development is approaching or has exceeded sustainable limits). More than 75% of river flows are withdrawn for agriculture, industry, and domestic purposes (accounting for recycling of return flows). This definition—relating water availability to water demand—implies that dry areas are not necessarily water scarce.
- Approaching physical water scarcity. More than 60% of river flows are withdrawn. These basins will experience physical water scarcity in the near future.
- Economic water scarcity (human, institutional, and financial capital limit access to water even though water in nature is available locally to meet human demands). Water resources are abundant relative to water use, with less than 25% of water from rivers withdrawn for human purposes, but malnutrition exists.

Figure 2.2: Global physical and economic water scarcity (adapted from WWAP, 2012).

The water resources system is highly complex. It has a variety of physical, biological and societal processes which evolves at multiple scales, speeds and multiple feedbacks processes (Falkenmark,1997; Pande and Sivapalan, 2016; Sivapalan and Blöschl, 2015). Similarly, society is composed of multi-sectoral, multi-actor and interdisciplinary. Sustainable management of water systems requires a systematic understanding of all relevant processes, acknowledgement of the interdependencies and new approaches to deal with this complexity in the local and global contexts (Konar et al., 2016; Savenije et al., 2014). The increasing complexity between systems, non-linearity of process interaction and uncertainty of human decision-making and management challenges science to provide solutions to the water issues that many societies now face (Bai et al., 2016; Sivapalan, 2015; Sivapalan and Blöschl, 2015).

Recently, the concept of sustainable development has attracted much attention among researchers, policy-makers and stakeholders. Water plays a major role in many sustainability issues that human societies encounter (Falkenmark, 2003; UN High Level Panel on Water, 2016). Sustainable water resource management is the key to poverty elimination, food and energy production, employment and maintenance of human health (UN, 2015). As indiscriminate development threatens critical ecosystem services and biodiversity, the need to care for the environment has emerged as an important consideration in sustainable water resource management. Appropriate solutions for sustainability issues require a deep understanding of human-water systems and an ability to provide reliable predictions of changes to freshwater resources, their distribution, circulation, and quality under natural and human induced changes from local to global scales, including changes constitute an important part of water management (Srinivasan et al., 2016).

Mismatch between the scale of water management and the scales of the processes being managed has created many of the problems in managing water resources (Cumming et al., 2005; Sivapalan and Blöschl, 2015). The time horizon over which strategic or planning decisions are made is also becoming longer (Montanari et al., 2013). In the past, components of the hydrological system (e.g., climate, vegetation, soils, topography, etc.) changed slowly in comparison to the time scales of hydrological processes and those of human decision-making. Therefore, treating them as fixed boundary conditions and human interaction as exogenous was often a reasonable assumption. However, separating the slowly varying boundary of the Earth System conditions from the fast varying hydrological processes may no longer be appropriate to understand the long-term dynamics (Sivapalan and Blöschl, 2015; Thompson et al., 2013).

We are at the stage where a more systemic understanding of scale interdependencies can inform us about the best sustainable governance of water systems, using new concepts like precipitation sheds, virtual water transfers, water footprints, and water value flow (Falkenmark, 1997; Konar et al., 2016; Savenije et al., 2014). When the scale of water issues is greater than the borders of local communities, the river basin is generally seen as the most appropriate unit for analysis, planning, and institutional arrangements. Since globalization of water transfers takes on different forms such as virtual water, it is argued that addressing water problems at the river basin scale is not always sufficient (Hoekstra and Hung, 2002; Konar et al., 2016). Many of today's local water issues carry a continental or even global dimension, which requires a governance approach that comprises institutional arrangements at a level beyond that of the river basin (Savenije et al., 2014).

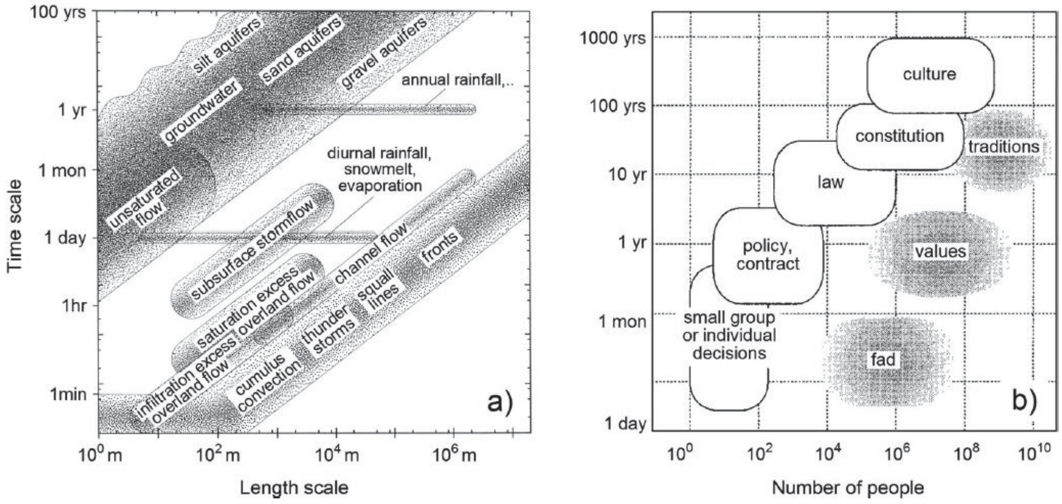


Figure 2.3: (a) Characteristic scales of hydrological processes and (b) characteristic scales of institutional processes (adapted from Sivapalan and Blöschl, 2015).

Due to the spatial connectivity in each water system, the solution to a problem in one part of it frequently leads to the emergence of another problem somewhere else in the system, which in turn impacts on other stakeholders or users (Chen et al., 2016; Savenije et al., 2014). What is visually apparent is the impact that upstream users have on downstream water availability in an open water system, both in terms of quantity and quality. A recent insight is that water resources are part of the global hydrological cycle, whereby terrestrial resources are connected through atmospheric tele-connections that transcend river basins. Until recently, there was a complete disregard for water resource linkages through the atmosphere, and the fact that land use in one part of the world impacts (positively or negatively) precipitation downwind (Savenije et al., 2014; Sivapalan and Blöschl, 2015).

In the Anthropocene epoch, changes in some earth system elements have reached the planetary level and exceeded sustainability limits (Bai et al., 2016; Steffen et al., 2015). All aspects of these changes imply risk and security issues for nearer or more distant futures, from the unexpected magnitude of some processes to unperceived connections between them, to the crossing of planetary boundaries (Steffen et al., 2015). Even though freshwater use has not passed the sustainability limit at a planetary level, spatial distribution of water availability creates risk in some river basin systems (Steffen et al., 2015).

Apart from climate, hydrological systems are heavily interconnected to human society through socio-economic, environment and technology factors. Society attempts to manage water sustainably with an eye on future development. Since human behavior and action is not easily predictable, the outcome of proposed solutions by the scientific community is also hard to predict. Intentions often have unintended outcomes, and there are heterogeneities in, and mismatches between, the temporal, spatial and institutional distribution of the intentional actions and unintended outcomes (Bai et al., 2016).

People think or reflect about experiences or processes, attach a value to them, and develop certain preferences. Holling (2001) suggests that human systems exhibit at least three features that are unique: foresight, communication, and technology. All of these unique human behavior aspects, including the informal nature of values and norms, add to the complexity of human-water systems and to the difficulty of modeling their behavior. An element that arises from the cognitive abilities of self-reflection is that human decisions do not necessarily follow any set of rules or are “rational”. The perspective on this issue may differ between the disciplines. In economics, human behaviors are viewed as rational. In other fields, human behaviors are seen as having both rational and irrational aspects (Sivapalan and Blöschl, 2015).

While the concept of the Anthropocene epoch reflects the past and present nature, scale and magnitude of human impacts on the Earth System, its true significance lies in how it can be used to guide attitudes, choices, policies and actions that influence the future. Yet, to date much of the research on the Anthropocene epoch has focused on interpreting past and present changes, while saying little about the future. Likewise, many studies on what may happen in the future have been insufficiently rooted on an understanding of past changes, in particular the long-term co-evolution of natural and human systems (Bai et al., 2016).

Navigating through the Anthropocene epoch requires a systematic thinking about the future, as both drivers and consequences (intended, unintended, and unanticipated) of societal actions accelerate and amplify, moving clearly away from a sustainable end. Forecasting the future with any level of consensus and/or reliability is difficult because forecasting entails error, and the future is an emergent property shaped by individual and collective choices, decisions and actions at all levels, and influenced by biophysical constraints (Bai et al., 2016; Srinivasan et al., 2016).

In the emergent new water management paradigm, we have observed that some basins have commenced a sustainable development strategy, for example the Murray-Darling basin (Kandasamy et al., 2014), and Lake Toolbin (Elshafei et al., 2015) while others have collapsed, for instance the Aral Sea (Micklin, 1988). A challenging puzzle in the research on sustainable water management is why some societies are able to successfully move to a sustainable path of socio-economic development and avoid environment degradation over decades-long timescales, while others fail. In part it may due to human interaction and unpredictability of collective action. Similar paradoxes have emerged, as highlighted in Sivapalan et al. (2014), i.e. peak water paradox, improved efficiency paradox, virtual water paradox, or employment paradox, which have provided the rationale for launching the new discipline of socio-hydrology (Sivapalan, 2015).

Yeston et al. (2006) argued that "Inevitably, water resource management is a political problem as well as a scientific one. It is clear that ensuring adequate supply will necessitate continuing collaborations across a great range of disciplines. But institutional, political, and economic options deserve more than cursory mention in science, since it is primarily these, rather than technical fixes alone, that "offer a measure of hope for the future"". Thus, a multi-disciplinary research approach is required. It is one including insights from hydrology and water engineering with knowledge of the social, economic and policy sciences to understand the dynamic and recursive relationship between the physics and ecology of water systems and social and economic developments.

In order to make strategic decisions that concern long-term investments, large-scale changes to human settlement patterns, and major policy changes, stakeholders and water managers are interested to know: (i) the future consequences of current decisions; and (ii) the mix of current decisions they should make to achieve a desired future outcome (Sivapalan and Blöschl, 2015). Their focus is on the long-term (decades to centuries) and large spatial scales (regional to national). It requires human decision-making to be an endogenous to system. If the long-term evolution of societal values and preferences is included in prediction models in a dynamic way (as well as the dynamics of the environment, technology, demography, economy, and governance), then they are amenable to decision-making over long time scales. Endogenous treatment of society in coupled water systems lead to answers for wider research questions on: (1) societal goals for the future; (2) major trends and dynamics that might favor or hinder them; and (3) factors that might propel or impede transformations towards desirable futures (Bai et al., 2016). An example of this would be how a society would adapt to the future and how to model its responses to water scarcity. There is a range of possible responses, such as living with scarcity, building infrastructure, implementing water savings measures, or reallocating water for ecosystem services. The response may depend on how a society values the environment: in some places a river drying up may be acceptable while in others this could be completely unacceptable (Troy et al., 2015). Thus, socio-hydrology can assist with management in three ways: (a) to facilitate stakeholder participation; (b) to help decision-makers through the generation and assessment of alternative futures; and (c) to learn from the experiences of other similar places, and move toward generalizations beyond individual case studies (Sivapalan and Blöschl, 2015).

2.2 Scientific frameworks for water resources management and water security analysis

In order to understand the hydrological dynamics, predict the available water for socio-economic development and effectively manage water resources, the field has evolved disciplines such as hydrology, eco-hydrology, hydrogeology, socio-hydrology, etc. Originally, hydrology focused on natural, pristine conditions to better understand hydrological processes and was dominated by approaches that treated catchments as lumped systems or 'black boxes', with an explicit focus on time (Sivapalan and Blöschl, 2015). Hydrology has increasingly been used to analyze water resources with improved understandings and expanded to study the effect of climate change on the water cycle. Soon after the rise of information technology, new observing technologies, multiple satellite data assimilation capacities, and new methodological opportunities opened up the science and supported a greater understanding of the relevant dynamics. There is clear enthusiasm for a new era that will replace empirical, lumped approaches by spatially distributed physically-based descriptions of the hydrological system.

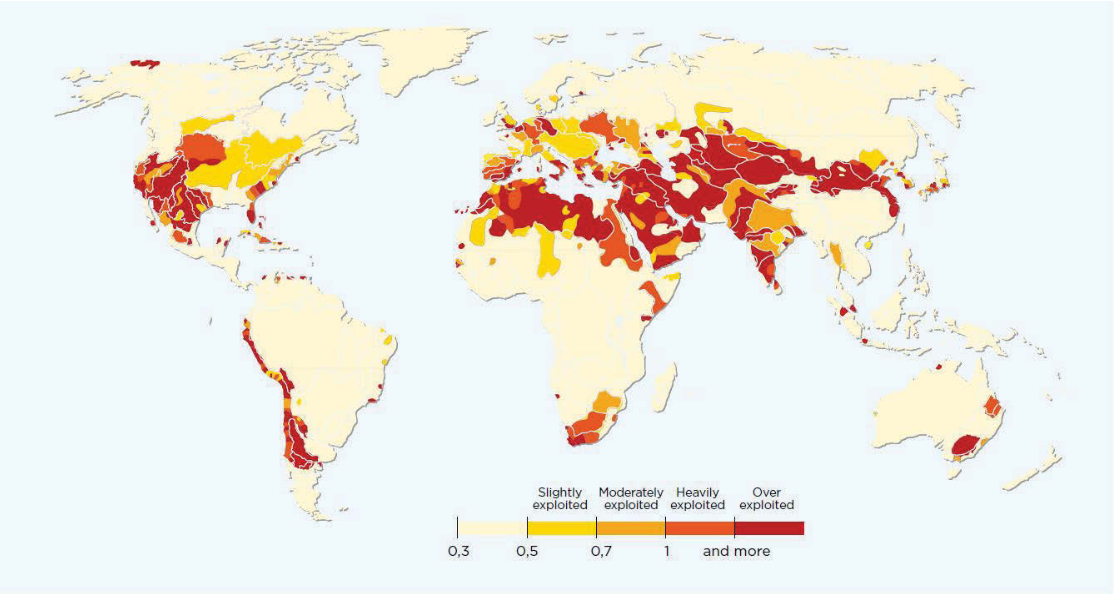


Figure 2.4 : Global Water Stress Indicator (WSI) in major basins (adapted from WWAP, 2012).

Since water is spatially and poorly distributed and this situation is compounded by human interaction, unevenly distributed water stress has been observed. The new paradigm is aimed at explicitly resolving space-related issues. Although scale issues permeated the debate for decades and particularly in reference to physically-based distributed modeling (Beven and Kirkby, 1979; Wood et al., 1988), the general approach appeared viable. Spatial data (e.g., remote sensing, digital terrain data) led to new types of models being available and new ways for the testing of such models (Sivapalan and Blöschl, 2015). Environmental processes such as chemical, erosion, and biological processes have been included in the hydrology model and then coupled to atmospheric models. However, as the focus shifted to capturing spatial heterogeneity and improved process resolution, the treatment of time was mostly limited to whatever time variability was in the climate inputs (Sivapalan and Blöschl, 2015).

Until the 1970s the field of water management was known by the term “water resources development”. In the 1980s it became more popular to refer to it as “water resources management” (WRM), and in the 1990s to “integrated water resources management” (IWRM). This change of names reflects the increasing recognition that water systems are not merely there to be used for human use; but rather, in a balanced manner between fulfilling human needs and sustaining ecosystems (Falkenmark and Rockstrom, 2006; Savenije et al., 2014). This idea was termed integrated water resources management (IWRM), and the concept was officially adopted during the International Conference on Water and the Environment (ICWE) held in Dublin in 1992 (Savenije et al., 2014).

Water systems have been studied with human effects as inputs largely because of the enormous complexity of human-water interaction. There is, however, an increasing number and variety of patterns that can no longer be explained without integrating anthropogenic processes (Blöschl, 2014). In recent years, it has become increasingly evident that regional water problems can no longer be resolved by water professionals as it is more and more interconnected with other development-related issues and with social, economic, environmental, legal, and political factors at local and national levels and sometimes at regional and even global levels (Biswas, 2004). Presently, hydrological analyses focusing on the interaction between connected systems have mainly been carried out by considering each system (and related models) separately (Montanari et al., 2013) using integrated water resources management (IWRM).

Integrated water resources management (IWRM) has been done by incorporating socio-economic and political factors. Such hydrological models have been used independently of potentially important co-evolutionary processes within the IWRM framework. As a consequence, models of hydrology are particularly suited to simulate and predict processes for catchments in pristine conditions, and the interaction with society has been simulated by treating them as exogenous variables that come from independently developed models of societal behavior. An early criticism of IWRM was that it was too impact orientated and that there was not enough focus on adaptation (Savenije et al., 2014). Such a framework may account for hydrological changes induced by shifts in external forcing or internal dynamics, but cannot account for more complex changes due to co-evolving model structures or parameters and multiple feedback between systems.

The IWRM framework considers systems' interactions separately and the anthropogenic effect such as decision-making and adaptation is considered as boundary condition. It cannot be used effectively for future projection over a long period in a complex dynamics of human water system. Further, IWRM mostly relies on the assumption of stationarity (Milly et al., 2008; Sivapalan et al., 2012), which allows predictive models to be conditioned through calibration using historical data before being extrapolated to the future conditions under assumed scenarios (Arnell et al., 2011; Moss et al., 2008; Vuuren et al., 2011). Thus an approach that incorporates the dynamic coupling of water and human action/reactions is therefore needed: a genuine two-way coupling rather than boundary conditions that has been the norm in the past. This can clearly explain an emergent behavior of a system with ‘slow-fast processes’ that produces interesting dynamics by the coupling that occurs across space and timescales. These cannot possibly be understood by looking at individual factors in isolation. There is a need for socio-hydrology in the field of sustainable water resource assessment to account for the feedback of hydrology’s impact on society as both co-evolve in real time. A better understanding of links between the two systems and feedback concerning it could guide long-term decision-making of sustainable water resource management.

In water management practice, the emphasis has been increasingly on interactions between planners, decision-makers and stakeholders. Much of the focus then was on decision-making under uncertainty and comparing alternative project options by the “systems approach” (Sivapalan and Blöschl, 2015). Since humans interact with a water system with feedback and adaptive mechanisms, it creates emerging dynamics and paradoxes. As a result, it became more important to understand how the different system (i.e. environment, society) interacted with water. In the scientific community, researchers have gradually expanded the scope of their analysis from hydrology to eco-hydrology and to socio-hydrology, in an effort to better understand the metabolism of the complex system and the dynamics of co-evolution and development. Compared to eco-hydrology, socio-hydrology has far more complex feedback mechanisms, largely due to the capacity of humans to adapt the environment. Humans, in comparison to ecosystems, are more mobile and have the capacity to change their environment by rapid communication, setting up of institutions, developing technology, implementing engineering interventions, and establishing economic incentives. Falkenmark (1997) proposed the inclusion of humans as part of water system analysis to acknowledge the need to understand the connection between people and water and first coin the term “hydro-social”. The assessment of the societal impacts of a physical water system may be the subject matter of hydro-sociology. On the other hand, hydro-economics and hydro-economic modeling aim at either: firstly, optimizing the economic objectives of a water system, such as conjunctive use of groundwater and infrastructure, cost-effective environmental flows in the context of bi-national river management; and secondly, the best strategy for water conservation and infrastructure expansion (Pande and Sivapalan, 2016).

In these ways, hydro-economics and hydro-sociology operationalize economic concepts and societal impact assessment, respectively, by incorporating them at the heart of water management. These approaches respond to ‘what if’ scenario-based questions, such as what would be the effect of ecosystems on the economic value of water, or what would be the positive and negative impact of infrastructure development, such as the building of new dams. Long-term socio-economic (such as population, wealth, etc.) and water infrastructure scenarios (e.g., demand projections and water policy) are needed to assess long-term impacts of societal decisions on water availability and food security. However, these scenarios remain ‘exogenous,’ i.e. with prescribed boundary conditions that nevertheless may change over time in response to water availability (Pande and Sivapalan, 2016).

On the other hand, humans can learn and adapt to any given situation. This makes prediction within the complex human–water system far less certain than within the ecosystem–water system interaction, although the latter can also experience unpredictable system shifts (Savenije et al., 2014). In the recognition of human coupling with natural systems (CHANS) (Liu et al., 2007b), research has been more interested in understanding the interaction within coupled human and natural systems. The approach emphasized the many complexities of coupled system behavior, but they are not evident when studied by social or natural scientists separately. For example, Liu et al. (2007a) demonstrated through examples that CHANS form complex feedback loops, involve strong non-linearities with thresholds, and exhibit critical transitions, emergent behavior, resilience, heterogeneity, surprises, and legacy effects. These complexities have major implications for modeling human decision-making behavior (An, 2012), as well as for management, governance, and policy (Sivapalan and Blöschl, 2015).

2.3 Emergence of socio-hydrology

Socio-hydrology studies how *people* organize themselves in the landscape with respect to water (Sivapalan et al., 2012). Ancient human settlements were mostly organized along streams (Di Baldassarre et al., 2013b; Elshafei et al., 2014; Liu et al., 2014), which they used as a means of transport and water supply for drinking and agriculture, and therefore access and proximity to water courses or sources governed the primary human settlement patterns. Major paradigm shifts in management in environmental resources management approaches have been mechanistic and technocratic, thus largely neglecting complexity and the human dimension (Pahl-Wostl, 2009). Socio-hydrology can potentially learn from human settlement patterns and migration dynamics by interpreting them in terms of access and proximity to water resources, policy implementation and socio-economic and technological factors. An important feature of non-linear systems is that fast processes interact with slow processes to produce complex and rich dynamics. For example, these interactions may lead to exceeding critical thresholds or tipping points. Climatic, hydrological and societal drivers often appear as shocks (floods, droughts, wars, economic collapse) and may push the system beyond resilience thresholds.

The discipline of "socio-hydrology" which promotes the coupled human-water system has been introduced relatively recently (Sivapalan et al., 2012). The previous use of the term "hydro-social" did not explicitly acknowledge the co-evolution of social systems and hydrological systems nor promote an investigation of methods to understand the nature of the complex feedbacks between these systems. Socio-hydrology promotes the concept that social systems and hydrological systems are inherently coupled and cannot be adequately represented independently (Troy et al., 2015). This field emphasizes understanding of emergent phenomena in changing water systems due to human interaction, such as the levee effect, adaptation to change, system lock-in, and system collapse due to resource depletion (Sivapalan and Blöschl, 2015).

The emergent dynamics observed in the basin management were a reflection of the self-organization of the human-water system within given hydro-climatic and socio-economic regimes, a result of balancing human productive forces related to human preferences for economic gain and environmental restorative forces that aim to preserve the natural environment (Sivapalan, 2015). In particular, socio-hydrology seeks to understand and interpret patterns and phenomena that emerge from the two-way feedbacks between human and water systems that arise naturally as part of water management decisions and actions. The subject matter of socio-hydrology is the many diverse phenomena that emerge from these two-way feedback systems and manifest as puzzles, paradoxes, exhibiting obvious differences. There are also similarities between places, reflecting their distinct hydro-climatic, eco-environmental, and socio-economic features. Examples include the agrarian crisis in booming emerging economies such as India (Pande and Savenije, 2016), increasing levee heights in urban environments even at the expense of increased flood risk (Di Baldassarre et al., 2013a) and the peaking in water resource availability as basins develop (Elshafei et al., 2015; Han et al., 2016; Kandasamy et al., 2014).

Water is used by multiple users. For example, peak water paradox emerges as the competition between human use and environment use. Competition between environment and agriculture (Elshafei et al., 2015; Han et al., 2016; Kandasamy et al., 2014; Liu et al., 2014) have increased since water utilization reached its capacity limit. The competition between water for humans and water for the environment is ultimately mediated by humans alone, acting for themselves and acting for the environment. In other words, this competition is really playing out within the minds of individual human beings and within society at large. It is not possible, let alone make future projections of any long-term dynamics, without understanding how the issues of economic gain, environmental degradation or flood risk are playing out in society, and how societal perceptions then impact on decisions with reference to human settlement, infrastructure development and environmental protection (Sivapalan, 2015). In addition, the awareness of ecosystem degradation and the technological capacity of society to curtail undesirable developments have mobilized global society to pursue "sustainable development" (Savenije et al., 2014). Changing values and preferences of society on water issues which arise through two-way feedback and social learning should therefore be considered as internal to the system if long-term projection is to be pursued (Sivapalan and Blöschl, 2015). It is now very important to understand and to model the changes in the values and preferences and associated cultural factors in order to predict a society's behavior more reasonably than based on assumptions about rationality, or utility maximization (Caldas et al., 2015; Sivapalan and Blöschl, 2015).

Socio-hydrology looks forward to understand changing human behaviors and decision-making in water management with feedback of human and water systems. It is also noted that human behavior is often unpredictable, for example human behavior that exacerbated rather than reduced flood risk (Loucks, 2015; Troy et al., 2015). Since socio-hydrology incorporates the human dimension with multiple feedbacks, it is expected to inform how socio-hydrological systems respond to and cope with perturbations and how these connect to the capacity for resilience (Mao et al., 2016).

Previously, the complex bi-directional interactions, feedbacks and critical thresholds were not studied due to lack of available data especially in social systems which evolve over a long period of time. In the past, the approach was to omit the human fingerprint and filter them out to get ‘clean’ data. There is a need for new data or to use existing data in a new way, that exactly addresses the human interaction (Blöschl, 2014). Recent developments in science, particularly in information technology and remote sensing, have enabled us to collect and share huge amounts of data providing spatial descriptions over a long period of time. The increasing use of satellites to monitor the globe from space provides global space-borne data (Levy et al., 2016), where a worldwide comparative analysis can be made of time and space contexts (Blöschl, 2006; Sivapalan and Blöschl, 2015) of watersheds. In particular, various sources of remote sensing data characterized by a spatial resolution useful for the observation of the most significant watershed dynamics such as population distribution data for tracking patterns of human settlements is available (Linard et al., 2012). Ceola et al. (2014) used night lights data to study the flood damage close to rivers in a way that data collected for completely different reasons were used to identify new patterns of human-water system interactions. Further, exponential development in computer hardware is providing massive computing power for analyses of huge data and the relationship between systems using state-of-the-art technology such as machine learning.

2.4 Co-evolution of water and society

The term “co-evolution” originated from biology to describe the simultaneous adaptation by closely interacting animal or plant populations, each of which exerts a strong selective force on the other (Sivapalan and Blöschl, 2015). Since then the term has become widely used in other fields to understand and explain the adaptive interaction between systems (Sivapalan and Blöschl, 2015). In the context of an agricultural catchment area, humans utilize water to produce food and enhance their socio-economic wellbeing. Once they reach the capacity level and yet continue to exploit water resources, it creates stress on water resources and the co-depending ecosystem and human system. This stress can be mitigated or overcome in two ways: by mobilizing more water resources (more supply) or managing water demand (reduce the demand). Most rivers in the world are regulated by dams and diverting structures (Vörösmarty and Sahagian, 2000) to satisfy people’s fresh water demands. Over-exploitation of water resources and the alteration of dynamics of natural system by humans have placed enormous stress on ecological systems such as wetlands, particularly in arid regions of the world (Bunn and Arthington, 2002; Kingsford and Thomas, 2004; Lemly et al., 2000).

Human regulation in an upstream part of river catchments aimed at reducing flooding and agriculture development causes significant declines in ecosystem functioning (Bunn and Arthington, 2002; Lemly et al., 2000; Micklin, 1988). Flood-dependent vegetation die-off (Kingsford and Thomas, 2004), and the impacts of salinization exacerbate problems (Northey et al., 2006). Biodiversity tends to be more reduced in areas that are infrequently flooded, compared to those that experience moderate flooding and this eventually impacts on the landscape (Kingsford and Thomas, 2004). When the ecosystem shows danger of demise and reduced utility to society, society's awareness of ecosystem degradation escalates. Once society passes through a threshold of awareness, people will attempt to change their behavior and change the management or policy strategy in order to effectively tackle the issue. Society learns from past action and changes its values and preferences of water use and water management. This may be seen as a cyclical process of social learning and adaptive management.

To some extent water stress can be managed by technology and infrastructure through water saving and demand management. Human over-exploitation of water needs to be managed by proper institutional responses, balancing sustainably so that economic benefits continue for humans and ecological systems remain healthy. The challenge of sustainable development of water resources calls for different institutional arrangements for water planning and management at the local level (e.g. an irrigation scheme) and at the watershed or river basin scale. In addition, it becomes increasingly clear that wise water governance includes a proper reflection of the concerns and constraints of water in other policy domains, such as in agricultural, energy and trade policies (Savenije et al., 2014).

2.5 Theories underpinning co-evolution

In natural resource management, co-evolution of society is studied using different theories which interconnect social systems and natural resource systems.

2.5.1 Social learning and Adaptive management

One important aspect is to understand the processes of social learning that precede any collective decision-making (Pahl-Wostl and Hare, 2004). The notion of social learning refers to processes of learning and change that are experienced by individuals and social systems. In the important work of Bandura (1977) social learning refers to individual learning based on observation of others and their social interactions within a group, e.g. through imitation of role models. It assumes an iterative feedback between the learner and their environment, the learner changing the environment, and these changes affect the learner.

In recent years, it has become increasingly evident that the human dimension plays a key role in resources management. Understanding of human collective action becomes more important so that resources can be managed more effectively. Human actions shows that this management cannot be explained by simple optimization (Sivapalan and Blöschl, 2015). Problems are complex, uncertainties are high, and prediction is only possible to a limited extent. Integrated approaches to resources management are advocated. This implies that management is not a search for the best solution to one problem but an ongoing learning and negotiation process where a high priority is given to questions of communication, perspective sharing and development of adaptive group strategies for problem-solving. This is known as social learning (Pahl-Wostl and Hare, 2004). Social learning was taken into account in a new approach called participatory agent-based social simulation (Pahl-Wostl and Hare, 2004).

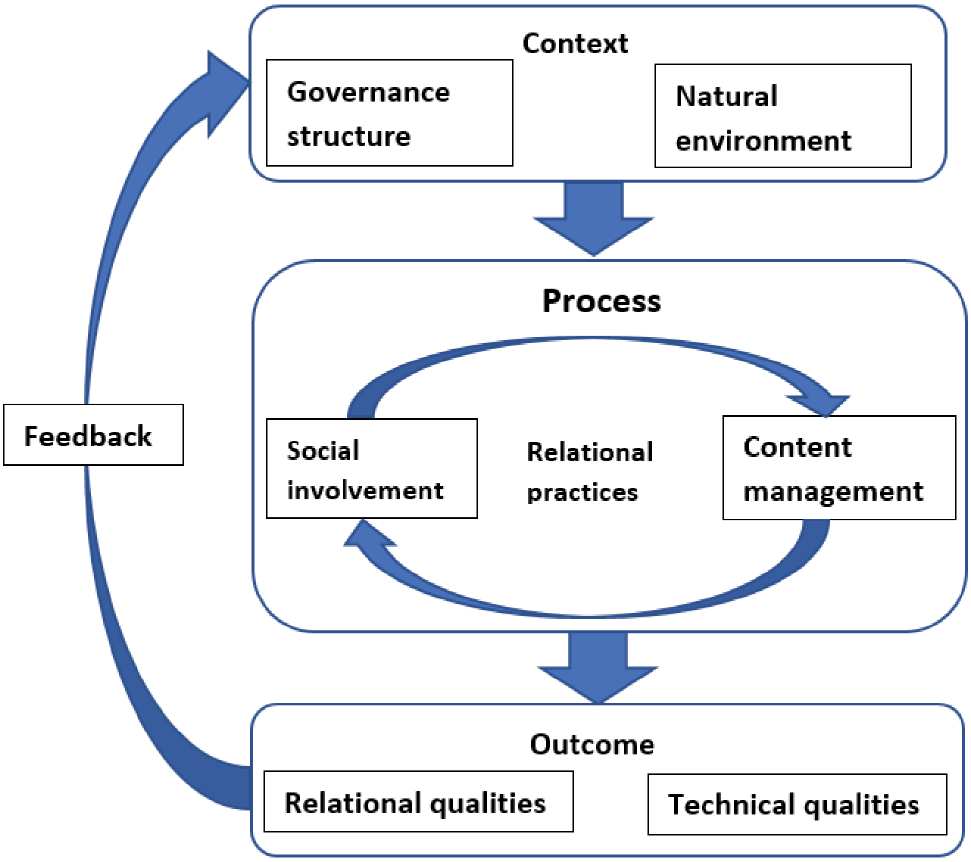


Figure 2.5: Conceptual framework for social learning for resources management (adapted from Pahl-Wostl and Hare, 2004).

Societies learns from the outcomes of their actions and incorporate those into their governance structures. Resource governance has often evolved over long periods of time and is closely intertwined with technological infrastructure, resources and society (Pahl-Wostl, 2002). Adaptive governance and social learning have been identified as essential for governing social-ecological systems during periods of abrupt change (Folke et al., 2005; Pahl-Wostl, 2007). Adaptive capacity is defined as the ability of a resource governance system to first alter processes and, if required, convert structural elements as a response to experienced or expected changes in the societal or natural environment (Pahl-Wostl and Hare, 2004). Analyzing the dynamics of such multi-level and complex governance systems provides a considerable challenge. However, the major conceptual frameworks in the social sciences of interest to resource governance studies (i.e. regime theory in political sciences, game theory, new institutional economics) are quite weak in their ability to analyze whether governance is seen as belonging primarily to the realms of politics, polity or policy (Pahl-Wostl and Hare, 2004). Related to the political dimensions, governance emphasizes the way of policy-making, how different preferences are translated to effective policy choices and different interests are transformed to create unitary action (Kohler-Koch, 1999).

To deal with the complexity of governance systems in a more systematic fashion the following four dimensions are identified as the basis for analyzing the characteristics of environmental governance regimes: (1) Institutions and the relationship and relative importance of formal and informal institutions; (2) Actor networks with an emphasis on the role and interactions of state and non-state actors; (3) Multi-level interactions across administrative boundaries and vertical integration; and (4) Governance modes - bureaucratic hierarchies, markets, and networks (Pahl-Wostl and Hare, 2004).

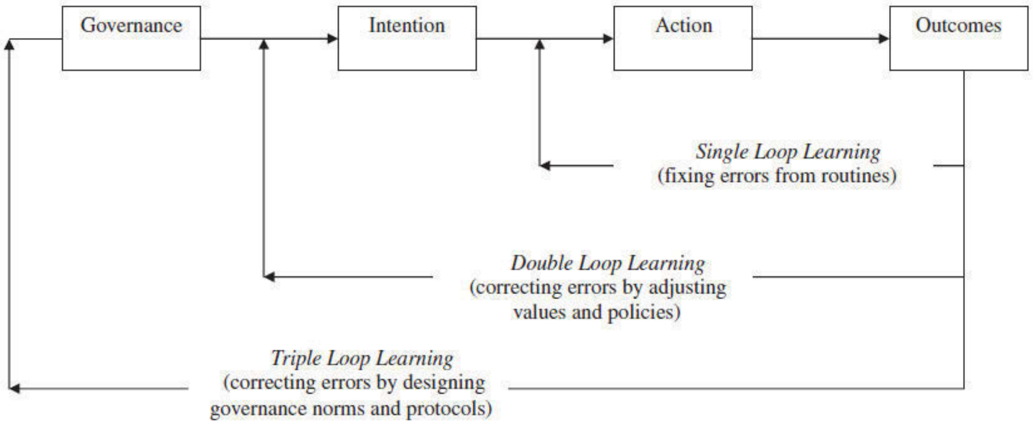


Figure 2.6: Sequence of learning cycles in the concept of triple-loop learning (adapted from Armitage et al., 2008)

Social learning is an iterative and ongoing process comprising several loops and enhances the flexibility of the socio-ecological system and its ability to respond to change. The concept of triple-loop learning is widely used in management theory to guide the concept and practice of managing changes in organizations. The triple-loop learning concept aims at a refinement of the influence of governing variables in terms of governing assumptions and governing values. Armitage et al. (2008) used the multiple-loop learning concept in the context of collaborative learning in environmental and resource management. They associated triple-loop learning with changes in norms and protocols of governance.

Single-loop learning refers to a refinement of actions to improve performance without changing guiding assumptions nor calling into question established routines. Incremental changes in established practice and action aim at improving the achievement of goals. This phase might also include a first improvement of capacity (i.e. the size of reservoirs) to make and implement collective decisions.

Double-loop learning refers to a change in the frame of reference and the calling into question of guiding assumptions. Reframing implies a reflection on goals and problem framing (priorities, include new aspects, change boundaries of system analysis) and assumptions of how goals can be achieved. It occurs when existing worldviews and underlying values are challenged and lead to fundamental changes in stakeholder behavior (Armitage et al., 2008).

Triple-loop learning refers to a transformation of the structural context and factors that determine the frame of reference. This kind of societal learning refers to transitions of the whole regime (e.g. change in regulatory frameworks, practices in risk management, dominant value structure). Transformation requires a recognition that paradigms and structural constraints impede on an effective reframing of resource governance and management practices.

Learning processes involve actors that go far beyond the established resource governance regime. Transformation implies a change in paradigm and, in the end, also in underlying norms and values. The structural change will lead to a transition of actor networks where new actor groups come into play, boundaries and power structures are changed, and new regulatory frameworks are introduced.

Table 2.1: Characterization of changes in governance regimes expected for single, double and triple-loop learning (adapted from Pahl-Wostl, 2009)

	Single loop	Double loop	Triple loop
Institutions-general	• No calling into question of established institutions, signs of unilateral reinterpretation	• Reinterpretation of established institutions by many parties	• Established institutions changed and/or new institutions implemented
Regulative institutions	• Existing regulations are strictly followed and used to justify established routines • New by-laws and interpretations of existing law to accommodate exceptions	• Regulatory frameworks identified as major constraints for innovation • More juridical conflicts about rule interpretation • Exemptions allowing innovative approaches and experimentation	• Formal substantial changes in regulatory frameworks, new policies implemented • Institutional change towards more flexible regulations that leave room for context specific implementation. • More process regulations
Normative institutions	• Established norms are used to justify prevailing system	• Established norms and routines are called into question	• Change which can be identified in public discourse and new practices • Relying on codes of good practice
Cultural-cognitive institutions	• Discourse remains in established paradigms that are refined. • Radical alternatives clearly dismissed.	• New ideas emerge beyond isolated groups • Strong arguments about alternative views-‘‘ideological’’ debates	• Discourse dominated by new paradigm (media, political debate, public hearings, conferences) • Powerful representatives of ‘‘main-stream’’ argue in new paradigm
Uncertainty	• Uncertainty used to justify non-action • Activities to reduce uncertainties. Reliance on science to find the truth solution • Discourse focuses on technical approaches to dealing with uncertainty with goal to improve predictive capabilities	• Uncertainty accepted and perceived as opportunity in processes of negotiations and reframing • Existence of different perspective and world views explicitly acknowledged • Established approaches to managing uncertainty and risks are called into question	• Uncertainty discourse emphasizes different perspectives and world views • New approaches to manage uncertainty (e.g. participatory scenario development) and risk (e.g. risk dialogues, robust action) are implemented with corresponding efforts to change structural constraints • Conscious decision-taking under (irreducible) uncertainty with the prospect of adapting the measures when necessary
Actor network	• Actors remain mainly within their networks-communities	• Explicit search for advise/opinion from actors outside of established network	• Changes in network boundaries and connections

	of practice • Established roles and identities are not called into question	• New roles emerge—e.g. facilitators in participatory processes • Arguments about identify frames- e.g. what does it mean to be an ‘‘engineer’’ • Boundary spanners of increasing importance that start to connect different networks—communities of practice	• New actors groups and roles have become established • Changes in power structure (formal power, centrality-new actors in centre) • Identity frames/roles get blurred/ less important, rather joint approaches than isolated performance according to one’s role
Multi-level interactions	• Vertical coordination in established patterns-e.g. increased regulation from the top level • Pattern of flow of authority (by institutions) does not change. Mainly uni-directional	• Increased informal knowledge exchange between levels • Informal coordination groups to improve exchange in planning processes established	• Formalized participation of actors at different levels • Established practices of knowledge exchange across levels • More polycentric structures and balance between bottom-up and top-down approaches
Governance mode	• No change in the relative dominance of governance types • Improvement of performance within established governance modes	• Other than dominant governance types start to become more visible and dominant governance type called into question (e.g. discussion of market based instruments if absent before, introduction of participatory approaches, emergence of bottom-up participatory processes, argument about dominance of one type—bureaucratic hierarchies or privatization) • Informal networks shaping discourse and supporting experimental innovations become more prominent	• New governance types implemented, established governance types sub More diverse governance structures– less dominance of one type • Learning networks challenging dominating structural assumptions become effectively connected to and influence established policy arenas

2.5.2 Risk and resilience theory

Risk and resilience management aims to both reduce hazards to prevent the system shifting to an undesirable position (e.g. degradation of ecosystems and living standards), and to move the system toward a desired position (Mao et al., 2016). More recent approaches to risk in the Anthropocene epoch emphasize the fundamental contribution of humans to risks that have increased costs to society. Risk and resilience study sees society as responding to natural hazards and risks to one that looks as emerging from socio-environmental interactions. It is observed that human perception and cognition have a clear role in the risk perception, the subsequent decision-making, and behavior of society to alleviate the risk (Bai et al., 2016). It has been emphasized, in the Anthropocene epoch, how risks are moving from a local or regional scale to a global one, highlighting some of the consequences of that shift, and the need for a global approach to these issues under the banner "Global Systems Science" (Bai et al., 2016).

Based on risk and resilience theory, socio-ecological system (SES) framework was proposed to identify the potential vulnerability of SES to disturbances (Anderies et al., 2004; Ostrom, 2009). All the links between components of this framework could fail and thereby reduce the system's resilience. It is found that the link between resource users and public infrastructure providers is a key variable affecting the robustness of SES (Anderies et al., 2004).

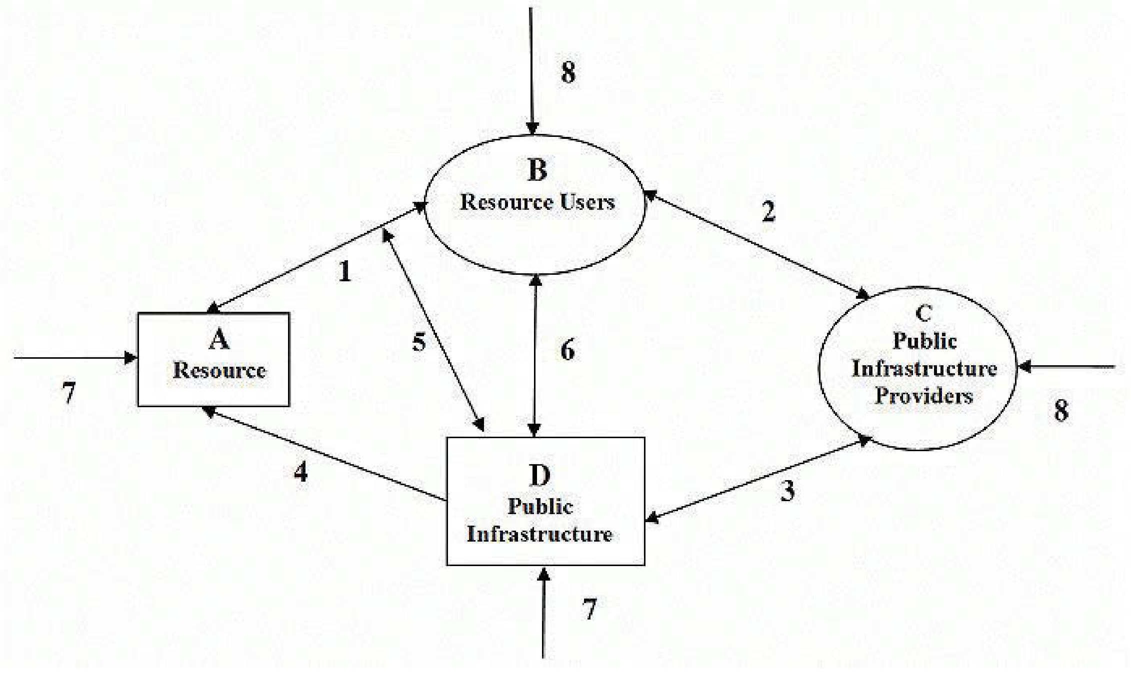


Figure 2.7: Conceptual model of a socio-ecological system. Numbered arrows show

links: (1) Between resource and resource users; (2) Between users and public infrastructure providers; (3) Between public infrastructure providers and public infrastructure; (4) Between public infrastructure and resource; (5) Between public infrastructure and resource dynamics; (6) Between resource users and public infrastructure; (7) External forces on resource and infrastructure; (8) External forces on social actors (adapted from Anderies et al., 2004)

2.6 Changing value and norms

The exact process of humans decision-making is always based on values and preferences of society (Sivapalan and Blöschl, 2015). In the context of socio-hydrology, Sivapalan and Blöschl (2015) defined the values as the “overarching goals of individuals and whole societies with respect to water use, conservation, and sustainability”. Dynamic changes in the values and preferences through human-nature interactions and feedbacks play an important role in management of water resource systems and are important predictors of changes in water management decisions and outcomes (Caldas et al., 2015).

It is understood that we cannot understand, let alone make future predictions of, water resource system dynamics, without understanding how the issues of economic gain, environmental degradation, and social inequities play out in society, and how social perceptions of these issues impact on management decisions relating to water consumption, allocation and pricing, human settlements, infrastructure development, and environmental protection (Blair and Buytaert, 2016; Srinivasan et al., 2016). Such an understanding will remain incomplete until we fully grapple with issues arising from human culture, including how components of culture – values, beliefs, and norms - relate to water uses, livelihood, and the environment (Sivapalan and Blöschl, 2015). It is increasingly recognized that cultural factors are likely to influence changes in water management decisions and outcomes (Caldas et al., 2015), raising questions about what have become ‘conventional’ assumptions about humans as rational, utility maximizers who make decisions based upon complete information. Although economic models of altruism and impure altruism (i.e. “warm glow” effect: caring about others or the next generation not just out of altruism but because they get pleasure out of it themselves) have been successful in predicting the effect of prevailing values and norms on human behavior and actions (Andreoni, 1989; Banerjee and Newman, 1993), they remain limited in accounting for the consequences of human actions on societal values and norms in return.

Several place-based socio-hydrology studies in basins dominated by agricultural development (Tarim: Liu et al., 2014; Murrumbidgee: Elshafei et al., 2014, van Emmerik et al., 2014; Lake Toolbin: Elshafei et al., 2015) have highlighted a shift in water use behavior from an initial focus on agricultural production to an increasing emphasis on environmental conservation, a shift that has been called the pendulum swing (Kandasamy et al., 2014). Socio-hydrology models developed to reproduce these observed dynamics attributed the shift to changing human values and norms, which were tracked indirectly through proxies (e.g., environmental degradation). For example, van Emmerik et al. (2014) modeled the human decision to allocate more or less water to agriculture or to the environment on the strength of a dynamic ‘social’ state variable called environmental awareness, which reflected societal perceptions of the environmental degradation within the prevailing value systems or culture (see also Di Baldassarre et al., 2013) for awareness of floods in the context of coupled human-flood systems. In the socio-hydrological model devised by van Emmerik et al. (2014) the human response to changing environmental awareness is captured through an appropriate constitutive relationship, chosen in a somewhat intuitive way. Hence, the parameters governing the constitutive relationship could only be obtained through calibration of the overall model and would always be challenged unless they are verified to be right for the right reasons. Prediction-wise, both in time and space, confidence in such place-based models will be low so long as the constitutive relationship cannot be independently validated or theoretically justified.

There is a need to generalize socio-hydrological models both for predicting future socio-hydrological outcomes in one location and/or to apply them at others. Case studies have demonstrated an inherently dynamic quality to changing values and norms with reference to water use or environmental behavior, but how to measure or “value” values and norms directly and independently of models remains as yet unresolved. Even if they can be measured in specific places, we need a broad theoretical framework that encapsulates the many physical and social controls that govern changing values and norms in order to synthesize data or measurements from many places across the globe and develop broad generalizations. These remain major challenges to the progress of socio-hydrology as the science underpinning sustainable water management (Pande and Sivapalan, 2016).

2.6.1 Values and norms in socio-hydrology models

Following Wescoat (2013), the socio-hydrology literature has tended to define values and norms as the over-arching goals of individuals and of whole societies in relation to water use, conservation, and sustainability. Prior research in socio-hydrology has allowed values and norms to undergo dynamic changes. Sivapalan et al. (2014) proposed a socio-hydrology framework which uses values and norms as drivers of the decision-making that shapes society's goals and actions, and are in turn shaped by the outcomes for human wellbeing that result (Figure 2.8). In this way, values and norms are seen as endogenous to coupled human-water systems, co-evolving with the changing dynamics of water resource systems (Norton et al., 1998; Sivapalan and Blöschl, 2015). So far in socio-hydrology research, values and norms have been lumped together and represented by proxy variables. Next, we illustrate this through several examples.

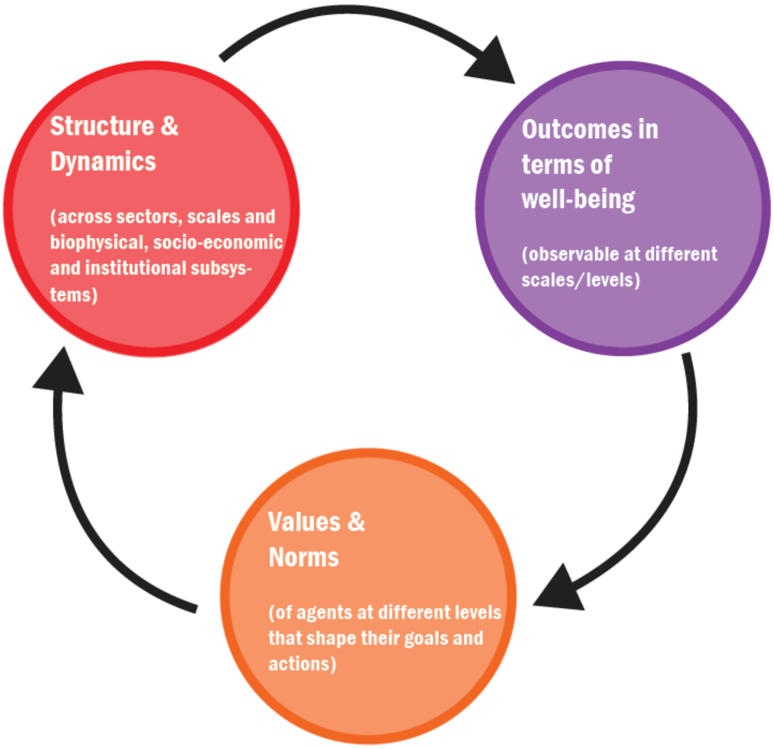


Figure 2.8: Socio-hydrology framework proposed by Sivapalan et al. (2014).

2.6.1.1 Environmental awareness

van Emmerik et al. (2014) developed a socio-hydrological model of the Murrumbidgee River Basin (MRB) in eastern Australia to explain an observed "pendulum swing", i.e. a shift in water management focus away from economic development and towards ecosystem health. This shift was hypothesized to be the outcome of changes in values and norms in the community in respect of economic wellbeing and ecosystem health. In the model, the dynamics of changing values and norms were represented by environmental awareness, a proxy state variable that reflected adverse changes to ecosystem health. It was assumed that environmental degradation occurred when too much water was extracted for agricultural activities aimed at advancing economic wellbeing of the community. As a result, less water reached downstream wetlands. When wetland storage went below a specified threshold, ecosystem health suffered noticeably and this was felt in the community, which was then reflected in more environmental awareness. Enhanced environmental awareness then triggered human action, in the form of reductions in water allocation to agriculture, leading to reductions in irrigated area, and increased water allocation to the environment. The situation would reverse itself upon a return of increased downstream environmental flows, restoration of wetland storage and improvement to ecosystem health.

The representation of environmental awareness in van Emmerik et al. (2014), although simple, represents a first attempt to explain the intuitive relationship between values and norms about perceived threats to ecosystem health and changes to water management actions. Note that other effects or characteristics of environmental degradation, such as changing water tables, or salinization of the soil, were not taken into account. Furthermore, regional or national policy is not taken into account in the formulation of environmental awareness. Finally, the functional form of the equation was calibrated using data on population, total irrigated area, agriculture water utilization.

2.6.1.2 Community sensitivity

Elshafei et al. (2014) expanded further on the intuitive causality between changes to community values and norms in respect of ecosystem health and consequent water management actions by humans. They elaborated on how agri-centric values conflicted with environmental values and influenced water use behavior and proposed a framework that modeled the competition between economic development and environmental awareness using ‘community sensitivity’, a new social state variable. They presented a feedback formulation where water use behavior is influenced by changing values and norms relating to the environment and economic well-being, as reflected in the community sensitivity. For the first time the authors brought in broader (e.g., regional) climatic, political and socio-economic contextual variables that may influence local values and norms in respect of water use, for instance rapidly diversifying economic growth. Elshafei et al. (2015) explicitly demonstrated that environmental degradation impacted on community sensitivity and consequently water use behaviors. The foundation of their proposed framework was driven by the hypothesis that the coupled system dynamics are driven by competition between a positive feedback loop (Economic-Population Loop) and a negative feedback loop (Community Sensitivity Loop).

2.6.2 Values, beliefs and norms as dynamic variables

So far in socio-hydrological modelling research, aspects of human culture that drive human behavior in respect of water management – in other words, values and norms – have been treated in a lumped way, represented by proxies, in a 'black box' way. Moving socio-hydrology forward requires opening the 'black box' of culture by questioning the assumptions behind and more clearly measuring and modelling cultural factors. For example, if values are conceptualized as over-arching goals of society (Wescoat, 2013), are they individual goals or collective goals associated with the emergent structure of a coupled human-water system, or both? Similarly, how malleable are values and norms as aspects of a coupled human-water system? Moreover, under what conditions should values and norms be expected to change, or remain stable? For that matter, what are the mechanisms through which values and norms might change, and the human behaviors and actions that result from them?

The ingredients for understanding the role of changing values and norms in coupled human-water systems can be summarized as: (a) forward loop: theories of how individual values influence individual norms and behavior regarding water use, (b) backward loop: theories of why and how collective behavior can engender change in individual norms regarding the use of water for agriculture or the environment, (c) role of institutions in enabling changes in water policy that reflect collective behavior towards the water environment, (d) data that can provide information on proxy variables including environment related behavior and patterns and (e) models that use proxy data to conceptualize processes (a)-(c) in interpreting related patterns. Future work in socio-hydrology will necessarily grapple with these types of questions that further elucidate the role of values and norms in coupled human-water systems.

2.6.2.1 Values, Beliefs, and Norms: VBN theory

One line of conceptualization seems particularly promising for advancing socio-hydrological research. The Values-Beliefs-Norms (VBN) theoretical framework (Stern et al., 1999; Ives and Kendal, 2014) is grounded firmly in social-psychological theory and has been empirically tested as a framework for understanding how cultural factors (i.e. values, beliefs and norms) shape environmental decision-making, and water use behavior in particular, in a wide array of contexts. Figure 2.9 presents a stylized version of a VBN model linking values, beliefs, norms, and behaviors. In this framework, behaviors are motivated by proximate norms, or obligations to act. Norms themselves are shaped, or activated by beliefs, including a person's awareness of the consequences of their actions, how a person ascribes responsibility for their actions, etc. More generally, norms are shaped by a person's ecological worldview, or how a person views human vis-à-vis the natural environment (i.e. are humans *a part of* the natural environment, or *apart from* the natural environment). Ultimately, the VBN framework posits values-deeply-held, guiding principles about right and wrong – as the basis of water use behavior in the context of socio-hydrology. Values are often assumed to be unchanging, relatively stable, and generally unquestioned principles that motivate water use behavior and water policy actions indirectly through beliefs and norms.

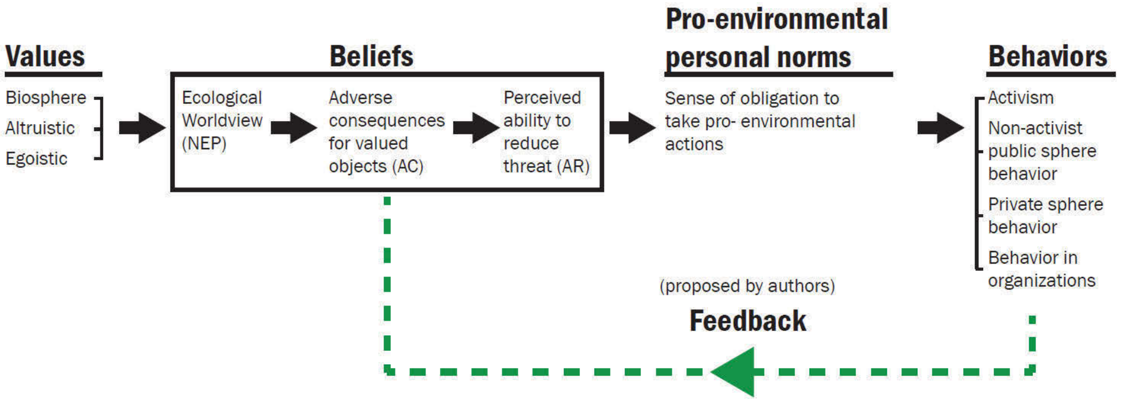


Figure 2.9: Value belief norm (VBN) theory (adapted from Ives and Kendal 2014; Stern 2000). The green arrow is suggestive of a feedback from communal behavior to individual beliefs.

The VBN framework can be incorporated into socio-hydrological models for the purposes of modelling dynamic feedbacks within the human component of the system or between the human and environmental components of the system (Caldas et al., 2015).

Incorporating VBN into socio-hydrological models requires addressing the questions raised above in greater detail, among others, but especially the question of where the feedbacks between values, beliefs, norms and behavior occur in the process of management and the competitive use of water resources.

To illustrate how values, beliefs and norms influence behavior, consider a simplified example of a farmer of English descent in the MRB who migrated into the basin in the early 1900s and farmed rice. The behavior of this farmer towards wetlands is influenced by how the farmer and the farming community *believe* their water use affects what they hold dear or value. Implicitly, this means that their behavior towards the environment depends on how they value water, or what they believe the water should be used for. These are questions of *values*, and values help navigate decisions that must be made about trade-offs between different valued end goals, or uses. Here, one key trade-off is between water for agricultural production (i.e. to support the viability of the farm operation and farmer's livelihood) and water for the environment (i.e. to support environmental flows, biodiversity, and ecosystem services). Humans can hold multiple values, and place different 'weights' or emphases on each of the values that affect a particular decision with regards to water use. The farmer may, for example, make a water use decision by drawing on a combination of self-interest/egoistic values (e.g., using water to support the economic well-being of their family, household, and farm), humanist-altruistic values (e.g., conserving water to preserve the long-term viability of the rural community), and biospheric-altruistic values (e.g., conserving water to preserve wildlife habitat and ecosystem services).

A first step toward modelling this type of VBN process could be to assign weights for each value, allowing behaviors to change in correspondence to the weights that each value type exercises over time. Scaling up from the individual-level, value types can be identified from prevailing complexes of VBN processes in a basin so that socio-hydrology dynamics in a basin are outcomes of generalized behaviors emerging from a distribution of basin residents laden with different value types and complexes. From this perspective, VBN elements at an aggregate level in a basin can become dynamic. For example, degrading ecosystem functioning, such as the drying of wetlands, can bring more uncertainty and risk over time to the things the farmer values (i.e. income, family, farming, community, the environment, etc.) and/or altering the farmer's beliefs (i.e. worldview, awareness of adverse consequences, or perceived ability to reduce threats to things of value), shifting their behavior away from a more egoistic, or agri-centric, orientation and towards wetland conservation and restoration. This is a very simplified example of a complex set of processes operating at multiple scales, but it illustrates how values, beliefs, norms, and behavior might be seen to co-evolve and change through feedbacks in a coupled socio-hydrology system.

There remain important gaps in how to identify the requisite components of VBN processes through measurement, how to scale up these processes from the individual level, and how to model feedbacks. However, as mentioned before, there has already been progress in this direction in the socio-hydrology literature. Place-based socio-hydrology models (van Emmerik et al., 2014; Roobavannan et al., 2017; Elshafei et al., 2014, 2015) have mimicked various regimes that result from a different balance between economic or agricultural development and environmental health due to changing values, beliefs and norms. van Emmerik et al. (2014) were able to model the four eras described by Kandasamy et al. (2014), from an exclusive focus on agriculture, to environmental restoration. A crucial aspect has been the inclusion of a sub-model to quantify environmental health. The community sensitivity framework of Elshafei et al. (2014) was applied to two Australian catchments, and in both cases different regimes could also be differentiated.

Interestingly, the inclusion of human feedback integrating a variety of influences as a response to changes in ecosystem health was done in a completely different way. In van Emmerik et al. (2014) a simple memory function governed by wetland storage sufficed, whereas in Elshafei et al. (2014) more complex community sensitivity equations were introduced, both linking water use-related beliefs and behaviors through bi-directional feedbacks. Roobavannan et al. (2017) advanced this a step further by representing community level belief about the environment, i.e. environment sensitivity, as a consequence of the distribution of weights that individuals attach to enviro-centric versus anthropo-centric values. Such a distribution was made contextual, i.e. it depended on economic diversification. The endogenous treatment of values and norms by these recent studies (van Emmerik et al., 2014; Elshafei et al., 2015; Roobavannan et al., 2017) have implicitly followed the general logic of elements of the VBN theory presented above, even if this was originally unintended (see Figure 2.9). They have therefore responded to the challenges of incorporating feedbacks from water use behavior to beliefs and water management norms, which is consistent with the notion of endogenous and dynamic culture as posited by Caldas et al. (2015).

2.6.2.2 Validation of Modeled Changing Values and Norms

Place-based socio-hydrological models have relied on proxy measures such as environmental degradation to capture changing values, beliefs, norms and behaviors and their parameters were obtained by calibration. Despite the advantages of this approach, confidence in these models remains low because the models struggle to be independently validated. To address the validation challenges faced to date in model-based socio-hydrology case studies, Elshafei et al. (2015) proposed that socio-centric approaches (such as newspaper content analysis) be employed to assess evolving community sentiment over long periods of time.

Along these lines, Wei et al. (2017) recently analyzed the content of newspaper articles to measure and quantify the evolution of societal values and preferences in relation to water management issues in Australia over a 169-year period. The results of Wei et al. (2017) are especially informative to the growing body of socio-hydrology literature focusing on Australian study sites, in particular the Murray-Darling Basin (MDB). Their findings support the hypotheses put forward in Kandasamy et al. (2014) and Elshafei et al. (2014), both of which postulate a shift in societal values from an anthropo-centric to an enviro-centric focus over time.

The work of Wei et al. (2017) thus signals an important step forward for the socio-hydrology research community as its results demonstrate how an autonomous socio-centric analysis method may be employed to provide independent validation for conceptual theories and coupled modelling approaches carried out within the same broad geographical region. This more complete analysis of societal values now enables us to go back and compare the results of this independent study against the predictions made by previous socio-hydrological models. More specifically, Wei et al.'s (2017) results corroborate those of Kandasamy et al. (2014) who detected a pendulum swing in societal sentiment in the Murrumbidgee Basin over a century timescale. As can be seen in Figure 2.11, observed (Figure 2.11a, Kandasamy et al., 2014) and modeled (Figure 2.11b van Emmerik et al., 2014) time series of economic development (proxied by total irrigated area and irrigation water utilization) correspond with the evolution of societal sentiment shown in the bottom panel of Wei et al.'s (2017) results (Figure 2.11c). Moreover, the narrative for each of the three phases described in Wei et al. (2017) repeats the timing and spirit of the phases depicted in Kandasamy et al. (2014), van Emmerik et al. (2014) and Elshafei et al. (2014, 2015) (see Figure 2.11).

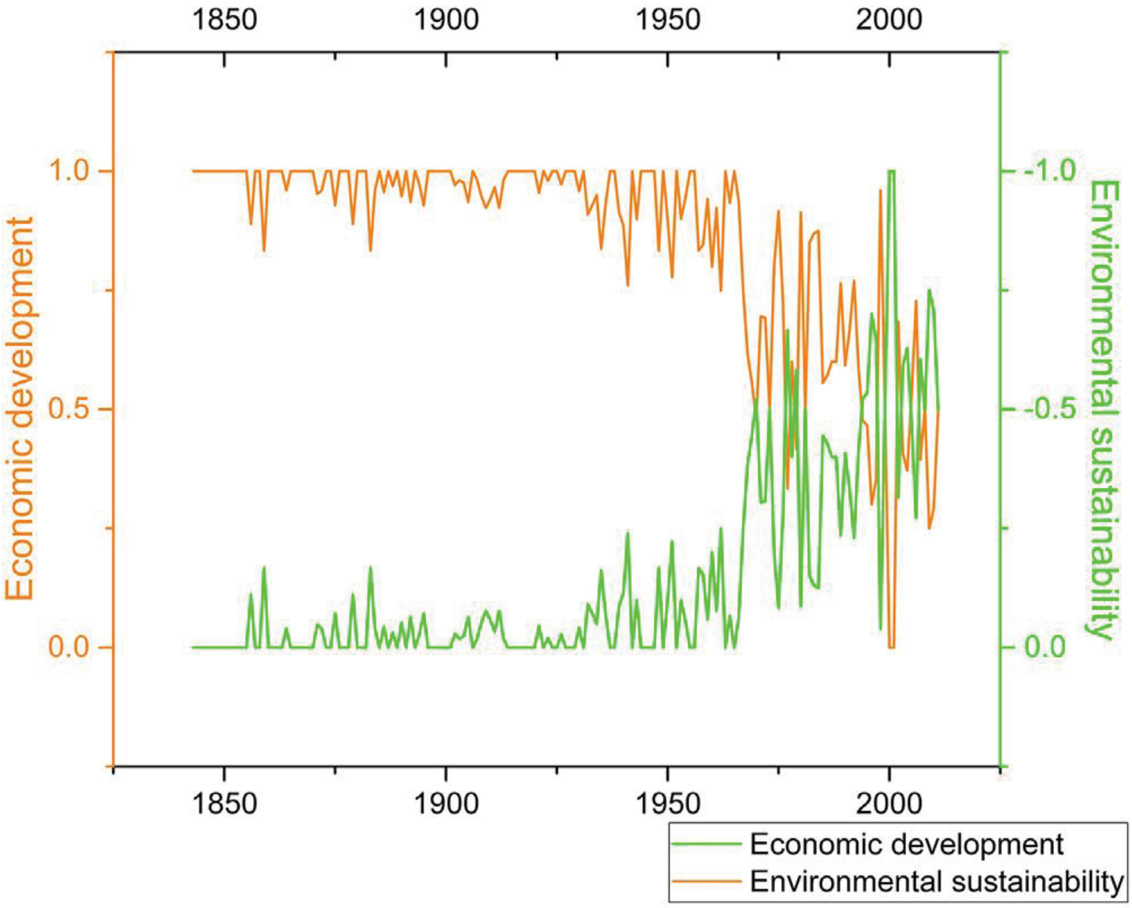
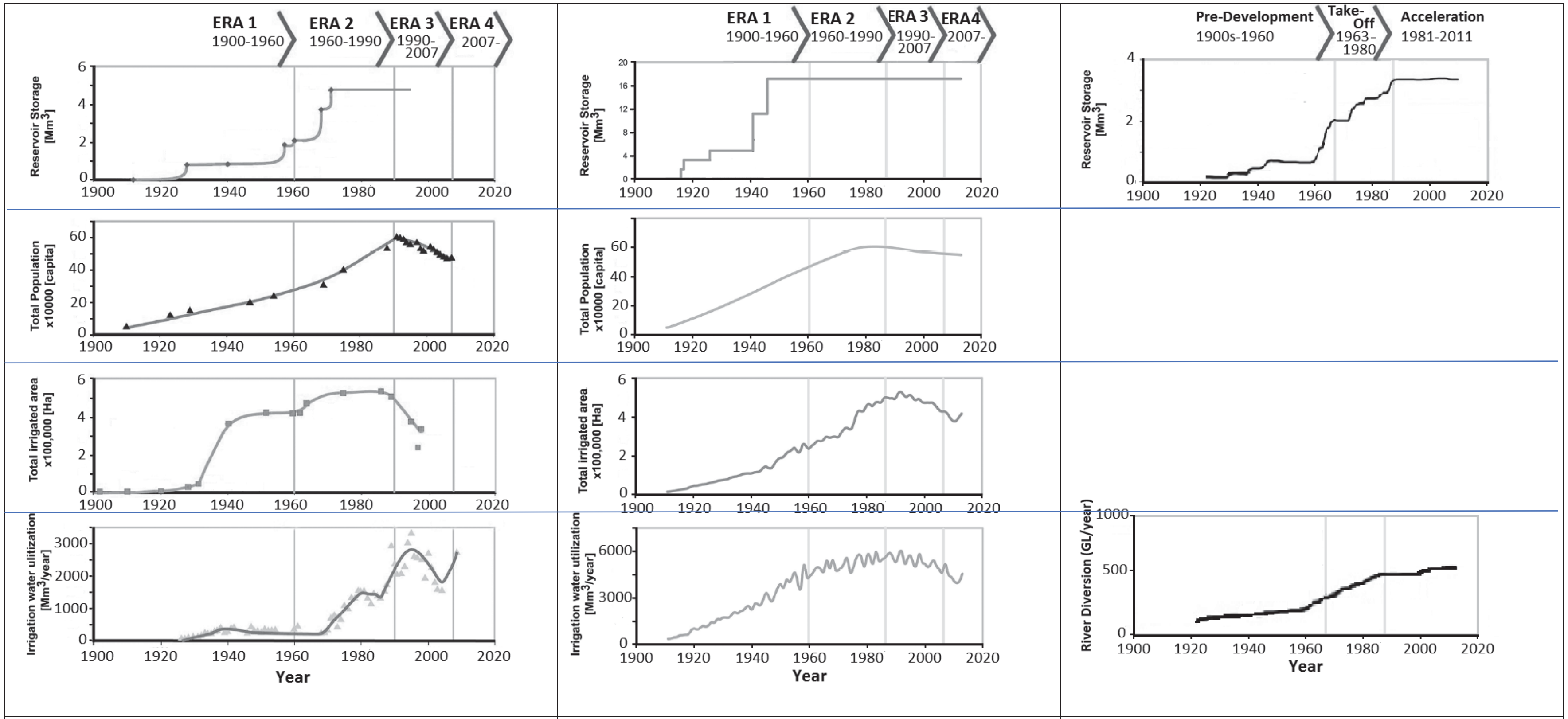


Figure 2.10: Evolution of the societal value of water resources for economic development versus environmental sustainability in Australia since European settlement. The Y axis shows the ratio of societal value for environmental sustainability and the societal value for economic development.

Another important implication of Wei et al.'s (2017) results in relation to Elshafei et al.'s (2014) proposed conceptual socio-hydrological model is that they provide strong support for theories underpinning the use of the composite ‘community sensitivity’ variable put forward therein. Figure 2.12a,b illustrates that when societal values are initially focused on economic development the change in the community sensitivity variable (dV/dt) displays a negative trend (i.e. society is predisposed towards anthropocentric behaviors), whereas as societal values start to favor environmental sustainability the change in community sensitivity variable trends positive (indicating a behavioral tendency to favor conservation). Wei et al.'s (2017) findings thus provide a strong validation for the non-linear dynamics observed in previously published coupled socio-hydrological models that adopted alternate proxies for modelling the change in societal values and norms with reference to water resource management over time. That is, Elshafei et al.'s (2014, 2015) composite community sensitivity variable and van Emmerik et al.'s (2014) environmental awareness variable.



(a) Observed data (Kandasamy et al., 2014) and modelled pendulum swing in the MRB.

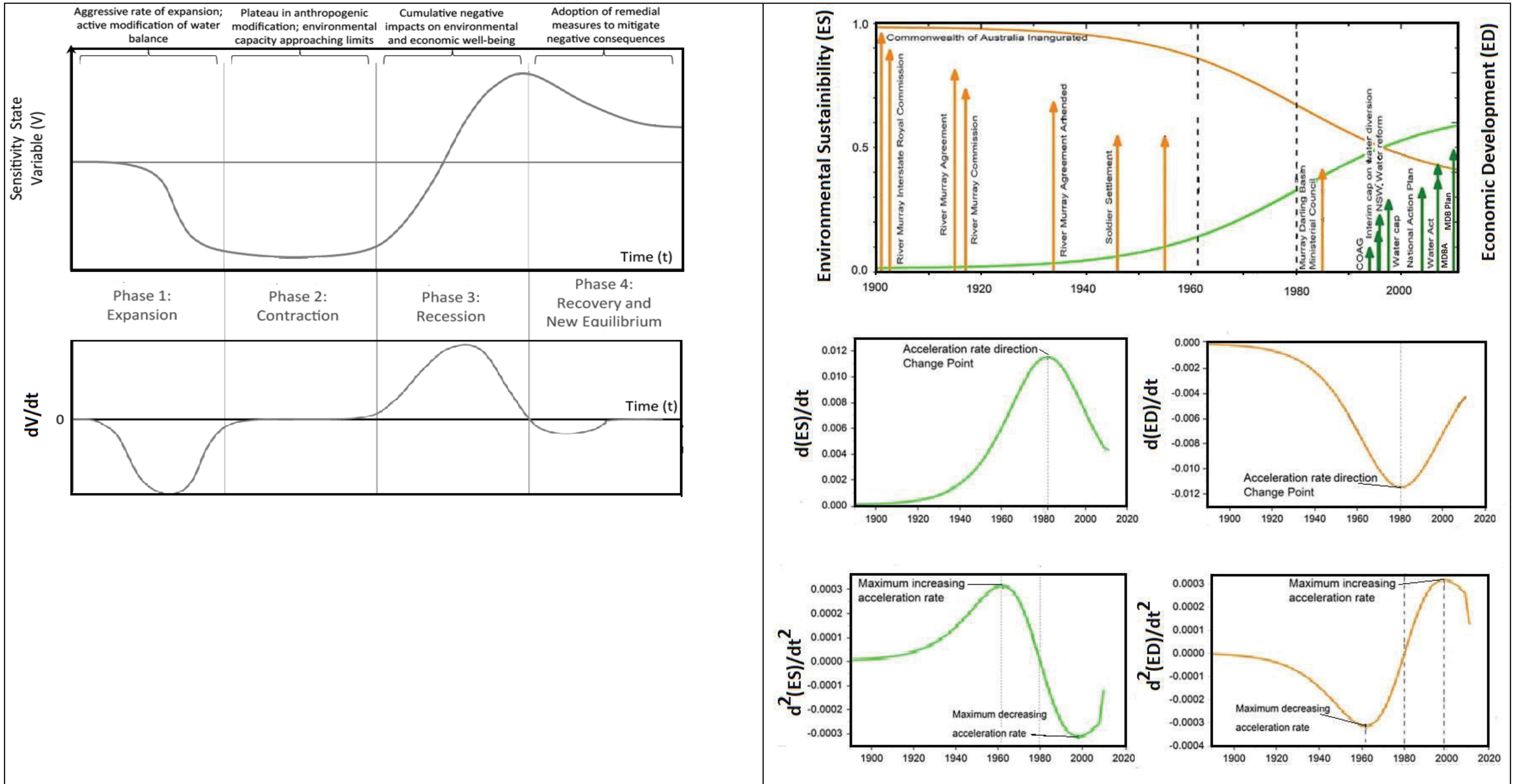
(b) Modelled pendulum swing in the MRB (van Emmerik, 2014)

(c) Murray-Darling data (which includes the MRB) depicted in Wei et al. (2017).

Figure 2.11: Observed and modelled pendulum swing in the MRB during the period 1910–2013. Era 1 (1900-1980) Expansion of agriculture and associated infrastructure, Era 2 (1960-1990) Onset of environmental degradation, Era 3 (1990-2007) Establishment of widespread environmental degradation, Era 4 (2007-2014) Remediation and emergence of environmental customer. The eras correspond to phases in:- **Elshafei et al (2015)** Expansion (1911-1960), aggressive rate of expansion and active modification of water balance; Contraction (1960s), plateau in anthropogenic modification; Recession (1970-2002), cumulative negative impacts on economic and environmental well-being; Recovery and new equilibrium (2002-present), Adoption of remedial measures; and in **Wei et al. (2017)** Pre-development (1900s-1960s) Societal values dominated by economic development; Take-off (1963-1980) Societal values reflected increasing environmental awareness due to outbreak of pollution events; Acceleration (1981-2011) Growing shift in societal values towards favoring environmental sustainability.

It is worth noting that Wei et al.'s (2017) results do not refer to a specific basin, but rather are intended to reflect a broader national or regional view. Validated socio-hydrological models that endogenized water-related beliefs and norms are distinct from regression-based models that are not causal (e.g., Wei et al., 2017). The in-built non-linear dynamics allow possible ‘extrapolation’ of the coupled human-water dynamics across a gradient of hydro-climates, societies and economies, although this requires more work and testing. Similar to regionalization techniques in hydrological modeling, socio-hydrological regionalization will mean how the parameters of the coupled socio-hydrological model, such as curvature parameter of the distribution function that trades off enviro-centric values with anthropo-centric values (Roobavannan et al., 2017), vary from society to society. Regression-based models cannot be extrapolated to another place or time because there are no causal linkages provided to explain the transitional shifts in societal values observed therein. In other words, regression models that do not internalize coupled human water system dynamics can at best be used for ‘interpolation’. In other words, they can only explain the dynamics within the domain of the data or data analysis.

Nonetheless, verification of coupled models with data such as those presented in Wei et al. (2017) is important as it enables the discovery of fundamental principles of human behavior through the validation of internal dynamics within the coupled models. Ultimately, it assists in the generalization of socio-hydrological system dynamics.



(a) An idealized sketch showing a hypothetical trajectory over time for (top) the Sensitivity state variable, and (bottom) the change in Sensitivity (dV/dt) in the case of an example catchment (Elshafei et al., 2014).

(b) Regression curves of societal value of economic development and environmental sustainability, and major turning points and development stages of each societal value (Wei et al., 2017).

Figure 2.12: Defining shifts and turning points in societal values.

2.6.3 From place-based to generalized models: challenges and opportunities

The pathway to generalization of socio-hydrological models is an important goal that allows future prediction (extrapolation in time) and translation of socio-hydrological models at other geographical locations (extrapolation in space). It provides an important means for the adoption of socio-hydrology in the practice of long-term or strategic water resource management. Generalization needs to address both the proxies used in socio-hydrological modelling and the data used to calibrate them, as recent socio-hydrological modelling studies have highlighted.

Models provide languages or templates in terms of which the following three aspects can be interpreted: 1) how beliefs and norms depend on values, 2) how values and norms influence individual behavior towards the environment, for instance the wetland health or releasing environment water for bio-diversity, and 3) how pro-environmental behavior of some people or groups in the community (e.g., rallies by the Green Movement) can influence the beliefs of others in the basin and bring about a change in water management (i.e. the feedback). Such templates also enlighten us with variables that need to be measured, so that multiple concepts via the models can be tested and can improve our understanding of how the system works.

For example, policy changes in the 1990s in the MRB led to increased environmental flow. To interpret this in terms of change in water management norms of the MRB, models need to link beliefs and norms to water use behavior within the basin. This needs information on a range of relevant values such as altruistic values (i.e. healthy MRB for present and future generations, enough money for the next generation) and egoistic values (i.e. making money), along with information on beliefs, norms, and behaviors, such as how water is being used.

2.6.3.1 Measurement of changing norms and values

Direct measurement of social value is often very difficult, resulting in the use of indirect methods (or proxies). Studies have attempted to understand social values on pro-environmentalism (Bengston, 1994; Ives and Kendal, 2013) and could be differentiated based on the method of measurement. Assigned values can be expressed in either monetary or non-monetary terms, and are relevant to economic and psychological approaches. In a social science context, assigned values have been quantitatively measured using a variety of techniques, including survey and interview approaches with the help of psychometric scales used in psychology (Bengston, 1994), social experiments in behavioral economics (Janssen et al., 2014; Yu et al., 2016) and content analysis (Seymour et al., 2010; Bark et al., 2016a; Xu and Bengston, 1997; Wei et al., 2017). Economic valuation offers another set of useful approaches to inform natural resource management (Farber et al., 2002; Pande et al., 2011; Loomis et al., 2000; Norton and Noonan, 2007; Wilson et al., 1999; Bark et al., 2016b). Non-market valuation (Smith, 1993), contingent valuation (Bateman et al., 2006) and other related techniques have been extensively used over the decades and enabled the exploration of how people 'trade-off' their environmental values in decision-making (Freeman et al., 2014). This enables: (i) values to be measured for large and diverse groups of people; (ii) changes in values to be tracked across groups of people or across time; and (iii) models to be developed to predict values based on other factors (e.g., demographics, cultural background).

It is less challenging to observe contemporary water-related behavior. However, as the time scale of analysis expands, the task of measuring behavior becomes equally challenging. Paleoclimate proxies such as $\delta^{18}O$ or tree rings have been extensively used to interpret water availability as well as social organization in the past (Pande and Ertsen, 2014; Staubwasser et al., 2003). These observations can be supplemented by other forms of indirect measurement of water-related behavior such as newspaper content analysis, activist organizations' membership records, and can strengthen proxy observations of pro-environmental behavior in the near past.

2.6.3.2 Utilization of new types of data

A challenge related to model transferability is generic data needs. If community sensitivity functions as outlined in van Emmerik et al. (2014), Elshafei et al. (2015) and Roobavannan et al. (2017) are able to assess some trade-off between enviro-centric and anthropo-centric values types, global socio-economic data sets such as the World Value Surveys (WVS, 2017) and UN demographic datasets (UN, 2017) might offer the possibility of quantifying values, so that models can be transferred to unmonitored locations. Whether such data sources can be used to quantify such values remains a very important open question.

In the past, the use of soft data in hydrological modelling has been demonstrated to provide additional insights into the functioning of ungauged basins, and has in some cases been used to successfully assess the realism of a model (see e.g., van Emmerik et al., 2015). Similarly, socio-hydrological systems face similar problems of extrapolation to other places, as numerical data series do not always exist to calibrate or validate socio-hydrological models. Wei et al.'s (2017) use of newspaper content data to compute a numerical expression of environmental sustainability and economic development demonstrates the benefits of further exploration of this type of new data sources since it can allow the calibration of socio-hydrological models. Future efforts should therefore not only be limited to developing new socio-hydrological modeling frameworks, but also entail finding new ways to access information and translate it into numerical expressions. For example, this could include indices such as FSR which can be used for model validation, and model realism assessment.

A new era of data-driven science (Peters-Lidard et al., 2017) is dawning, with increased computational power, new proxies and alternative data sources. Smart distillation of information from alternative sources (e.g., web databases, social data, other types of Big Data) may provide the valuable auxiliary data required to take the next step in socio-hydrological model development and provide an innovative way to find and quantify the social proxies which are currently difficult to justify. This will need to be combined with online data monitoring such as smart sensing and citizen science monitoring as well as field campaigns to validate model results as well as to obtain socio-hydrological data relating to, for instance, environmental sentiment, local societal values, and fertility conditions. In the future, socio-hydrologists could exploit or mine data/information from such varied sources, leading to the inclusion of Big Data science in socio-hydrology. This new paradigm represents a clear set of opportunities for data-mining and data-driven modelling methods in socio-hydrology. These apply machine learning and 'computationally intelligent' algorithms to elicit, characterize, quantify and model the myriad, implicit structures and relationships embedded within complex, multivariate datasets. In so doing, they offer a pathway for formulating new understandings of the saliency and power of socio-hydrological variables, and the inter-relationships and behaviors that exist between them (Mount et al., 2016).

2.7 Methodology for scientific investigation in socio-hydrology

Socio-hydrology having evolved from the experience of the past borrows some of its basic theories from the different disciplines such as socio-ecology. The way to move forward in new discipline remains open and there has been extensive discussion on this matter (Pande and Sivapalan, 2016; Sivapalan and Blöschl, 2015). The method of scientific inquiry attempts to understand and interpret emergent phenomena by means of a cyclic process of hypothesis generation, testing of the hypothesis through data analysis, and hypothesis update (Pande and Sivapalan, 2016). The method of scientific inquiry to explore feedbacks in coupled human–water systems therefore requires: firstly, the development of knowledge of possible processes that contribute to the generation of observed phenomena; and secondly, historical or contemporary data that allows comparison and contrasting of the performance of phenomena that can be simulated through model predictions (Pande and Sivapalan, 2016). In socio-hydrology, we begin by exploring socio-hydrological phenomena by identifying variables that could possibly affect them, and which could be used to explore emergent patterns in available data such as population, crop production, salinity, water allocation, capital. Data analysis is then performed in an attempt to understand casual interaction. Based on this understanding, hypotheses are formulated on how selected variables behave over time and how these variables interact with each other (Pande and Sivapalan, 2016). A socio-hydrology model can then be built to test the hypothesis and to generate diverse emergent phenomena under different initial and boundary conditions.

Sivapalan and Blöschl (2015) proposed a 7-step model building guide. It starts with understanding phenomena and establishing the context of the problem, both in space and in terms of governing variables. Compared to other conventional modelling studies, socio-hydrological phenomena tend to be more complex due to time scale interactions that may include tipping points, regime shifts, and system lock-ins. In the second step, a perceptual model that describes the system would be developed. It is often useful to start the perceptual model by drawing causal loops that represent the feedbacks of the system. The causal loops could be drawn based on a narrative of the problem or based on preliminary data analyses. Since socio-hydrology is an interdisciplinary subject, experts from different fields are expected to become involved in fostering the building of the model. In the third step, state variables are selected and these are the backbone of the model, so they should be selected with care. Clearly, this choice is an art, although one strategy that can be adopted is to start simple and add more variables only as required to reproduce the phenomenon of interest. All the variables included in the model should be measurable, either directly or through the use of appropriate surrogate or proxy information in order to calibrate and validate. In the fourth step, casual factors that affect the state variables are selected. Causal factors affecting each state variable can be external factors, other state variables or the state variable itself. Due to the complexity of socio-hydrological models, it is suggested to first decide what causal factors to include in each equation (Step 4) before specifying the exact functional relationships (Step 5). Causal loop diagrams (Step 2) could be used as guides on the choice of causal factors.

In the fifth step, functional relationships are described that explain the feedbacks between the state variables as well as the effects of the external forcings. The functional relationships can be conceptualized using intuition (as is often the case in conceptual models), through recourse to data analysis (if the appropriate data exist), taken from the literature on related studies, or can be based on consensus principles, for example logistic growth (Elshafei et al., 2014). In many other branches of environmental science, dimensional analysis may assist in keeping these functional forms compact and parsimonious. Non-dimensionalizing the relationships may reduce the number of parameters (Viglione et al., 2014).

In the sixth step parameters are estimated. Because of the many coupled processes involved, it is suggested to estimate the parameters by disassembling the model into its parts and subsequently reassembling them. In some case parameters are needed to be calibrated with observed data. Finally, the model is validated. Validation could be done by splitting the data and this can create different time periods, different places, or different response variables. For the validation of the entire reassembled model, there are two possibilities. The first is when a given socio-hydrological phenomenon of interest is repeatable in space or time. It could occur in different periods at the same place or it could occur at different places in the same period. The second possibility is when the socio-hydrological phenomenon of interest is not repeatable, i.e. it has unique features that are very unlikely to be repeated. In such a situation, it will not be possible to validate the model in the normal sense. This means that the model will likely have little predictive power beyond the case study of interest. However, the model can still be very useful to explain the local socio-hydrological phenomenon and to explore the system dynamics, including time scale interactions. In all instances, it is important to explore the solution space to understand the interaction of slow and fast variables, in particular the role of changing values in time and space, and the associated model uncertainties (Sivapalan and Blöschl, 2015).

Table 2.2: Seven steps of framing and modeling hydrological versus coupled dynamic environmental versus socio-hydrological processes (adapted from Sivapalan and Blöschl, 2015)

	Hydrological Models (Simple Systems)	Coupled Dynamic Environmental Models (Complex Systems) Framing in Addition to Hydrological Models	Socio-hydrological Models (Complex Systems With Humans) Framing in Addition to Coupled Environmental Models
Step 1: Phenomenon, domain, scale	• Specify phenomenon (e.g., rainfall-runoff transformation, scaling of floods) • Specify control volume (e.g., catchment) • Specify study period (e.g., events) • Specify purpose of modeling (e.g., flood estimation)	• Choose control volume by considering what process to internalize and what process to leave out as external forcing (external forcing should not be affected by system behavior) • Study period typically longer (e.g., centuries) • Phenomena typically more complex (e.g., vegetation patterns)	• Phenomena are typically even more complex (e.g., macroscale phenomena such as levee effect, irrigation paradox). These phenomena are often defined through narratives
Step 2: Perceptual model	• Bottom-up (mechanistic) from laboratory experiments (e.g., Darcy) or top-down from response data (e.g., UH) • Based on hydrological data and prior knowledge (e.g., existing modelling concepts)	• Usually bottom-up due to complexity of processes (top-down approach of inferences from response data tends to break down) • Guided by observed patterns of environmental data and prior knowledge • Causal loop diagram to conceptualize process interactions, including interactions between time scales	• Causal loop diagram assisted by narratives of phenomena to visualize alternative hypotheses • Decision on whether phenomena are represented explicitly or to emerge from system dynamics • Allow for change in values if appropriate • Possibly allow for role of "social preferential flow" and randomness in human decisions
Step 3: Choice of state variables	• Conventional choices (e.g., water stores, groundwater, unsaturated	• Small number of variables usually of advantage, so variables of minor influence may be omitted and	• Choice of variables is more difficult due to four subsystems: natural (e.g., pollution),

	zone, lakes, snow)	variables with similar effects may be combined • Variables should be measurable • Classify into fast and slow variables	infrastructure/technology (e.g., reservoirs), socio-economics (e.g., wealth, population, values), institutions/ governance (e.g., land use planning) • Values are a key state variable for a long-term treatment strategy • Mediating variables that drive others are useful, if they have independent dynamics
Step 4: Causal factors that affect state variables	• Causal factors can be state variables or external forcing, e.g., soil moisture change=f(water potential; precipitation, radiation) • Preliminary data analysis and learning from other places may also assist	• Larger choice of factors, e.g., landform change=f(soil moisture, runoff, vegetation; tectonic uplift, precipitation) • Causal loop diagrams and known balance equations (e.g., sediment balance) may assist in choice of factors (and therefore coupling)	• Still larger choice of factors e.g., change in infrastructure=f(flood damage, wealth; global economy) • Causal loop diagrams and known balance equations (e.g., financial budget) may assist in choice of factors (and therefore coupling)
Step 5: Functional relationships for Step 4	• Based on universal laboratory (e.g., Darcy) or field data-based (e.g., Chezy) relationships • Possibly requires upscaling • Balance equations imply additive relationships • Dimensionality arguments (e.g., resistance is proportional to velocity in laminar flow but velocity squared in turbulent flow)	• Wider range of possible equations (e.g., Exner equation) • Use of local data may require upscaling • Dimensional analysis gives guidance on combining parameters (Buckingham Pi theorem) • Scaling analysis to help identify fast and slow state variables (if equations are known), possibly revise state variables (Step 3)	• Additional guidance by socio-economic data (e.g., surveys, censoring) and narratives • Translate narratives into cause-effect, i.e. functional relationship • Use of local data (particularly in comprehensive models) • Additional guidance by the implications for system dynamics (e.g., concave versus convex utility functions; bi stability of system)

Step 6: Parameter estimation	• Usually parameters inferred from response data (e.g., parameter calibration on hydrographs) • Uncertainty analysis of parameters, possible parameter ranges, and their impact on model predictions	• Measurement of parameters more common as calibration often difficult • Laboratory and field experiments • Learning from other environments • Proxy data (e.g., soil depth inferred from vegetation height)	• Disassemble model into components and estimate parameters separately for different streams of data (e.g., surveys, censoring, financial data, demographic) in addition to environmental data • Possibly calibration to multiple, observed time series • Reassemble model and estimate feedback parameters against emergent phenomena • Evaluate effect of model parameters on path dependence and lock-ins of model dynamics
Step 7: Model validation and uncertainty	• Testing model against independent records of response data (e.g., hydrograph from a period not used for parameter estimation) • Testing model against other state variables (e.g., soil moisture, snow, groundwater) • Identify sources of possible mismatch If model validation not satisfactory (relative to the goals), go back to Step 1 and reframe problem	• Test model against spatial patterns of state variables (e.g., vegetation patterns, meander patterns) • Chrono sequences to assist in testing long (co-evolutionary) time series • Explore solution space including the interaction of slow and fast variables, critical transitions, and equilibria to assist in process understanding, possible model revision, and extrapolation to other places	• Test component models against different streams of data • If phenomena are repeatable in space or time, test model against similar situations at different places or in different time periods • If phenomena are not repeatable, no full validation is possible (because information on phenomena has been used for parameter estimation) • Sources of uncertainty may include non-optimal behavior of humans

Once the coupled system is modelled then the behavior of the coupled system is studied. If these generated patterns of variables are corroborated by observed historical data then the proposed hypotheses, until they are falsified, are possible explanations of the observed phenomenon (Pande and Sivapalan, 2016). If the model variables show a trend different from what has been observed, then the hypotheses about how the variables change in time or how they interact with each other need to be updated or new hypotheses are formulated. Simulations are repeated until a satisfactory comparison of the observed phenomenon is achieved.

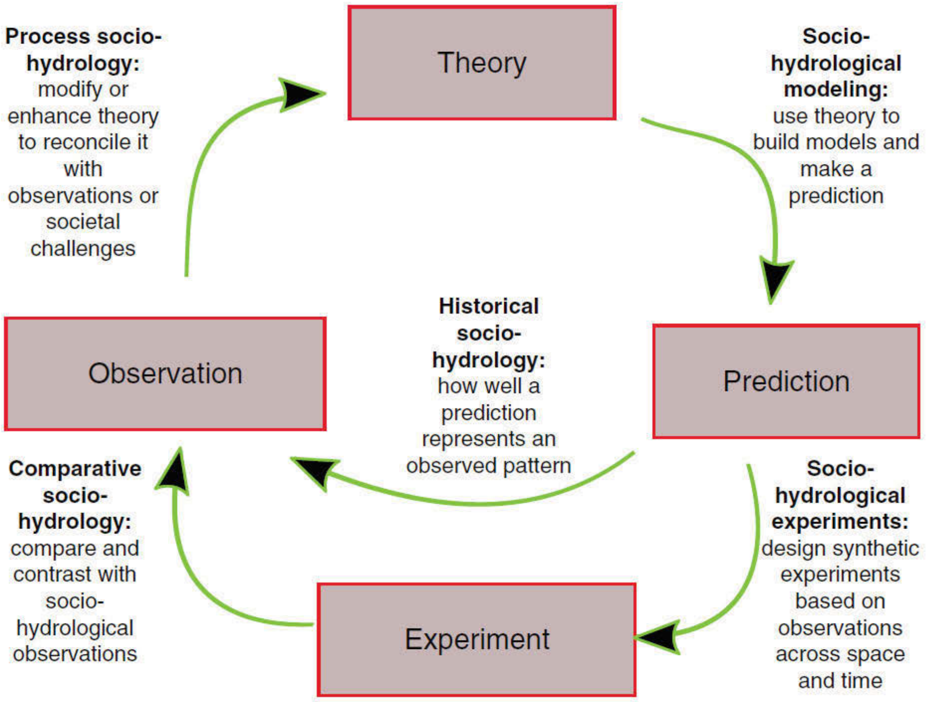


Figure 2.13: The three sub-disciplines of socio-hydrology and the method of scientific inquiry. This demonstrates that the standard method of scientific inquiry can be implemented to the diversity of coupled human–water systems using the three different but complementary pathways of socio-hydrology.

The feedbacks interaction of human-water systems could be identified by studying where our understanding of the system is lacking. This can be done through a iterative process of hypothesis building, data evidence collection, and updating the hypothesis. Figure 2.13 presents a proposed generic framework developed by Pande and Sivapalan (2016) for the implementation of scientific inquiry into the diversity of coupled human-water systems. In order to understand the socio-hydrological phenomena and search for generalized theories, the pursuit of scientific inquiry can follow three different but complementary pathways (Blair and Buytaert, 2016; Pande and Sivapalan, 2016;

Sivapalan, 2015): (i) Historical socio-hydrology; (ii) Comparative socio-hydrology; and (iii) Process socio-hydrology.

Historical socio-hydrology aims to understand a coupled system from its immediate or distant past and understanding emergent patterns. It documents an emergent phenomenon in a single location, hypothesizes mechanisms through which it may have arisen, and confronts these types of hypotheses with patterns in the historical record.

Process socio-hydrology aims to understand and hypothesize the nature of observed social and hydrological processes that contribute to the dynamics of the coupled human-water system. It helps us to build hypotheses about how different parts of the coupled human-water system may be dynamically interconnected.

Comparative socio-hydrology aims to compare and contrast different coupled human-water systems across socio-economic, climatic and other gradients. It allows us to study the same phenomenon or phenomena comparatively across many locations (i.e. river basins), formulate broader hypotheses and build up generalized theories.

2.7.1 Historical Socio-Hydrology

A better understanding of major trends and dynamics of society and the environment across all scales is vital to manage water resources as these trends and societal dynamics influence and shape future development pathways. A promising approach seeks to obtain a deep understanding of contemporary system functioning. Particularly important is observing trends through time and understanding the co-evolving relationships between different drivers and response variables at different scales (Bai et al., 2016).

Kandasamy et al. (2014) is the first study to explore the place-based coupled dynamics concerning a human-water system in the Murrumbidgee river basin where agriculture has long dominated. Their analysis used long-term historical social and hydrological data and explained the “pendulum swing” in the water allocation between agriculture and ecosystems and the subsequent outcome in socio-economic terms. They proposed broad patterns of socio-hydrological dynamics in terms of key variables. Technological innovation, including building up of reservoir capacity, facilitated the economic growth in the basin. One of the key observations made was that society changed its values and preferences of how water is used.

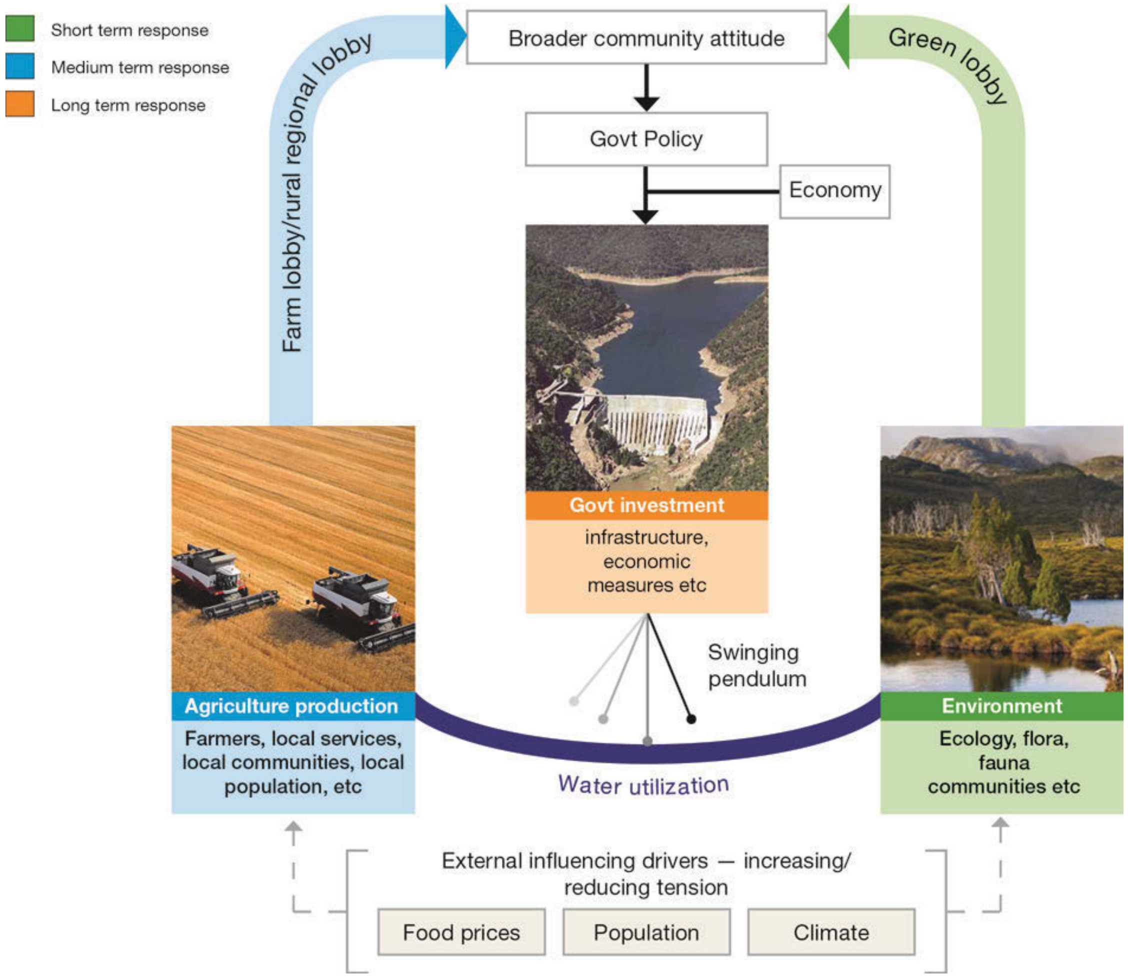


Figure 2.14: Proposed framework for socio-hydrological modelling: interactions and feedbacks between human and environmental systems leading to new (whole system) dynamics (adapted from Kandasamy et al., 2014).

Similarly Liu et al. (2014) provided a long-term historical perspective on the socio-hydrological dynamics in the ancient Tarim River basin, China. They explained co-evolutionary dynamics of water and humans from the opening of the Silk Road to the present day. The Taiji-Tire model, a refinement of a special concept in Chinese philosophy, was used to explain the co-evolution of system interactions among its components. The human-water Taiji represents the core of the human-water relationship for a specific socio-hydrological system. The human-water tire contains the external natural and social conditions. Two boundaries are illustrated and represent two kinds of relations: (i) the direct human–water interaction as water consumption in the inner Taiji, which is the internal human–water relationship; and (ii) the indirect impact of external factors that affect the water quantity and quality as well as the social productive force.

In the same vein, Han et al. (2016) provided a historical analysis of the coupled human-groundwater system centered on the Cangzhou region in China from a socio-hydrological perspective. The history of the co-evolution of the system was divided into five eras (i.e. natural, exploitation, degradation and restoration, drought triggered deterioration, and returning to balance). They also used the Taiji-Tire model to interpret the co-evolution.

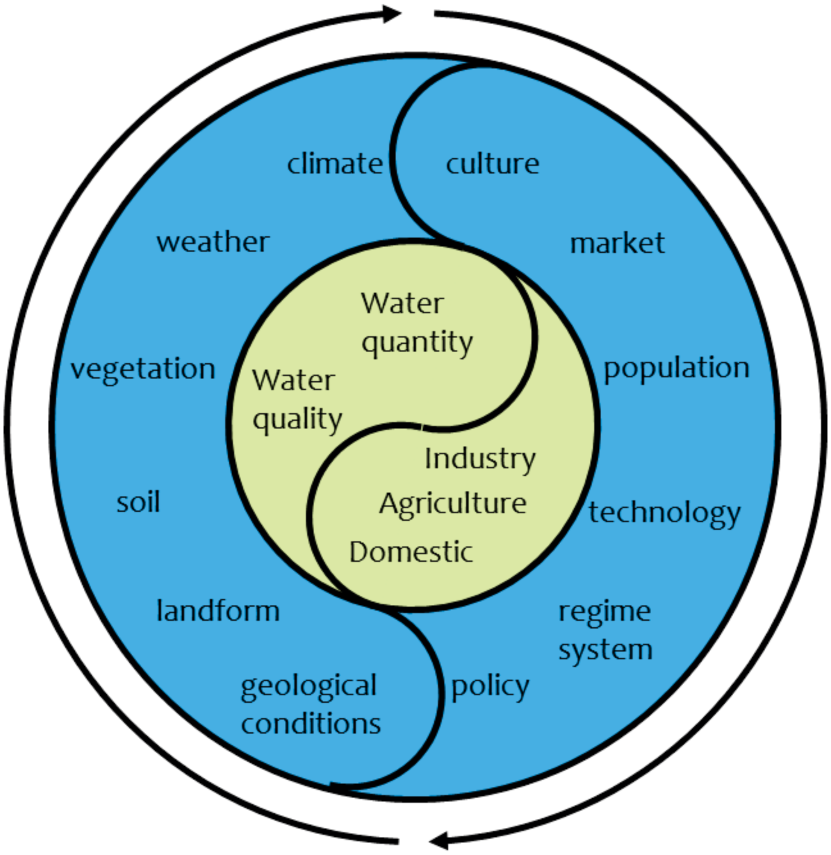


Figure 2.15: The Taiji–Tire model applied for historical socio-hydrological analysis in TRB (adapted from Liu et al. 2014)

In a comparative historical study, Pande and Ertsen (2014) argued that changing patterns of water resource availability may have been behind the rise and fall of the Indus valley (Harappan, South Asia) and Hohokam (North America) civilizations. Lack of water resource availability may even have led to basin-scale solidarity. For example, the Harappan civilization rose to maturity over a course of 500 years when both the summer monsoon and winter rainfall were weakening, implying increased coordination at basin level. Ertsen et al. (2014) further argued that since socio-hydrology deals with human decision-making and water management, the actions of humans at fine time scales such as managing irrigation systems at daily scales may have played a crucial role in guiding the coupled human-water system trajectories of ancient societies. Further lumped treatment of human agencies together in decision-making, assuming that collective social structures of states, companies, and also social class or gender is questioned. They also indicated the merit of agent-based modelling in this approach.

Kuil et al. (2016) suggested that a modest reduction in rainfall may have led to an 80% collapse in population in the ancient Mayan civilization in South America. They also found that overcoming hydroclimatic variability through building of reservoirs might have helped the Mayan civilization to sustain longer economic growth and higher population growth. Fernald et al. (2014) provided an interesting modelling framework to understand the socio-hydrological resilience of traditional irrigation communities in New Mexico by studying key hydrological, ecological, economic, and socio-cultural dimensions and their interactions. Zlinszky and Timár (2013) proposed that historical maps can be used to document past trajectories of coupled human–water systems. Historic maps and data sets could be a reliable source of information serving to help understand the interaction of systems, although the past may not always be good guide for future interpolation. Dermody et al. (2014) explored the resilience of the Roman Empire using a virtual water network. They found that irrigation and virtual water trade increased the empire's resilience to inter-annual climate variability. However, urbanization arising from virtual water trade likely pushed the Empire closer to the edge of its water resources.

These studies explored historic patterns to develop theories and models of coupled human–water systems to help us understand documented cases of socio-hydrological resilience. These studies highlight the challenges of identifying locations with appropriate datasets at decade to century time scales to discover phenomena and to generate and test plausible hypotheses about the mechanisms behind these phenomena.

2.7.2 Comparative Socio-Hydrology

Srinivasan et al. (2012) analyzed the causes of freshwater scarcity in 22 basins around the world and grouped them into six "syndromes": 1) groundwater depletion; 2) ecological destruction; 3) drought-driven conflicts; 4) unmet subsistence needs; 5) resource capture by elites; and 6) water being reallocated to nature. They also explored how improved water policies may be designed to reduce inequity, vulnerability, and unsustainability of freshwater use.

Scott et al. (2014) addressed the impacts of increased efficiency in water use and water savings on the resilience of socio-hydrological systems by studying three river basins. They showed that water ‘saved’ through irrigation technology improvements may lead to unintended consequences for water use at multiple scales and in multiple sectors.

Konar and Caylor (2013) conducted an empirical analysis of the relationships between virtual water trade, population, and development in Africa. They found that increases in virtual water imports do not lead to increases in population growth but nor do they diminish human welfare. They also emphasized the importance of infrastructure sharing across nations to increase the resilience

2.7.3 Process Socio-Hydrology

Recently, several studies have been carried out to understand the dynamics of coupled human-water dynamics from different perspectives. van Emmerik et al. (2014) developed a generic model to explain the dynamics of the Murrumbidgee River basin; in this endeavor they were inspired by Kandasamy et al. (2014). The model includes several constitutive relationships that make it determinate. van Emmerik et al. (2014) was able to model the four eras described by Kandasamy et al. (2014), from an exclusive focus on agriculture to environmental restoration. A crucial aspect has been the inclusion of a sub-model to quantify environmental health. Their model was able to mimic spatial population migration, the first spatially explicit socio-hydrological and growth model. It included technological adoption and aggregated production at basin scale.

Similarly, Elshafei et al. (2014) hypothesized that this pendulum swing was in fact indicative of a gradual change in the community’s sensitivity to water stress over time and proposed a more generic model framework based on resilience theory. The community sensitivity model concept developed by Elshafei et al. (2014) was applied to Lake Toolbin (Elshafei et al., 2015). The model was able to successfully identify the positive and negative feedbacks, the presence of threshold behavior, time scale differences between fast and slow moving variables, differences in time lags resulting from disparate resistance levels of the natural system, and the degree of adaptive learning inherent in the human system.

Liu et al. (2015) developed a conceptual dynamical model by coupling the water balance equation for hydrological processes and logistic growth equations concerning the evolution of vegetation, irrigation, and population. The model was applied to Tarim River Basin in China. Four state variables, i.e. water storage, vegetation cover, irrigated crop area ratio, and human population were adopted to represent the states of hydrological, ecological, economic, and social sub-systems, respectively. Each growth equation contains several colonization terms and mortality terms, which are jointly determined by the state variables of different sub-systems through the corresponding constitutive relationships.

Srinivasan et al. (2010) developed a unified hydrological-economic model to simulate the dynamic feedback interactions responsible for urban water supply in Chennai, India, where consumers depend on many sources of water and invest in coping mechanisms. It helped identify a management option to reduce the vulnerability of the water supply system. Srinivasan (2015) developed the model with the feedbacks between the human, engineered and hydrological water supply system in an effort to evaluate the implications for water security when different technology and management policies were in place.

Di Baldassarre et al. (2013a) presented a conceptual approach to explore the complex dynamics of floodplains as fully coupled human-water systems and discussed the coupled nature of humans and floods in flood prone societies. Di Baldassarre et al. (2013b) conceptualized the human flood interaction incorporating economic, political, technological, and social processes and reproduced reciprocal effects between floods and people as well as the emergence of typical patterns. Di Baldassarre et al. (2017) discussed the importance of the new approach to explicitly account for human interactions with both drought and flood events, and presented a stylized model simulating the reciprocal effects between hydrological extremes and changing reservoir operation rules.

Zhang et al. (2014) studied the impact of water saving irrigation on regional groundwater dynamics in the Tarim River Basin and the secondary salinization introduced by such anthropogenic activity. Grames et al. (2015) developed an optimization model where the inter-temporal decision of an economic agent interacts with the hydrological system. They also demonstrated how optimal control theory can be applied to socio-hydrology. Chen et al. (2016) used the community sensitivity concept to understand the changing values and preferences in the flood prone communities based in the Kissimmee River Basin, Florida, that resulted in restoring the river after previous channelization. This in turn had been the result of friction between upstream and downstream users. O’Connell and O’Donnell (2014) used agent-based modelling to investigate the adaptation strategies to reduce flood hazards in a coupled socio-hydrology system. Ribeiro Neto et al. (2014) explored the future vulnerability of infrastructure in the urbanizing Capibaribe River basin, Brazil, under the pressures of climate change using climate model outcomes, a hydrological model and net flow model.

Gober and Wheater (2014) used socio-hydrology to explore the water security challenges in the Saskatchewan River Basin, Canada, and indicated the symptoms of a coupled water-human system that was reaching critical thresholds and tipping points. Konar et al. (2013) explored the dynamics of virtual water trade under climate change conditions. They found the total volume of virtual water trade is likely to decline due to climate change, where trade in crops will decline, leading to higher crop prices in a scenario of decreased virtual water content yet high agricultural productivity. Pande et al. (2013) studied the effect of water scarcity on technology, agricultural production, and population growth in one basin using the overlapping-generation model.

2.8 Socio-hydrological modeling

Since human-water systems co-evolve over time, mathematical models are useful to generate and test a hypothesis in a quantitative way, and investigate the system interactions causing these phenomena (Sivapalan and Blöschl 2015; Troy et al., 2015). It also can be used as a tool to develop and advance socio-hydrological theory and in particular the dynamics and feedbacks concerning coupled water-human systems (Troy et al., 2015). The dynamics are parsimoniously described in a model by a set of coupled non-linear differential equations to characterize how physical, economic, political, technological and social processes co-evolve over time (Sivapalan, 2015). Extensive discussion and a review of the modelling approach in socio-hydrology are provided in Blair and Buytaert (2016).

A significant challenge is to incorporate the complexity of human behavior into mathematical models (Troy et al., 2015). If modelers were able to predict human behavior under various socio-economic and hydrologic scenarios, and how that behavior influences the performance of our water resource systems, it would be better able to manage and perhaps derive additional benefits from them. It is such stakeholders whose behavior and decisions will impact on how water resource systems are designed and operated and how well these systems meet various economic and social objectives (Loucks, 2015). Many elements of water availability influence different levels of societal development, and modeling presents one way to understand how to overcome the adverse consequences from poor water management and avoid such situations by predicting it beforehand. Specially, incorporating behavioral responses to water scarcity and hydrological extremes in hydrological models constitutes a rich arena for future innovations (Troy et al., 2015).

In summary, socio-hydrological models could be used to: 1) understand the system interactions; 2) forecasting and predicting future scenarios; and 3) evaluate policies and decision-making. Complexity of model and structure could change according to the purposes of the model being studied. It could be a comprehensive system model or stylized model. The more realistic, detailed and place-based models are better suited to analyzing and quantifying the socio-hydrological interactions and feedbacks in real time in specific places (Yaeger et al., 2014). Place-based conceptual socio-hydrological models can potentially be employed for decades to centuries scale predictions as well. They would involve substantial data collection and experimentation (e.g., detailed process modeling) to parameterize the social and hydrological processes and the socio-hydrological feedbacks. However, this presents major difficulties for several reasons (Thompson et al., 2013): (i) uncertainty of model structure and model parameterization which arises due incomplete understanding of system and equifinality; (ii) inability to capture the highly adaptive and the (sometimes or apparent) irrational behavior of humans; and (iii) inherent lack of predictability and uncertainty due to the highly non-linear nature of the coupled socio hydrological systems, for example strong dependence on initial conditions. Therefore, application of these models, in order to be meaningful, needs explicit treatment of uncertainty through the use of stochastic methods (Sivapalan, 2015). On the other hand, stylized models simplify the systems considerably but have less power to characterize what happens in a specific place. Nonetheless they can be useful to serve as tools for comparative studies and synthesizing data to generate generic models applicable to a wide range of places. Discovering common organizing principles is also possible (Sivapalan, 2015).

There are a range of modeling approaches that can help move in this direction including agent-based models (ABM), system dynamics (SD), pattern-oriented modelling (POM), Bayesian networks (BN) coupled-component modelling (CCM), scenario-based modelling, and heuristic/knowledge-based modelling (Blair and Buytaert, 2016). Agent-based models are often used by social scientists to conceptualize human-water interactions on the basis of rules generated through field surveys aimed at characterizing the behavior of human (or social) agents. Agents models are considered to be a better representation of heterogeneity of society (Ertsen et al., 2014). Such agent-based models, upon aggregation can serve to help us understand emergent behavior at the whole-system level (Sivapalan, 2015).

The dynamical systems concept is mostly used to represent the co-evolutionary processes mathematically. The concept assumes that the change in the state of a system over time is a function of the state at the same time, and future states follow deterministically from the current state (Sivapalan and Blöschl, 2015). The stability of the dynamic system can be examined easily in this system. Since the equations are linear the eigenvalues of the coefficient matrix directly give the stability properties. In situations where parameters of a model change with time, eigenvalues also change and it could be indicative of an early warning of collapse (Sivapalan and Blöschl, 2015). The ability to detect early-warning signs as suggested above would therefore make a fundamental difference to water resource management as it is usually practiced now, where problems are “fixed” only once they occur (Sivapalan and Blöschl, 2015).

The models which are being developed are abstract and imperfect representations of an actual system as are the individual equations comprising the model. As such, a given equation or model will have an imperfect fit. However, by using different representations of an equation (or model), the goodness-of-fit can be evaluated, such that the equation formed with the best fit would be chosen as the best hypothesis for the relationship between variables (Troy et al., 2015). As the complexity of coupled systems increases, modelling becomes increasingly difficult. This provides many opportunities for new model types that conceptualize evolutionary processes including humans (Blöschl, 2014).

In socio-hydrology, researchers are currently learning how to conceptualize and model the coupled human-water system. Socio-hydrology model development is also seen as a process of not only inventing the variables and identifying the parameters and their relationships that would describe the possible ranges of behavior, but also developing the model components in such a way that does not just produce the results we should expect (Loucks, 2015). Several conceptual socio-hydrology models, consisting of coupled, non-linear differential equations have been published in the past (Di Baldassarre et al., 2013a, 2013b; Elshafei et al., 2015; Kuil et al., 2016; Srinivasan, 2015; van Emmerik et al., 2014). The model predictability is questioned because the models have so many calibrated parameters that they can capture any dynamics or if indeed it is because the mathematical model accurately captures the relationships that exist (Troy et al., 2015). It is suggested that models be treated as a hypothesis test tool in order to overcome this problem. It is also suggested multiple hypotheses (or multiple model forms) be used to test and accept the dynamics, relationships, and perhaps threshold behaviors of the coupled socio-hydrological system (Troy et al., 2015).

2.9 Difficulties in socio-hydrology studies

The great challenge of socio-hydrology is finding universal laws of system interaction. Unlike positivist natural sciences which rely on 'laws', socio-hydrology encourages diverse perspectives (a post-positivist approach) on a phenomenon of interest. This is because social sciences that are bereft of any one way of interpreting a phenomenon or phenomena, play an equally important role in socio-hydrology. Socio-hydrology deals with a complex system involving feedback loops between social and water systems so it is in essence an interdisciplinary field (Levy et al., 2016). Social variables such as "environmental awareness" and "community sensitivity" arise from the social realm and definitions and methods of quantification fall within the realm of the social sciences. The social science method typically involves community surveys, followed by statistical analysis to test hypotheses, and culminates in a narrative or a description of the state of play in a given place. Controls or cause-effect relationships, if they exist, appear implicitly in the narrative. It is not common to seek general descriptions, or seek ways to extrapolate to other places. On the other hand, the natural science method typically involves development of a concept or a hypothesis (e.g., water balance in hydrology), choosing a set of observable variables, followed by building a numerical model, and testing its prediction against data to test the hypothesis. Therefore discovering cause-effect relationships of the whole system and achieving a generalization, including the ability to extrapolate to other places becomes quiet challenging (Sivapalan, 2015).

Multiple interpretations of a particular phenomenon, testable within the method of scientific inquiry, could be proposed and tested on real world data to ultimately develop a generalized understanding of a phenomenon under investigation that is applicable across space and time. For example, the levee effect has been interpreted both as an emergent property of non-linear but prescribed dynamics of coupled human-water system as well as a consequence of system optimization.

As well, several variables cannot easily be expressed in quantitative terms, and even if they can be defined as such, there are real challenges to measuring these in the field (Levy et al., 2016). The conceptualization, quantification and measurement of all variables, especially social variables, suffer from scale issues, a result of discrepancies between the scales at which they may be measured and the scales at which they are modeled. These limitations impact adversely on our ability to develop, calibrate and validate (Sivapalan, 2015).

CHAPTER 3

Allocating environmental water and impact on basin unemployment: role of a diversified economy

This chapter includes the major part of

- Roobavannan, M., Kandasamy, J., Pande, S., Vigneswaran, S., Sivapalan, M. 2017. Allocating environmental water and impact on basin unemployment: Role of a diversified economy. Ecological Economics, 136, 178-188, http://dx.doi.org/10.10 16/j.ecolecon.2017.02.006.

3. Allocating environmental water and impact on basin unemployment: role of a diversified economy

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CHAPTER 4

Role of sectoral transformation in the evolution of water management norms in agricultural catchments: A socio-hydrologic modeling analysis

This chapter includes the significant part of

- Roobavannan, M., Kandasamy, J., Pande, S., Vigneswaran, S., Sivapalan, M., 2017b. Role of Sectoral Transformation in the Evolution of Water Management Norms in Agricultural Catchments: A Socio-hydrologic Modeling Analysis. Water Resour. Res. 1–22. doi:10.1002/2017WR020671

4. Role of Sectoral Transformation in the Evolution of Water Management Norms in Agricultural Catchments: A Socio-hydrologic Modeling Analysis

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CHAPTER 5

UNIVERSITY OF TECHNOLOGY SYDNEY

Sustainability of basin development under uncertain future climate and economic conditions: socio-hydrologic analysis

5. Sustainability of basin development under uncertain future climate and economic conditions: socio-hydrological analysis

5.1 Introduction

The increasing demand for land and water resources to support increasing populations and their sustainable management is receiving more attention from water supply managers and other stakeholders. Societies are evolving and adapting to increased pressure on natural resources. Along the Murrumbidgee River, goals have changed at various stages during the basin's development based on changing societal values and preferences, both being influenced by internal and external factors (Kandasamy et al., 2014). Danger signs are becoming evident with rapid population growth and economic development in recent times but the limited water resources are reaching their sustainable usage limit, making further development tenuous. Decision-makers are more concerned than ever over food and water security and sustainable resource development (Vogel et al., 2015).

Harnessing water for development influences the social and economic aspects and these co-evolve as a coupled human-water system (King et al., 2012; Sivapalan et al., 2012; Troy et al., 2015). Water managers have an obligation to manage water sustainably both in terms of how infrastructure is used (hard measures) and how institutions implement policies (soft measures) (Vogel et al., 2015). Infrastructure (e.g. building a dam) does not help when resource utilization reaches full capacity and then starts to decline.

Previously, the manner in which water could be managed was analyzed using frameworks in which society was treated as exogenous to the system without the inclusion of the co-evolutionary dynamics. The field of socio-hydrology treats society as endogenous to the coupled human-water system. Here society's changing values and preferences are made endogenous to the system (Gober and Wheater, 2015; Sivapalan et al., 2012). Socio-economic and environment stresses influence how water is used and managed by community, and in doing so has produced new dynamics and paradoxical observations (Sivapalan et al., 2014). In order to properly manage water resources, changes in how society 's value and preference and their consequences have to be more clearly understood.

In addition, competition among users (environment, agriculture, energy and domestic) for water is increasing. Water and humans interact with each other at different speeds (fast-slow process). The slow time-scale of ecological processes makes it difficult to foresee and to address problems especially within the perspective of the fast time-scale of human activities and decision-making (Sivapalan, 2015; Sivapalan and Blöschl, 2015). In Australia, the Murray-Darling Basin Authority (MDBA) has become focused on efficient management of water and natural resources in the basin. It has identified several emerging issues in the basin's management: 1) changes in land and water use; 2) changes in economic conditions globally and locally; 3) changes in community values and preferences; 4) effect of major climatic events such as floods, droughts and increasing temperature, and changes in precipitation; 5) changes in science and technology; and 6) changes in institutional arrangements and relationships (Sinclair Knight Merz, 2013). An assessment of the impact of emerging issues informs the authority on how to act in a timely manner and in effective ways. Several studies have been conducted on each of these issues separately but without considering feedbacks within systems (Khan et al., 2006; Kirby et al., 2014; Wheeler et al., 2014, 2013). Isolated analyses such as these are not able to provide the information about some of the paradoxical observations that have occurred and will again in the future.

Recent attempts to endogenize societal dynamics and understand co-evolution have progressed in different ways. van Emmerik et al. (2014) used an environment awareness variable which depends simply on the amount of water in wetland storages in the catchment to capture society's changing values and preferences. Elshafei et al. (2014) proposed a more generic framework called "community sensitivity" to capture the changing values and preferences and applied the framework to two Australian catchments. Further, Roobavannan et al. (2017) used the community sensitivity framework and modified it to investigate the influence of economic diversification on historical changes with particular reference to values and preferences in the Murrumbidgee.

Sustainable development has emerged as a guiding principle for long-term global development and rests on three pillars: economic, environmental and social. Brundtland (1987) defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The United Nations Development Program (UNDP) uses the Human Development Index

(HDI) to measure development across the countries (UNDP, 2016). This has been criticized for not considering the environmental dimension. In turn, Togtokh (2011) proposed a human sustainable development index (HSDI) to include an environment dimension to compare nations' sustainable development. It also emphasized that recent past and current development practices are not sustainable. Policy-making consistent with sustainable development is important from the basin level to the global level. Managers are keen to "crystal ball" the future so that the conditions which allow sustainable development to occur under human-water system co-evolution can be better understood and regulated.

It is important to understand the changes in values and preferences and the reliability of system development to meet the water requirements for socio-economic activities. This is occurring in an era when current uncertain climate and economic conditions will determine the future. This study analyses the sustainability of societal development and the reliability of system performance that are threatened by changes in climate variability, economic uncertainties and changing values and preferences of society.

In this study, we wish to understand how external imposed conditions (exogenous drivers) can support basin population growth, the basin's economy and protect the basin's environment in a sustainable manner. The aim of this chapter is two-fold. The first is to project the basin's development into a myriad of future conditions while at the same time recognizing that society's values and preferences will change in an endogenous manner. Doing so will show how the basin might evolve and ideally so that prosperity and environment sustainability are both achievable. The second is to analyze the reliability of the coupled-system to meet the water use requirements necessary. This study attempts to use dynamical modeling to answer questions of how the basin's future is shaped by exogenous drivers in a non-stationary climate, changing growth of Australia's economy and different rates of economic diversification. Dynamical modeling is widely used to study the co-evolution of non-linear systems and system-of-systems. The mathematical properties of the dynamic system could serve to examine and understand the stability of systems. Stylized dynamical modeling seeks to understand the complexity of coupled human-water interaction and potential control of the system to avoid its collapse (Anderies, 1998; Sanderson, 1994). It is also used to identify early warning signs of system collapse.

In the next section, the dynamical system model is presented together with a description of the models used to prepare the exogenous drivers.

5.2 Methodology

5.2.1 Socio-hydrologic model

In order to understand the sustainability of the coupled socio-hydrological system under different conditions, this study extends what has been presented in Chapter 4 to include variable (stochastic) external forcing. The complete description and explanation of model section of water availability, agriculture, environment health, population dynamics, sectoral transformation and community sensitivity is available in Chapter 4 (see Figure 4.1) so it is not repeated here. The response function of community sensitivity was modified considering different management options as shown below. The allocation of water to the environment (Q_E) and agriculture (Q_A) is simulated by the response sub-model. It models the response function that determines the overall degree and direction of action by resolving the competition between community sensitivity (V) to the environment and the demand for agricultural expansion (D_e) (Elshafei et al., 2014). This response function (X) is conceptualized as,

$$\mathrm{X} = \begin{cases} -K_d De\,, & F(V) < {V_c}^* \\ F(V) - K_d De\,, & F(V) \geq {V_c}^* \end{cases} \qquad (5.1a)$$

where K_d is scaling factor, ${V_c}^*$ is the critical community sensitivity and $F(V)$ is normalized sensitivity estimated as,

$$F(V) = \min(1, \frac{\dot{V}}{V_m - V}) \qquad (5.1b)$$

where V_m is an arbitrary constant reflecting the maximum sensitivity of the particular community.

In addition to $F(V)$, the X function (Equation 5.1a) is driven by the degree of inducement for agricultural expansion (D_e) (Elshafei et al., 2014) to reflect the community's aspirations for economic well-being and prosperity in the future:

$$D_e = [\frac{\dot{P}}{P} + \mathrm{Ub}\,](1 - \frac{L_a}{L_m})(1 - \frac{R_e}{S_c})] \qquad (5.1c)$$

where $\frac{\dot{P}}{P}$ is population growth within the basin and U_b is unemployment. A growing population and unemployment increase the demand for agriculture expansion so that jobs are made available. The extent of development is fueled by the extent to which critical natural resources within the basin have been utilized, namely land (L_A / L_m) and water ($R_e\,/S_c$) resources. The capacity usage is included since management decisions are progressively less likely to acquiesce to expansion pressures as usage levels approach the capacity (Elshafei et al., 2014). Here, R_e is total committed water to be extracted, for purposes such as irrigation and town water supply. Committed water is updated as a summation of maximum amount of water withdrawn for agriculture previously ($Q_{A,\,(t-1)}$) and currently ($Q_{A,\,t}$) plus the town water supply at time t ($Q_{T,\,t}$). In order to capture the reduction of town water supply demand due to changing population in the long-term, committed town water supply was assumed to be equal to demand of that year. L_m is the maximum land available for agriculture and S_c is the reservoir capacity of the dams. The ratio between committed water volume and storage capacity is used as an indicator of the availability of water resources for further development.

The response function is transformed into water management action through a translation function (Elshafei et al., 2014), here adapted to the Murrumbidgee River basin. Water withdrawn for agriculture (Q_A) depends on the community response (X) and water allocation (W_A). In the Murrumbidgee, during past severe droughts water management was suspended. In this situation, it is extremely difficult to predict how water is managed but likely to be decided at that time based on the conditions that best overcomes the risk. Here, when the dam storage (S) is less than 1000 GL, water management is assumed to be suspended. Incorporating these, a simple formulation for water withdrawal for agriculture (Q_A) is defined below, following Di Baldassarre et al. (2013) and Elshafei et al. (2015):

$$\dot{Q}_A = \begin{cases} \eta_E \frac{\dot{W}_A}{W_A}\, Q_A, & \mathrm{X} > 0, S \geq 1000 \\ -\eta_A \mathrm{X} + \eta_E \frac{\dot{W}_A}{W_A}\, Q_A\,, & \mathrm{X} \leq 0, \mathrm{S} \geq 1000 \\ \min(0, \eta_E \frac{\dot{W}_A}{W_A}\, Q_{A}), & S < 1000 \end{cases} \tag{5.1d}$$

where $\eta_{A,}\ \eta_E$ are translation parameters previously estimated through calibration and outlined in Chapter 4. Since water allocation (W_A) depends on water use and climate, and reveals a linear relationship with storage (S) (as shown in Chapter 4), it is assumed to be a linear function of storage (*S*). The change in withdrawn agriculture water is then given by:

$$\dot{Q}_A = \begin{cases} \eta_E \frac{\dot{S}}{S} Q_A, & \text{X} > 0, S \geq 1000 \\ -\eta_A \text{X} + \eta_E \frac{\dot{S}}{S} Q_A, & \text{X} \leq 0, \text{S} \geq 1000 \\ \min(0, \eta_E \frac{\dot{S}}{S} Q_A), & S < 1000 \end{cases} \tag{5.1e}$$

Similarly, assuming there is an environmental allocation function that obeys a similar formulation as Equation 5.1e, the environmental water delivered in response to environment stress is given by:

$$\dot{Q}_E = \begin{cases} \eta_E \frac{\dot{S}}{S} Q_E, & \text{X} < 0 \text{ } and \text{ } S > 1000 \\ \eta_A \text{X} + \eta_E \frac{\dot{S}}{S} Q_E, & \text{X} \geq 0 \text{ and S} > 1000 \\ -1 * Q_E, & S < 1000 \end{cases} \tag{5.1f}$$

where $\dot{Q}_E$ is the change in the amount of water delivered to the environment.

5.2.2 External Drivers

The model was driven by climate (inflow) and economic inputs (GDPc, Australian unemployment). This section explains how those inputs were created stochastically to assess the sustainability of the basin level socio-hydrological system in an unknown future.

5.2.2.1 Inflow to the dams

The climate driver, inflow to the dams, was modelled using the first order autoregressive model as shown below (Garcia et al., 2015):

$$I_t = \rho_q \left(I_{t-1} - \mu_q\right) + \sigma_q \left(1 - \rho_q^2\right)^{0.5} a_t + \mu_q \tag{5.2}$$

where ρ_q is first order lag coefficient, μ_q is average inflow to the dams, σ_q is the standard deviation of inflow to the dams, and t is time, a_t is a random variable with general gamma distribution. Distribution parameters are estimated based on the data.

5.2.2.2 Australian real and nominal Gross Domestic Product (GDPc) and unemployment rate

Nominal GDPc and unemployment rate are the economic external drivers which are used in the community sensitivity sub-model and population model (Figure 4.1e, f). External economic drivers were modelled based on macroeconomic theory and its parameters estimated using the linear regression and vector auto-regressive (VAR) method. Assuming a country's economy as a single sector, based on Cobbs-Douglas production function, total production is modelled as:

$$Y = AK^{\alpha}L^{1-\alpha} \tag{5.3a}$$

where Y is total aggregate product, A is total factor of productivity (TFP), K is capital and L is labor in production. α is share of capital productivity in terms of output. The real gross domestic product per capita could be modelled as

$$\frac{Y}{P} = \frac{AK^{\alpha}L^{1-\alpha}}{P} = GDPc^{R} \tag{5.3b}$$

where P is the population. Population is assumed to grow at the rate of γ_p.

$$P = P_0 \exp(\gamma_p t) \tag{5.3c}$$

where P_0, t are initial population and time respectively. By taking logarithms of both sides,

$$\ln GDP_c^R = \ln A + \alpha \ln K + (1-\alpha)\ln L - \ln P_o - \gamma_p t \tag{5.3d}$$

It is assumed that TFP and capital grows at the rate of γ_T, γ_K, respectively.

$$A = A_0 \exp(\gamma_T t) \tag{5.3e}$$

$$K = K_0 \exp(\gamma_K t) \tag{5.3f}$$

where A_0, K_0 and γ_T, γ_K are initial value and growth rate of TFP and capital, respectively. From equation 5.3d, e, f:

$$\ln GDP_c^R = \ln A_0 + \gamma_T t + \alpha \ln K_0 + \alpha\gamma_K t + (1-\alpha)\ln L - \ln P_o - \gamma_p t \tag{5.3g}$$

We assume efficient allocation of labor and equate marginal productivity of labor to wage rate (w) (Borjas, 2010).

$$\frac{\partial Y}{\partial L} = w = A(1-\alpha)(\frac{K}{L})^{\alpha} \tag{5.3h}$$

Applying a logarithmic transformation,

$$\ln w = \ln A + \ln(1-\alpha) + \alpha \ln K - \alpha \ln L \tag{5.3i}$$

We then assume that the wage growth rate is increasing exponentially as has been historically observed.

$$w = w_0 \exp(\gamma_w t) \tag{5.3j}$$

where w_0, γ_w is initial wage rate and wage growth rate respectively. From equations 5.3d, i,

$$\ln GDP_c^R = \ln A_0/\alpha + \gamma_T t/\alpha + \ln K_0 + \gamma_K t + \frac{(1-\alpha)}{\alpha}\ln(1-\alpha) - \frac{1-\alpha}{\alpha}\gamma_w t - \ln P_0 - \gamma_p t \tag{5.4k}$$

Since $\ln A_0$, $\ln P_0$, $\ln K_0$ are constant, equation 5.3k is transformed into a stochastic equation, adding shocks ($\mathcal{E}_g$), and into a linear regression equation.

$$\ln GDP_c^R = \mathrm{C_g} + \frac{\gamma_T t}{\alpha} + \gamma_K t + \frac{(1-\alpha)}{\alpha} \ln(1-\alpha) - \frac{1-\alpha}{\alpha} \gamma_w t - \gamma_p t + \mathcal{E}_g \qquad (5.3l)$$

where $\mathrm{C_g}$ is constant and $\mathcal{E}_g$ is residual. Then labor demand is estimated from 5.3g as shown below.

$$\ln L = C_L + \frac{\ln(GDP_c^R)}{1-\alpha} - \frac{\gamma_T t}{1-\alpha} - \frac{\alpha}{1-\alpha} \gamma_K t + \gamma_p t + \mathcal{E}_L \qquad (5.3m)$$

where C_L is constant and $\mathcal{E}_L$is a residual. From this the unemployment rate of Australia (U_A) can be defined as:

$$U_A = 1 - (E_A) \qquad (5.3n)$$

$$E_A = (\frac{L}{P\phi})$$

where E_A is employment rate and ϕ is the participation rate. It could be transformed as shown below.

$$\ln E_A = \ln L - \ln P - \ln \phi \qquad (5.3o)$$

Assuming participation rate grows at a growth rate of γ_ϕ , we obtained the linear regression equation for employment rate,

$$\ln E_A = C_E - \ln L - \gamma_p t - \gamma_\phi t + \mathcal{E}_E \qquad (5.3p)$$

where C_E and $\mathcal{E}_E$ is a constant and a residual, respectively.

The parameters of equations 5.3l, m, p are obtained based on the linear regression method with observed real GDPc, total employment or labor involved in production, and employment rate (see Table 5.1).

Figure 5.1 illustrates the residuals ($\mathcal{E}_g, \mathcal{E}_L, \mathcal{E}_u$) which represent the shocks in the system that are actually unpredictable. Residuals are modelled using the vector auto-regressive model (VAR) to model the auto- and cross-correlation structure of the residuals. The residuals display the trend in the data. The auto-correlation function (ACF) was checked with the data and the differenced data in order to check for stationarity (see Figure 5.2). The stationarity is displayed by the differenced data (Figure 5.2).

Table 5.1: Model Coefficients and constants. Coefficients were obtained from data or literature and constants are obtained using linear regression.

Coefficients	Value	Reference
γ_T	0.011	ABS, 2010
γ_K	0.07	World Bank, 2014
γ_p	0.015	World Bank, 2014
γ_w	0.034	ABS, 2015
α	0.41	ABS, 2010
Constant	Value	
C_g	10.8	NA
C_L	-1.8	NA
C_u	-15.53	NA

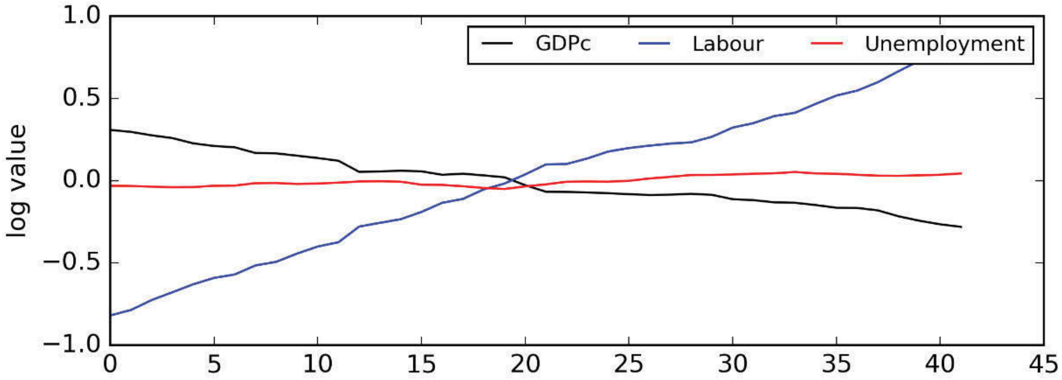
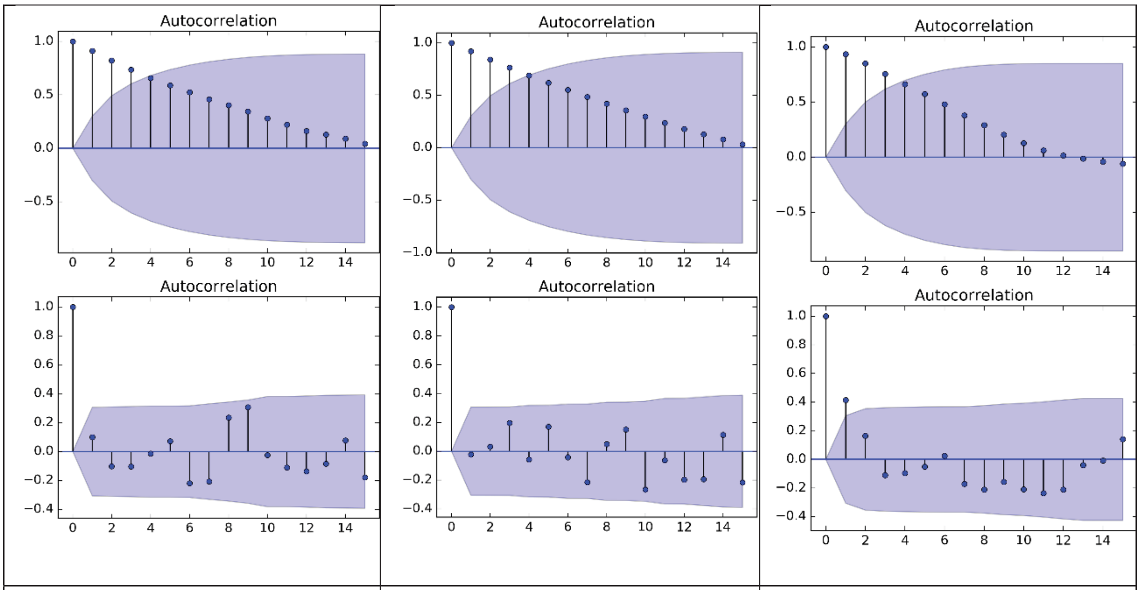


Figure 5.1: Residual of GDPc, Labor in production and employment rate.



(a) ACF of GDPc (top) and differenced GDPc residual data (bottom)

(b) ACF and PACF of labor (top) and differenced labor residual data (bottom)

(c) ACF and PACF of unemployment (top) and differenced unemployment residual data (bottom)

Figure 5.2: (a) Auto correlation function (ACF) of (a) GDPc (top) and differenced GDPc residual data (bottom),(b) labor (top) and differenced labor residual data (bottom), (c) employment (top) and differenced employment residual data (bottom).

Differenced data was used to fit the VAR(p) model. The order of model is selected based on the Akaike information criterion (AIC) method. Since the minimum value for AIC is obtained with first order lag, VAR(1) was identified as fitting the residuals well.

Table 5.2: AIC score for different orders of model

```
==================================================
          AIC        BIC        FPE           HQIC
          ----------------------------------------
0       -28.31     -28.18*   5.050e-13     -28.27
1      -28.68*      -28.15   3.518e-13*    -28.49*
2       -28.52     -27.60    4.170e-13     -28.20
3       -28.31     -26.99    5.302e-13     -27.85
4       -28.02     -26.31    7.474e-13     -27.43
5       -27.72     -25.61    1.119e-12     -26.98
==================================================
```

* Minimum

AIC-Akaike information criterion, BIC-Bayesian information criterion, FPE-Final prediction error, HQIC-Hannan-Quinn information criterion

The nominal GDPc ($GDPc^N$) which influences community sensitivity was obtained by considering inflation. Inflation was accounted for by commodity price index (CPI). The nominal GDPc is given by

$$GDPc^N = GDPc^R * CPI/100 \quad (5.4)$$

CPI is modelled using the differenced first order auto-regressive model as shown below.

$$CPI_{t+2} - CPI_{t+1} = \rho_c\big((CPI_{t+1} - CPI_t) - \mu_c\big) + \sigma_c\big(1 - \rho_c^2\big)^{0.5} a_t + \mu_c \quad (5.5)$$

where ρ_c is first order lag coefficient, μ_c is average of differenced CPI, σ_c is the standard deviation of differenced CPI.

Table 5.3: Estimated ARMA model coefficients for external forcing

Coefficients **	Inflow (q)	CPI (c)
ρ_i	0.3099	-0.2443
μ_i	2762.2 (GL/year)	2.24
σ_i	1241.4 (GL/year)	1.49

** subscript i = q, indicates the coefficients for inflow model; i=c, it indicates the coefficients for commodity price index (CPI) model.

In order to understand effect of a non-stationary climate and growing economy on the sustainable development of the basin, capital growth rate (γ_K) of Australia which drives the $GDPc^R$ growth, average inflow to the dams (μ_q) and capital growth rate of basin (γ_c) were varied to create a combination of scenarios. Capital growth rate of Australia and the basin (γ_K, γ_c) varied between 95% and 105% of the observed value. Similarly, mean of inflow (μ_q) was varied between 50% and 150% of observed mean inflow. A combination of different external conditions (i.e. inflow, GDPc, capital growth rate) was considered as a scenario. For each scenario 50 ensembles were created. The dynamical model was implemented in Python using the PyDSTool module (Clewley, 2012).

5.2.3 Analyses of the basin's sustainable development

Even though a general definition of sustainable development includes the economy, environment and social dimensions, in this study we measure the sustainability as the basin's ability to support population and economic growth while catering for the future needs of the basin's environment. Examination of development indicators among nations (i.e. GDPc, population, environment health) show that seeking extremes of high population growth or significantly improved ecosystem services do not lead to sustainable development. For a given exogenous condition, a basin's population growth can be high but ecosystem services can be low and unemployment can either be high or low. In this study external conditions (forcing functions) which could yield better sustainability were analyzed, and a comparison of scenarios was carried out. In order to find a sustainable development scenario, each variable of the sustainable indicator was normalized and the Basin Sustainable Development Index (BSDI) was estimated in a manner similar to the Human Sustainable Development Index (Bravo, 2014) (HSDI) as shown below:

$$I_{vj} = \frac{vj - vj_{min}}{vj_{max} - vj_{min}} \tag{5.7}$$

$$BSDI = \sqrt[j]{I_{v1} * I_{v2} \dots * I_{vj}} \tag{5.8}$$

where I_{vj} is normalized index of each variable, j is number of variable selected as indicators. vj_{max}, vj_{min} is the maximum and minimum of variable vj among all scenarios. BSDI was estimated from population, ecosystem services and employment rates.

5.2.4 Basin reliability analysis

In this study, system reliability to meet rising water demand with society's changing values and preferences was investigated. The bottom-up approach considers society's changes in value and preferences with specific reference to water use and society's ability to adapt to cope with water stress such as a change in water policy (Mehran et al., 2015). The bottom-up approach relies on available infrastructure, institutional capacity, social conditions, and perception of water vulnerability (Mehran et al., 2015). Here we use the water storage resilience (WSR) index to indicate whether demand could be managed by man-made dam storage and inflow (Mehran et al., 2015).

$$\text{Water storage resilience index (WSR)} = \frac{S + I - Q_E - Q_{of} - O_{min} - Q_{dem}}{Q_{dem}} \tag{5.9}$$

where Q_{dem} is water demand for the given period which includes agriculture water demand and town water demand; and O_{min} is minimum operational requirement. The basin reliability index was measured as percentage of time over 100 years for cases where WSR was greater than zero.

5.3 Results

5.3.1 Stochastic external conditions

In order to understand the condition of the basin in the future and the conditions that may lead to unsustainable development, the model was rerun with non-stationary climate (i.e. inflow), growing Australian economy (i.e., GDPc) and with different basin capital growth rates. The exogenous drivers of basin development, i.e. climate (i.e., inflow), Australian GDPc, and basin capital growth rate (γc) were varied by changing the mean of inflow(μ_q) between 50% to 150% of observed mean inflow, and capital growth rate of Australia and the basin (γ_K, γ_c) between 95% to 105% of the observed values, respectively. For each scenario, 50 ensamples were created stochastically as explained in section 5.2.

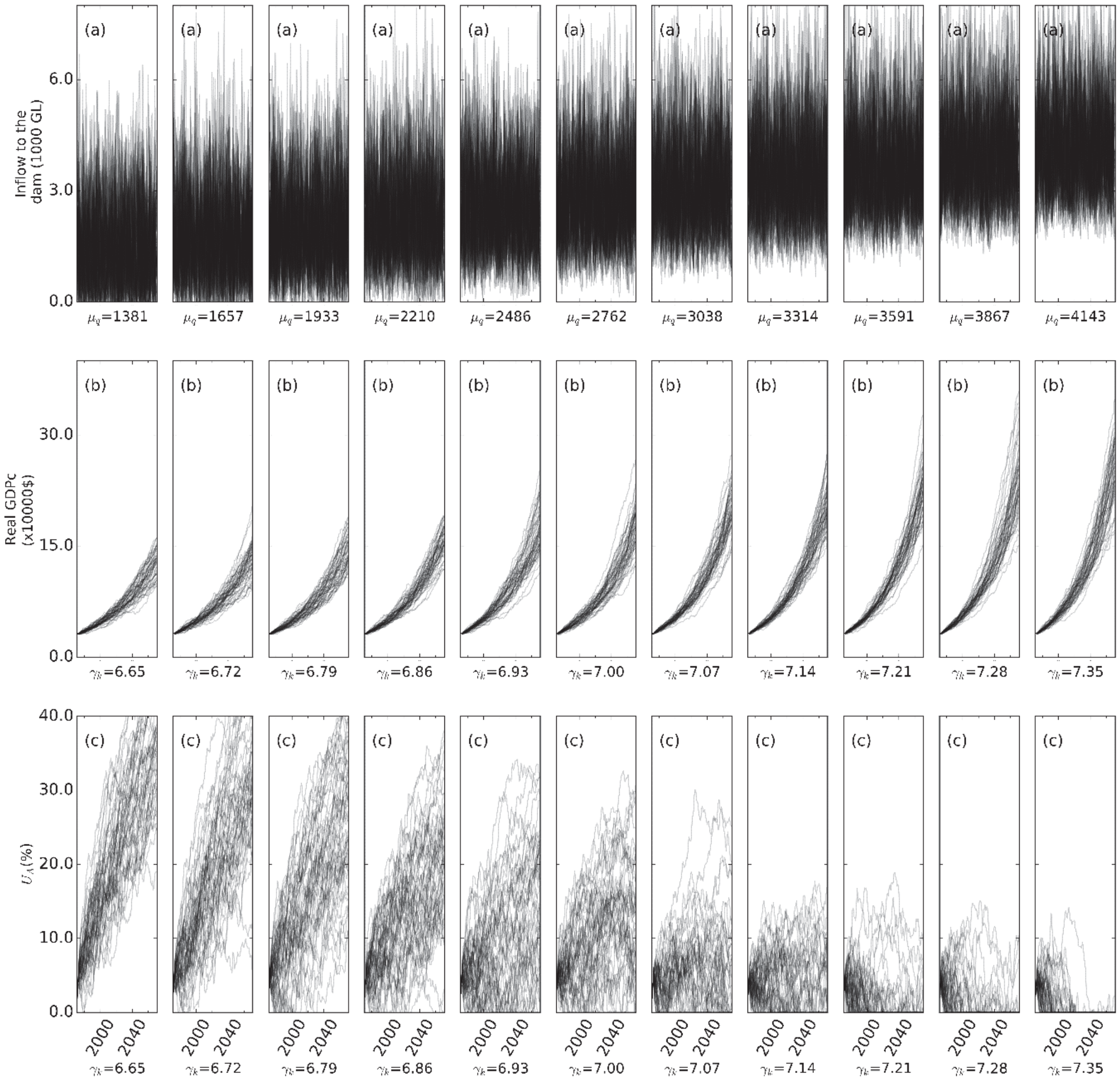


Figure 5.3: (a): Projected inflows to the dam trajectories when the mean of GDPc growth (μ_g) and mean of inflow to the dams (μ_q) were changed from 50% to 150%. (b): projected real gross domestic product per capita (GDPc) when the capital growth rate of Australia (γK) was changed from 95% to 105% of observed capital growth rate and (c): projected unemployment rate trajectories when the capital growth rate of Australia (γK) was changed from 95% to 105% of observed capital growth rate. Model simulation was carried out from 1971 to 2070.

Figure 5.3a depicts the projected inflows to the basin's dams if the climate changes and displays non-stationarity. The mean inflow is expected to increase to ~4000GL when the mean inflows rise to150% of observed mean inflows, assuming variability will be the same as what has been already observed. Figure 5.3b,c shows the projected real GDPc and Australian unemployment rate if the country's capital growth rate changed from 95% to 105% of observed capital growth rate. Australian real GDPc is expected to increase to about 8.2 times relative to 1971 when the capital growth rate of

Australia is increased by 105% of observed capital growth rate. The Australian unemployment rate will be less when the economy grows quickly. Furthermore, the unemployment rate will reach ~40% if capital growth rate is reduced to 6.65% and will reach zero in some years if the Au stralian capital growth rate increases although it could be affected by external shocks.

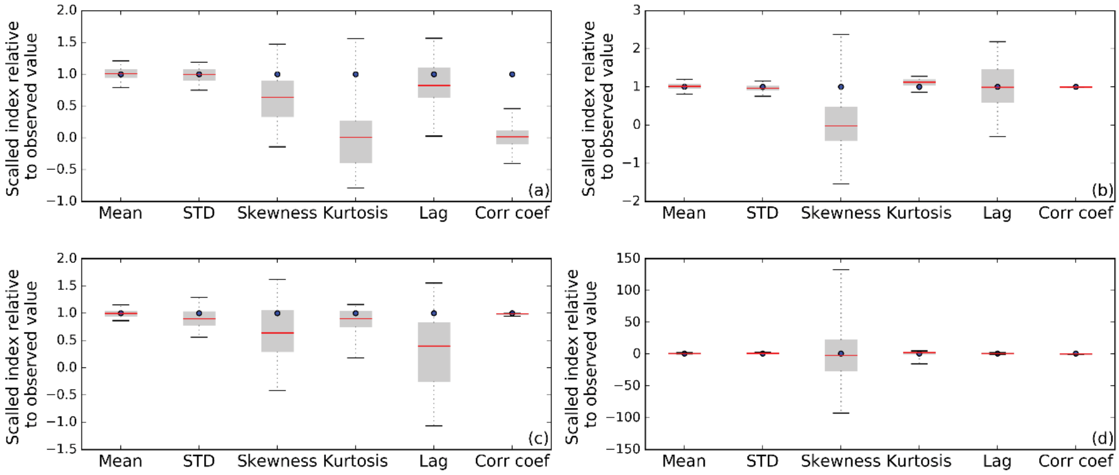


Figure 5.4: Comparison of modelled and observed variable data statistics of (a) inflow, (b) Commodity price index (CPI) reference to 2012, (c) real GDPc of Australia and (d) unemployment rate of Australia. Data statistics were calculated for period 1971-2012. Box and whisker plot shows statistics of stochastic input relative to observed data statistics. Correlation coefficient (Corr coef) was calculated between observed and modelled variables.

Figure 5.4 shows the performance of the stochastic models in predicting inflow, CPI, real GDPc and unemployment rate of Australia. The models used to derive the four inputs replicate the observed statistics, i.e. the mean, standard deviation, skewness, Kurtosis and first order lag, reasonably well.

5.3.2 Basin development and its uncertain future climate and economy

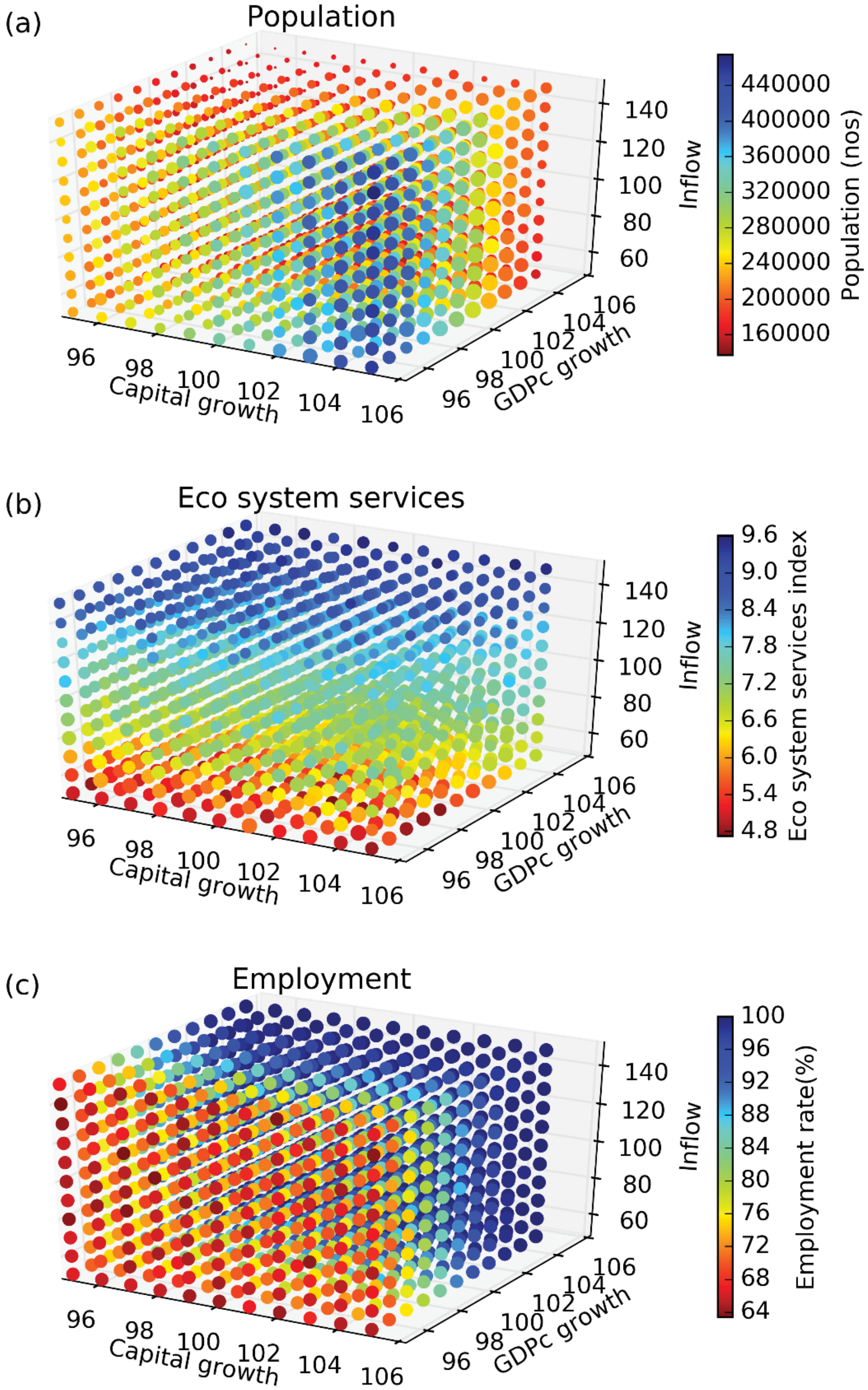


Figure 5.5: (a) Population, (b) ecosystem services, and (c) employment rate after 100 years for non-stationary climate (inflow), changes in the growth of Australia's economy (GDPc) and capital growth in the basin. Size of circle indicates the standard deviation of ensamples.

Figure 5.5 shows the mean basin population, ecosystem services and employment rate in the basin after 100 years of non-stationary external drivers (basin inflow, Australian GDPc, and capital investment in the basin). In this section, we analyze the impact of changes under the *mean conditions of external drivers* to obtain the level of sustainable development of the basin. The sustainability index was derived from basin population, ecosystem services and employment rate (see section 5.2.3). We examine how the index varies with these three variables.

Basin Population: Figure 5.5a shows the population in the basin after 100 years. Here, blue indicates a high mean basin population and red shows a low mean basin population. The size of a circle indicates the standard deviation of the samples.

Figure 5.5a shows how a stronger Australian GDPc (i.e. increasing growth rate of capital in Australia) reduces the basin population, for a given mean inflow and basin capital growth rate. Strong Australian economic growth corresponds to a smaller unemployment rate (outside the basin). When the Australian unemployment rate is lower than that in the basin, it creates a negative attractiveness that entices the basin population to leave. Consequently, the attractiveness of migration to the basin declines and population growth falls through out-migration.

In the same way, if the labor demand in the basin falls due to changes in water management that allocates more water to the environment or if less capital is invested (i.e. not following the same level of economic growth outside the basin), it will result in rising unemployment in the basin. Eventually, this increases the unemployment (economic) gradient between inside and outside of the basin and induces the basin population to migrate. In doing so the gradient readjusts downwards. In this way a strong Australian economy mitigates against high unemployment in the basin despite the basin's poor economic conditions.

Figure 5.5a shows that high inflow by itself does not bring about a high population. Increasing inflow supports agriculture production and employment and an increasing population. Nonetheless, this effect of inflow in supporting population growth is less notable because the basin is more diversified. In 1971, the agriculture sector made up 24% of the basin's economy and reduces over 100 years for non-stationary change.

Increasing basin capital growth increases the basin's population (Figure 5.5a). A high basin capital growth rate supports diversification in the basin by facilitating industry growth, employment in the industry sector and increases the attractiveness of migration. Migrants to the basin are more likely to be employed in the growing industry sector. In this way it can be seen in Figure 5.5that in a diversified economy, rising capital investment has a more significant effect than favorable climatic conditions (high inflow). Figure 5.5a shows that the maximum population size among all the scenarios occurs when the basin capital growth rate is high and when the Australian economy is weak (low GDPc). Conversely, the smaller population size occurs when the basin's capital growth rate is low and when the Australian economy growth is high. Inflow wields little influence.

Uncertainty in the projections (standard deviation of samples, i.e. larger size of circle) increases with larger capital investment into basin and weaker Australian economy (Figure 5.5a). Population growth is affected by the migration which depends on the gradient of unemployment rate between basin and outside. Figure 5.5c shows that for a low Australian GDPc, the basin unemployment rate is high and its variation (standard deviation) is large. This implies a high level of uncertainty in the unemployment rate when the Australian economy growth is low. This uncertainty propagates the basin population through a greater fluctuation in migration to the basin.

Elsewhere, uncertainty decreases with smaller capital investment and with a stronger Australian economy. For example, when the basin capital investment is low it attenuates the effect of uncertainty arising from the outside unemployment rate since the demand for labor in the basin will be low and its population would tend to migrate away from the area.

Ecosystem services: Figure 5.5b shows the projected ecosystem services in the basin after 100 years of non-stationary drivers. Increasing inflow supports ecosystem services as more water will be available (Figure 5.5b).

A strong Australian economy also improves the ecosystem services (Figure 5.5b) as society is more affluent, cares about the environment and delivers more environmental water. Ecosystem services will function at their poorest when the Australian economy is weak and society is less focused on the environment; and when the mean inflow is low and there is less water available. Ecosystem services will be best if both the GDPc

(Australian economy) and inflow is high (150% of observed). There are no significant changes in the ecosystem services because the basin's capital growth is already diversified.

Unemployment: Figure 5.5c shows the projected employment rate at the end of 100 years of non-stationary model input. There is a rise in the employment rate in the basin when the Australian GDPc rises. When the Australian economy is strong, the Australian unemployment rate will be low (Figure 5.5c) and the basin's population leaves to seek better employment prospects elsewhere. In the model, migration is driven by the unemployment gradient between inside and outside of the basin in a manner that tends to readjust the gradient towards zero. Basin unemployment rate tends to follow the rate outside the basin because cost of migration or resistance to the migration is considered low (attractiveness coefficients (μ) is high).

Even though rising capital investment creates new jobs in the industry sector, its influence on employment is marginal (Figure 5.5c). The employment rate is principally influenced by high GDP_c through out-migration. Similarly, there is little influence caused by inflow, principally since the agriculture sector as a portion of the basin's economy diminishes over the projected 100 years.

Basin employment rate peaks when the economy outside the basin (GDPc) is strong (105% of observed Australian capital growth rate). The lowest employment rate will be when the Australian economy's growth is weak. A more extensive study is needed to understand the drivers of migration in the basin.

The preceding discussion outlined how each component of the sustainability index was affected by external drivers. The trends were sometimes conflicting and the basin sustainable development index BSDI was calculated to compose them (eqn. 5.8) and plotted in Figure 5.6. Blue dots represent a more sustainable development in the basin where the BDSI is high while and red means low sustainable development.

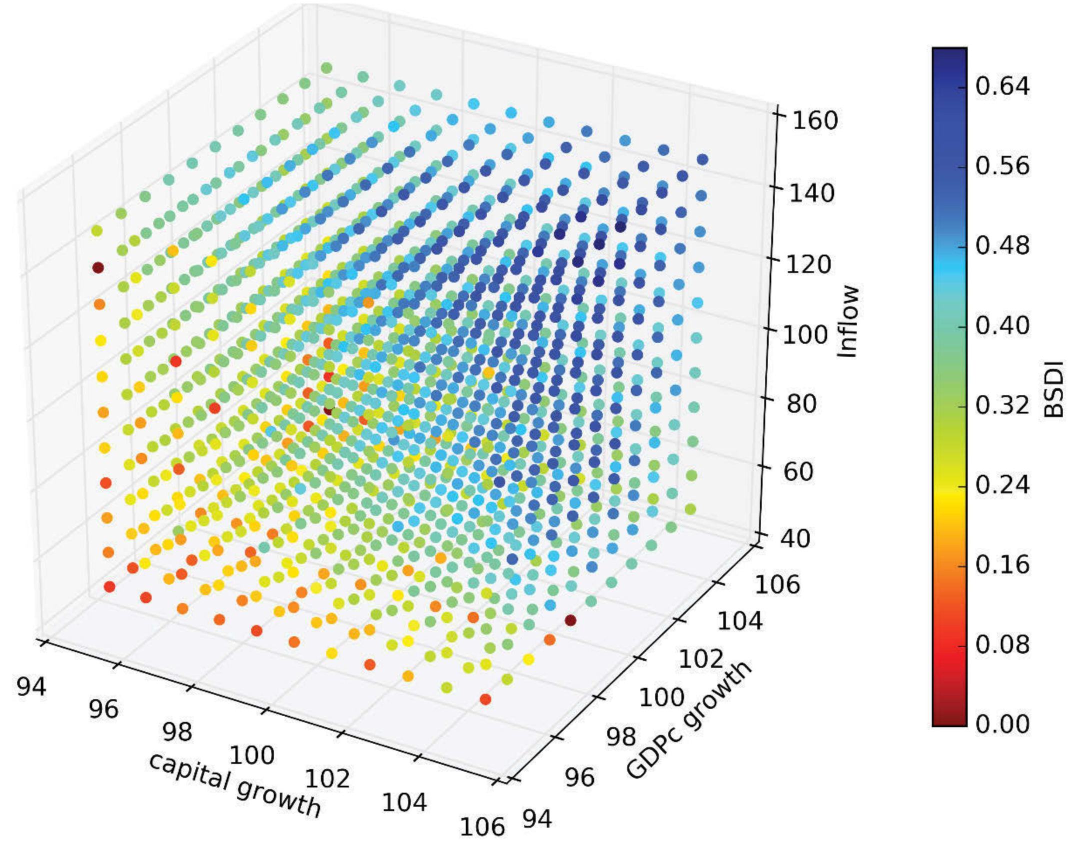


Figure 5.6: Basin Sustainable Development Index (BSDI) for non-stationary climate (Inflow), changes in the growth of Australia's economy (GDPc) and changes in basin capital growth rate.

Strong capital investment in the basin leads to sustainable development. Similarly, good basin inflow supports sustainable development.

A higher or lower GDPc (Australian economy) compared to the observed growth (current Australian economy which is moderate) would generally lead to less sustainable development although it further depends on the state of the inflow and rate of basin capital growth. This emerges from the conflicting trends seen in Figure 5.5. A strong GDPc is good for employment (Figure 5.5c) but poor for population size (Figure 5.5a). Ecosystems are better with a strong GDPc but the trend is not as strong (Figure 5.5b). *This means that a moderately growing GDPc (or moderately growing Australian economy) is better for sustainability*.

The best conditions for sustainability are strong capital investment, good basin inflows and a moderately growing GDPs. *It is worth noting that these conditions apply to a basin with a diversified economy.* Conversely, the poor conditions for sustainability are low capital investment in the basin, poor climatic conditions (i.e. low inflows) and either strong or weak economy outside the basin.

5.3.2.1 Influence of basin capital growth

Figure 5.7 shows the projected labor demand in industry (Figure 5.7a), agricultural labor share (Figure 5.7b), water delivered to the environment (Figure 5.7c), ecosystem services (Figure 5.7d), population (Figure 5.7e) and basin unemployment rate (Figure 5.7f) when the basin capital growth rate (γ_c) is varied, where both the Australian capital growth rate (γ_K) (for GDPc) and mean of inflow to the basin dams (μ_q) is kept as observed.

When the basin capital increases, labor demand (Figure 5.7a) increases as does industrial production. The agriculture sector is constrained by the amount of available land and water resources. Better and improving technology feeds rising productivity (specifically reducing labor demand in agriculture) and together with a growing employment in the industry sector reduces the labor share of the agricultural sector (Figure 5.7b), i.e. the portion of labor employed in agriculture relative to total employment. This diversifies (Figure 5.7b) the basin's economy so that there is a shift from agriculture to industry. Here, the livelihood of a larger portion of the population depends on the industry sector and less on agriculture. Such a basin society is more disposed to value the environment, deliver environmental water (Figure 5.7c) and increases the quality and efficiency of ecosystem services (Figure 5.7d).

The effect on unemployment is less distinct (Figure 5.7f). Creation of more employment in the industry sector, through increasing capital, tends to reduce the basin unemployment rate. However, unemployment in the rest of Australia may be high depending on the state of the Australian economy. If this is the case then there is an increase in the attractiveness and in-migration resulting from the unemployment gradient between inside and outside the basin. In-migration together with the natural population growth in the basin increases its population (Figure 5.7e) and returns the unemployment rate gradient to zero between inside and outside of the basin (Figure 5.7f, Figure 5.3c with γ_K=7 %).

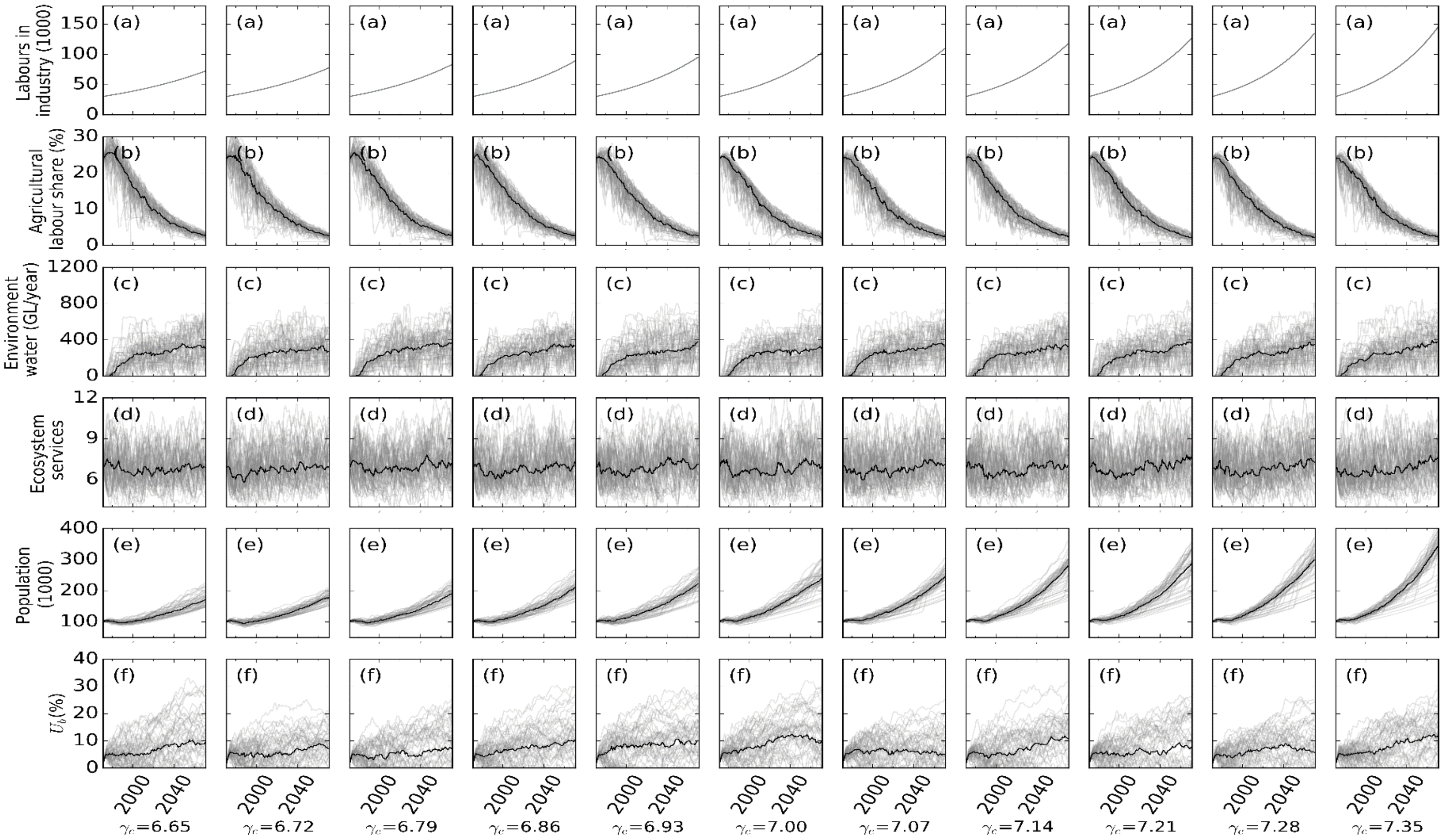


Figure 5.7:(a) Projected labor demand in the industry sector, (b): projected labor share of the agriculture sector, (c): projected delivery of environmental water, (d): projected ecosystem services, (e): projected basin population, (f): projected basin unemployment rate trajectories when the basin capital growth rate (γ_c) is changed from 95% to 105% of observed capital growth rate. The change in the basin capital growth rate is given on the axis. Gray color lines show the ensamples projections and black line shows the median of ensamples.

In *a basin that is increasingly more diversified* (Figure 5.7a and b – going from left to right):

- Where there is an increase in employment (Figure 5.7a) and a strong basin economy, there is a rise in the population growth (Figure 5.7e) in the basin without degrading the environment.
- Conversely, in a weaker basin economy it still displays moderate rises in population (Figure 5.7e), delivery of environmental water (Figure 5.7b) and more or less maintaining ecosystem services (Figure 5.7c).
- Balancing the community's preferences remains in favor of maintaining water delivery to the environment and ecosystem services. The basin trajectory maintains a sustainable balance between the economy and the ecosystem.

5.3.2.2 Impact of changes in inflow

Figure 5.8 shows the delivered environmental water (a), ecosystem services (b) and withdrawal of water for agriculture (c) when mean of inflow to the dams (μ_q) is varied and both the Australian capital growth rate (γ_K) and basin capital growth rate (γ_c) are retained as observed.

When the inflow to basin dams increases, delivered environmental water increases (Figure 5.8a) and ecosystem services increase (Figure 5.8b). In the competition for water to help the environment and the economy within the basin, a *more diversified economy* means that society is more sensitive to ecosystem degradation since a smaller population depends directly on agriculture:

- If the basin inflow reduces due to drought or to climate change, the ecosystem might suffer but it would not be as bad as in the past as environmental water will be delivered, albeit in smaller amounts (Figure 5.8a, left hand side (LHS) plots).
- If the inflow increases the amount of environmental water also increases in proportion. At the same time the withdrawal of agriculture water increases (Figure 5.8, RHS plots) but plateaus at higher levels of inflow. The consumption of water does not feed unsustainable economic expansion but is consumed in a measured manner commensurate with ecosystem requirements (Figure 5.8a and b).
- In this setting, in a basin where the *economy is diversified*, society manages water wisely and the basin will be on a sustainable development path.

When the mean inflow increases, it facilitates growth in agriculture and stimulates demand for agriculture labor, providing an opportunity for population growth. Nonetheless increasing the inflow to basin dams has less influence on the population growth (Figure 5.5a) than a growing Australian economy or increasing capital investment in the basin. This is because the relative contribution of agriculture to the total basin economy diminishes over the projected 100 years.

The fluctuation in the amount of water withdrawn for agriculture use increases when the inflow is low (Figure 5.8c). Fluctuation in water withdrawal affects continuity in cultivation and production, farm incomes and cash flows, and will subsequently increase financial insecurity. Similarly, when the mean inflow is low, even though society intends to divert water to the environment, fluctuations in environmental water are high (Figure 5.8a) and the lack of continuity means that the health of the ecosystem is poorer (Figure 5.8b).

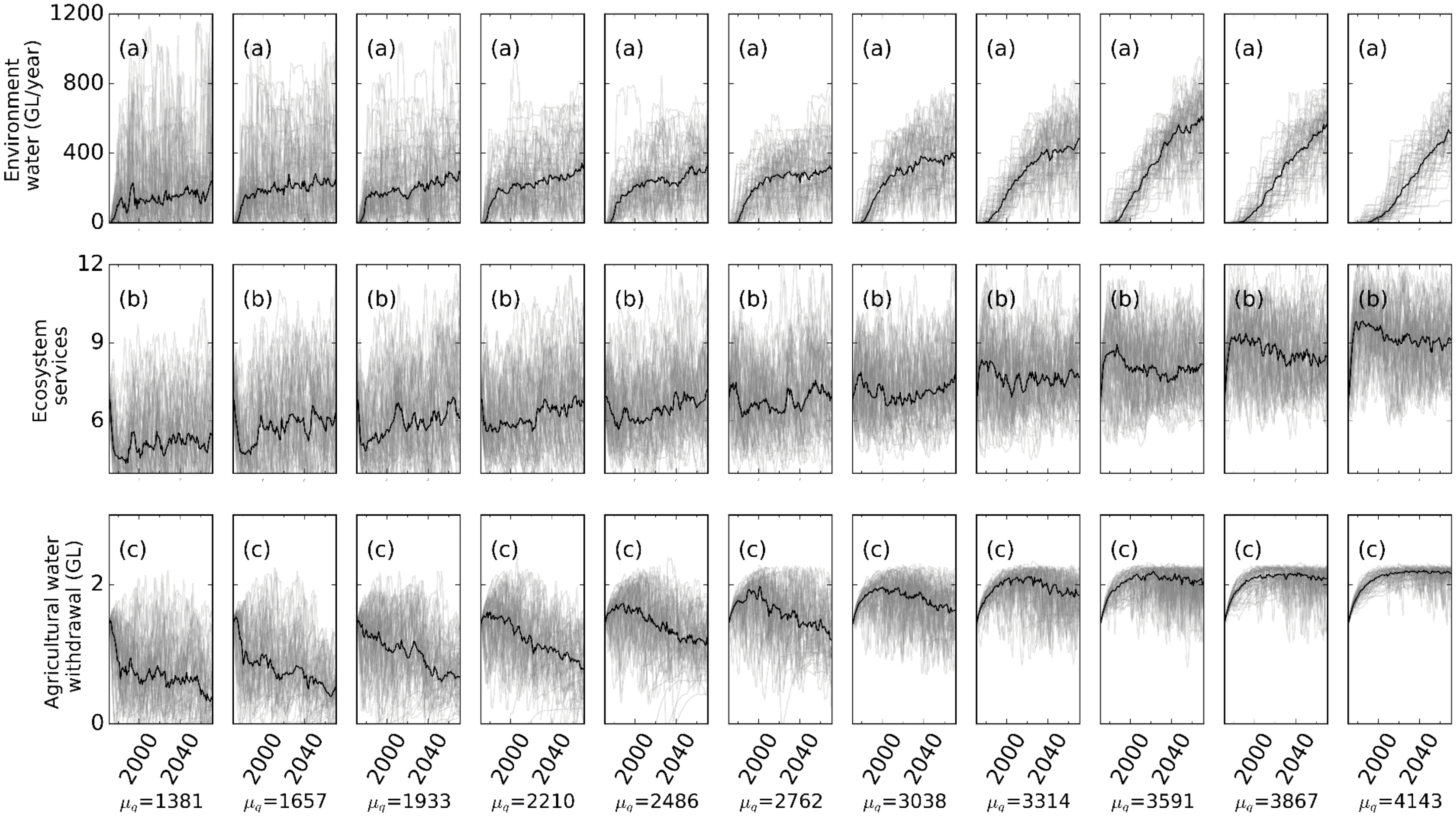


Figure 5.8: (a) Projected environment water, (b): projected ecosystem services, (e): projected agriculture water withdrawal trajectories when the basin mean inflow changed changes from 50% to 150% of the observed growth rate. Gray color lines show the ensamples projections and black lines show the median of ensamples.

5.3.2.3 External economic growth

Figure 5.9 shows the projected delivered environmental water (a), ecosystem services index (b) and agriculture water withdrawal (c) when the capital growth rate of Australia (γ_K) changes from 95 % to 105% of the observed value. Meanwhile the growth of capital (γ_c) investment in the basin and mean of inflows to the basin dams is kept at observed values.

When the Australian economy (outside the basin) grows, migration from the basin occurs and leads to higher per capita income. In this situation, ecosystem services increase (Figure 5.9b) as more environment water is delivered (Figure 5.9a). When the GDPc rises, society becomes more affluent, values the environment, can afford to be supportive of the environment, increases the environmental water and ecosystem services in the basin improve. When the Australian economy growth is strong (Figure 5.9c, left to right), at the initial stage agriculture water withdrawal declines quickly and then flattens. However, the amount of water withdrawn after 100 years is similar for all the scenarios considered. This shows that in a strong Australian economy, society's ambition to retain sustainable water usage and management is achieved more quickly.

For given capital and inflow, a strong Australian economy may not support population growth (Figure 5.5a) but does support ecosystem services (Figure 5.5b). A weaker Australian economy will increase population growth in the basin (Figure 5.5a), increase the unemployment rate (Figure 5.5c) and reduce the ecosystem services (Figure 5.5b). Therefore, a low growth of Australia's GDPc (due to high unemployment rate, fewer ecosystem services) or high growth of Australia's GDPc (due to smaller population) leads to low sustainable development for a given basin's economic growth condition (Figure 5.6). This reinforces the finding in the preceding section that:

- a modest growth (similar to observed levels) in the national economy is better for sustainability.

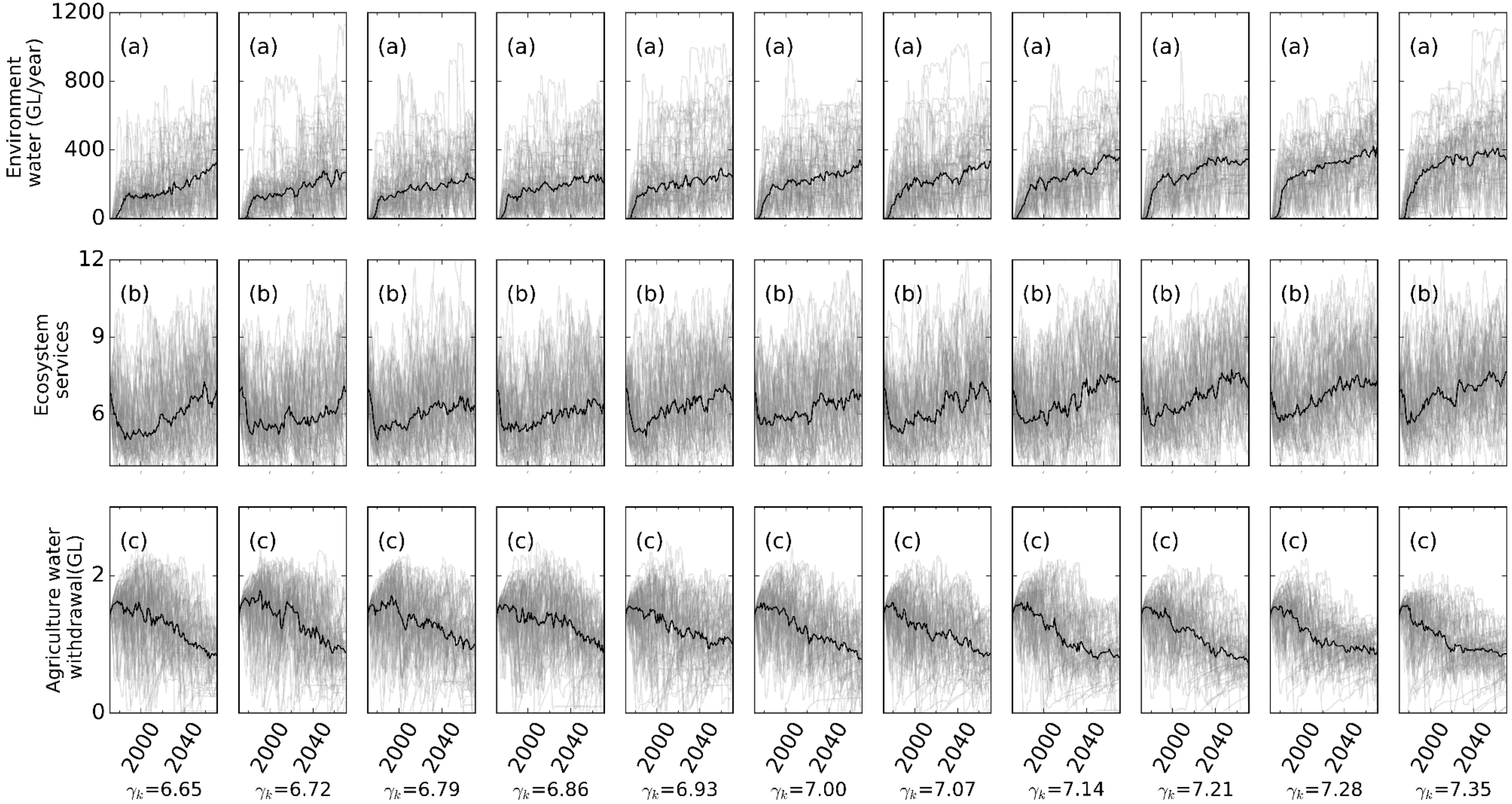


Figure 5.9: (a) Projected environment water, (b): projected ecosystem services, (c): projected agriculture water withdrawal trajectories when the outside economy grows at different rates (i.e. when the Australian capital growth rate is changed from 95% to 105% of observed capital growth rate). Gray color lines show the ensamples projections and black lines show the median of ensamples.

5.3.3 Importance of economic diversification for sustainability.

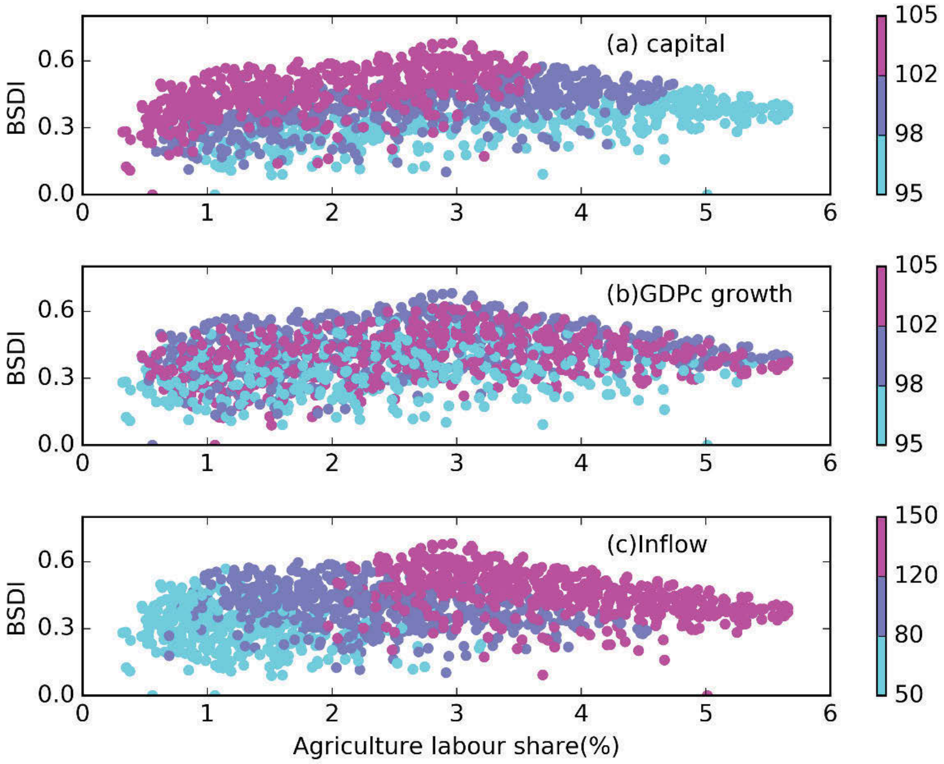


Figure 5.10: Relationship between sustainability (BSDI) and agriculture labor share (diversification) among all scenarios. (a) classified according capital growth rate (b) classified according to GDPc growth and (c) classified according to mean inflow. Range of classification is color coded in terms of low medium and high.

The previous sections showed how the basin's sustainability (Figure 5.6) varied in response to the three drivers (basin inflow, capital investment and Australian GDPc). Diversification of the basin's economy increased over the projected 100 years of non-stationary climate (basin inflow), basin capital investment and Australian GDP (see, for example, Figure 5.7a, b). The results of the preceding sections all related to a diversified catchment context. In this section we explore in more detail how economic diversification affects sustainable development. To do this, the BSDI was plotted against diversification for all scenarios and classified into 3 groups based on conditions of the external drivers. Figure 5.10 shows the BSDI plotted against agriculture labor share (indicator of diversification).

A smaller agriculture labor share indicates a more diversified economy (Figure 5.10a). The BSDI generally increases with a larger capital investment in the basin, supporting the findings arising from Figure 5.6. When the BSDI is classified according to basin capital growth, the spread of points is influenced by the other two exogenous drivers, i.e. GDPc and inflow). When more capital is invested, sustainability appears to decrease with diversification. This is because for given capital, inflow variability affects sustainability more than diversification.

When the GDPc growth rate is near observed levels (mid-range), sustainability is high (Figure 5.10b). This reiterates the earlier finding that for a diversified basin economy, *a more modest (observed levels) Australian economic growth* is better for sustainability.

Figure 5.10c is classified based on the inflow. High inflows are required to provide sustainability to the basin with lower economic diversity. Low inflows do not affect the sustainability of more diversified catchments as they are equally likely to have a low or high index. Moderate inflows provide medium to high sustainability for the basin where diversity is in the mid-range.

The effects in Figure 5.10 are not completely obvious. Climate cannot be controlled and for the benefit of insights that help the management of water, a relationship between sustainability index and agriculture labor share (i.e., diversification) was plotted for observed inflows while basin capital growth rate and the Australian economy was changed. When the agriculture industry’s labor share is low the basin is more diversified.

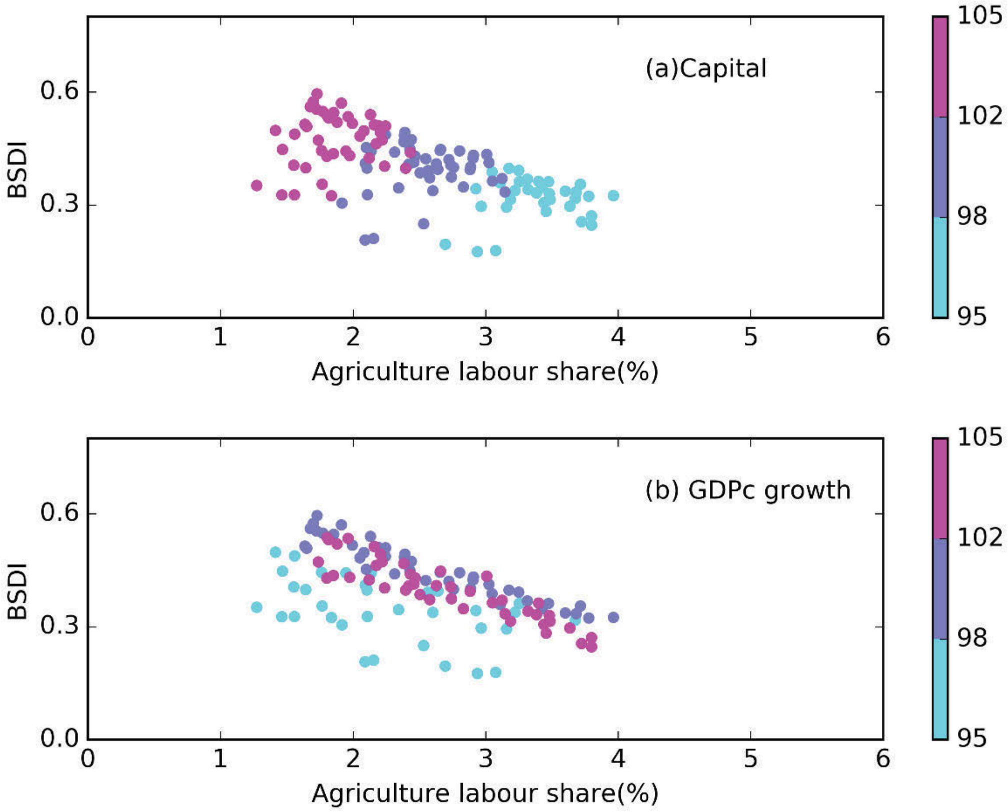


Figure 5.11: Relationship between BDSI (sustainability) and agricultural labor share (diversification) for given inflow. (a) classified according to capital growth rate (b) classified according to GDPc growth. Range of classification is color coded in terms of low, medium and high.

Figure 5.11 shows that *increasing diversification of the basin economy leads to sustainable development of the basin*. Figure 5.11a and b shows the influence of capital investment in the basin and Australian GDPc, respectively. Figure 5.11b indicates that the highest sustainability is achieved when there is moderate growth in Australian GDPc. All three ranges of GDPc display the same trend, i.e. increasing sustainability with economic diversification. This reiterates the earlier finding that sustainability is enhanced in a climate of moderate national economic growth.

Figure 5.11a classified according to capital investment in the basin also shows the same trend. However, this time the data appear in clusters. High capital investment growth rates create a more diversified economy and those data points cluster to the left of the plot, i.e. lowest agriculture labor share and therefore most diversified economy. In the same way mid-range and low-range capital investment create mid- and low-range diversified economies and these data points cluster accordingly on the plot. The trend in each cluster is the same, i.e. increasing sustainability with economic diversification.

When the basin is more diversified, society cares more about the environment and delivers water to the environment and at the same time, basin population grows with high employment in the industry sector.

This has implications for future planning. The basin's community can prepare for future sustainability by investing in economic diversification particularly during good times. This bodes well for sustainability when the economy worsens. We summarize:

- Diversifying the economy by investing capital in other non-agricultural economic sectors provide pathways for a basin to enjoy a sustainable future.
- Sustainability is enhanced in a climate of moderate (observed) national economic growth.
- Further, based on the preceding sections, when the *economy is diversified*, society manages water wisely. Noting that Australia is a land of floods and droughts, during periods of low basin inflows the ecosystem might suffer but it would not be as bad as what has happened in the past. During high basin inflows the consumption of water does not feed unsustainable economic expansion. Instead it is consumed in a measured manner commensurate with ecosystem requirements.

5.3.4 Basin reliability analysis

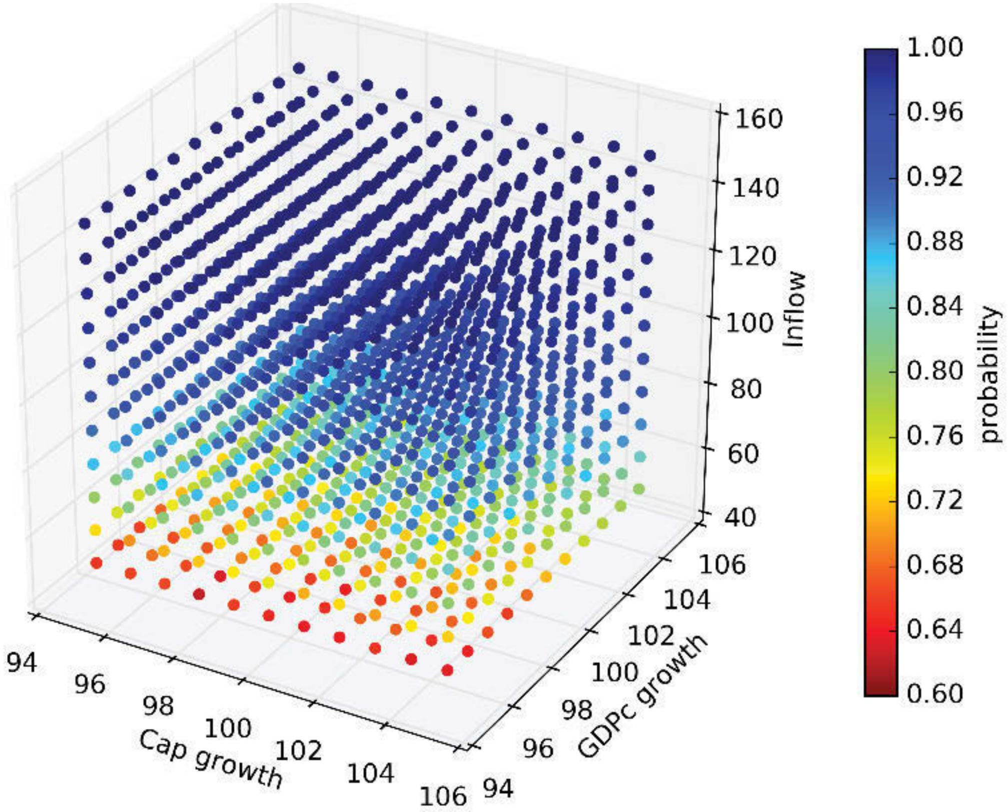


Figure 5.12: Probability of storage and inflow fulfilling socio-economic demands over a 100-year period.

This section describes how the *variability in external drivers* will affect the reliability of the system to meet the demands for water when the mean condition of external drivers changes. Figure 3.12 indicates the probability of satisfying water demand over 100 years of non-stationary climate (basin inflow), basin capital investment and Australian GDPc. Blue indicates that the system can more reliably meet the water demand and red represents less reliably.

Unsurprisingly higher inflow increases the system's reliability to meet the demand for water. At the other end, when the basin inflow is low, an increasing Australian economy (outside the basin) increases the system's reliability as smaller amounts of water are allocated to agriculture (Figure 5.9a). Furthermore, as the basin population migrates, the requirement for town water supply decreases, but in the Murrumbidgee region this component is small.

The reliability of meeting the basin's water demand declines when the economy outside the basin is weak (more people remain in the basin) and when the basin inflow falls (see Figure 5.12, lower half of diagram). When the Australian economy is weak relatively more water is allocated to agriculture (Figure 5.9c). This poses a threat to future development of the basin. Conversely, a strong Australian economy as mentioned previously, increases the reliability. An increase in the capital investment causes no notable change in the reliability of the system to meet the water demand.

5.4 Discussion and conclusion

Society's changing values and preferences concerning how water is managed and used and how economic stress and ecosystem stress can occur, add another dimension to the uncertainty of sustainable water management. Society's adaptive capacity and changing values and preferences create another unknown for water managers. 'Crystal balling' and finding possible alternative operating parameters is critical to maintaining or increasing the sustainability of society through good water management and avoiding system collapse. It is important to view the issues as a holistic canvass of complex problems with multiple feedbacks as this will inform emergent behavior of a coupled socio-hydrological system and provide a method of devising possible adaptation/ mitigation options that stakeholders can rely on. In addition, it also informs plausible trajectories of society in the future but also the possible collapse of the system. In this study, sustainability of basin development (BSDI), and reliability in terms of being able to meet the water demands for socio-economic activities under various external stresses were investigated. This was done under the assumption that society changes its values and preferences.

Dynamical system modelling which incorporates the socio-hydrology framework was used to account for stochastic non-stationary climate, growing economy and changes in community sensitivity. It shows possible basin development paths and exogenous conditions which could lead to sustainable basin development.

Modelling was carried out for 100 years for a non-stationary climate (inflow), growth of Australia's economy (GDPc) and growth of capital investment in a basin. The impact of changes under the mean conditions of external drivers to the sustainable development of this basin were collated in terms of the BDSI. It was derived from basin population, ecosystem services and employment rate (see section 5.2.3). The following phenomena occur for *diversified basins*:

- Diversifying the economy by investing capital in other non-agricultural industries provides pathways for a basin to enjoy a sustainable future.

- Sustainability is enhanced in a climate of moderate (observed) national economic growth.
- Society manages water wisely when the *economy is diversified*. Noting that Australia is a land of floods and droughts, during periods of low basin inflows when droughts are prevalent, an ecosystem might suffer but it would not as bad as what had been experienced in the past. Conversely, during high basin inflows the consumption of water does not feed unsustainable economic expansion. Instead it is consumed in a measured way that is commensurate with ecosystem requirements.

In terms of reliability, variability in the following conditions do occur for *diversified basins*:

- The reliability of meeting the basin's water demand is low when the national economy is weak. Conversely, a strong national economy increases the reliability as well as the overall demand for water.
- An increase in the capital investment leads to no notable changes in the reliability of the system to meet demands for water.

Society is generally a heterogeneous institution, but its values and preferences are influenced by their dependence on economic activity. Diversification of the economy, meaning a change from agriculture to industry shifts community values to ones where environment protection is emphasized. It also increases the system's sustainability by maintaining the balance between environment and economy. Increasing diversification by investing capital in industry sector leads to sustainable development.

To come up with a more generalized view of changing preferences of water use, it is important to understand the interaction of society and the factors that influence people's preferences and policy-makers' decisions. Much more research is needed here. The model results show that technology plays a major role in water management. Further studies are required to understand the benefits of increasing productivity by increasing capital investment in the basin and continued investment in technology development and implementation, both of which increase sustainability. It should be acknowledged that investment of capital and growth of the industry sector were assumed to exist at a constant rate. Incorporating a model for capital accumulation would provide a better picture that informs future basin water management.

CHAPTER 6

Conclusions and recommendations

6. Conclusions and recommendations

6.1 Conclusions

Risk related to water such as flood and drought have been modified by human action to support and continue many societies' continued advance. In risk analysis, human actions are treated as exogenous. This is questionable if reasonable predictions for future sustainable development are required. Socio-hydrology has been proposed as a method of treating human systems endogenously. Socio-hydrology imposes significant challenges in understanding the interaction between society and water systems because they are closely connected in many ways. How humans make decisions and the factors that influence decision-making related to water management are now important questions in socio-hydrology. Acknowledging that the prediction of an individual person's actions is very difficult, socio-hydrology attempts to predict the collective actions of a society.

This thesis investigated the role of economic diversification in reducing the adverse impact arising from changing water management systems and how economic transformation in one particular sector contributed to change of the wider society's values system as occurred at the Murrumbidgee River Basin. First, the impact of water management in a diversified economy was studied. It was observed that even though the change in water management curtailed agricultural employment, the basin's unemployment rate dropped and median household income increased. We first explored how this so-called "unemployment paradox" came about through data analysis. A simple dynamical model was built to reinforce our understanding and interpretation of the data. The unemployment paradox resulted from a growing industrial sector that facilitated sectoral transformation in the Murrumbidgee region and from migration to/from the basin as residents sought to improve their economic circumstances. The main contribution of Chapter 3 went beyond replicating the unemployment dynamics of MRB and in fact it highlighted the advantages of *economic diversification and the role of a strong national economy* in keeping basin unemployment low. It demonstrated how the model developed could become a learning tool to simulate alternative realities as outlined in sections 3.4.1 and 3.4.2. Through this study, it is found that an open, diversified economy could facilitate the introduction of unpopular measures such as reduced allocation of water to agriculture. Conversely, basins that do not have 'well' diversified economies might experience unfavorable economic conditions when: firstly, introducing policies to allocate water more sustainably between humans and the environment; or secondly, introducing unpopular water conservation measures. This is further exacerbated in weak economies. Such conditions may even discourage the introduction of sustainable water management practices such as giving water back to the environment.

Chapter 4 explored how the values system that drove collective human action in a heterogeneous society. The community sensitivity concept proposed by Elshafei et al. (2015) that simulates the values system was modified in this study. This study provided a rigorous validation of the community sensitivity concept, and further extended it to represent a distribution of values that change the basin's economic dependence on agriculture. It is suggested that the trade-off between economic well-being and environmental health at the community level depends on the distribution of individual beliefs that vary with contextual factors such as economic diversification. The model consequently explains the importance of sectoral transformation (or economic diversification) in changing beliefs and water management norms. The model was also able to capture the threshold dynamics between the two systems.

This study used numerous proxies unique to the Murrumbidgee River. The fish species richness (FSR) (Yoshikawa et al., 2014), served as a proxy for environmental health, to evaluate the ecosystem's health in river basins. It used endogenous time series of economic development (or the total irrigated area and irrigation water utilization) and depended on proxies for technology (patents) in validating endogenous concepts of norms and culture. While limiting its generalizations, a socio-hydrological model of this type can be a useful tool to assist in the debate on the future of agriculture along the Murrumbidgee River and elsewhere (eg. Lake Urmia in Iran). The information and insights that the socio-hydrological model provides can inform how communities transform in response to water reallocation, and open up different adaptation pathways.

The model that was developed for the purposes of investigation in Chapter 4 was further modified to explore the plausible futures for the Murrumbidgee River basin. In the future, the basin will be subjected to uncertain climate and economic conditions in which society and the water supply system will co-evolve. Modelling was carried out over a 100-year period for a non-stationary climate (inflow), growth of Australia's economy (GDPc) and rising capital investment in the basin. The impact of changes under the mean conditions of external drivers on the sustainable development of the basin was expressed in terms of the basin sustainability development index (BDSI), derived from the basin's population, ecosystem services, and employment rate.

Finally, there are major implications for future planning. The basin's community can prepare for future sustainability by investing in a more diversified economy and this is typically most easily done when the national economy is thriving. Doing this will bode well for the region's sustainability when the economy later recedes. This assumes the political system remains unchanged and community sensitivity thresholds are unchanged.

6.2 Recommendations for future studies

The following recommendations are made for future extension of analyses of this topic. Firstly, this study does not specifically address food security issues which are receiving more attention from policy-makers and decision-makers. As the population and economy grow the demand for food increases. In recent times, Australia despite being a traditional food producer is importing more food to satisfy people's demands. In this study, the agriculture industry and specifically employment in this sector were considered factors that influence community sensitivity. Agricultural imports into Australia increased following changes to water management in the mid-1990s (see Figure 6.1). What happens in a basin has knock-on impacts for other basins in a country, and when cumulated, do not remain localized but in fact can influence what happens in another country.

The MDB is the 'food bowl' of Australia, and the water management policies did give rise to increased food imports (see Figure 6.1). The diversified and relatively affluent economy of the Murrumbidgee Basin was able to afford improved environmental conditions by offsetting food production to other regions of Australia or further afield. Thus, improved conditions in that region may have led to increased water use or land conversion somewhere else. This is an important issue that is often neglected within such basin-level studies. The "pollutant heaven" hypothesis helps to understand this issue in the global context. It could be used in a future studies to understand sustainability in a global context so that the food security issue can be analyzed in in a way similar to Lambin and Meyfroidt (2011).

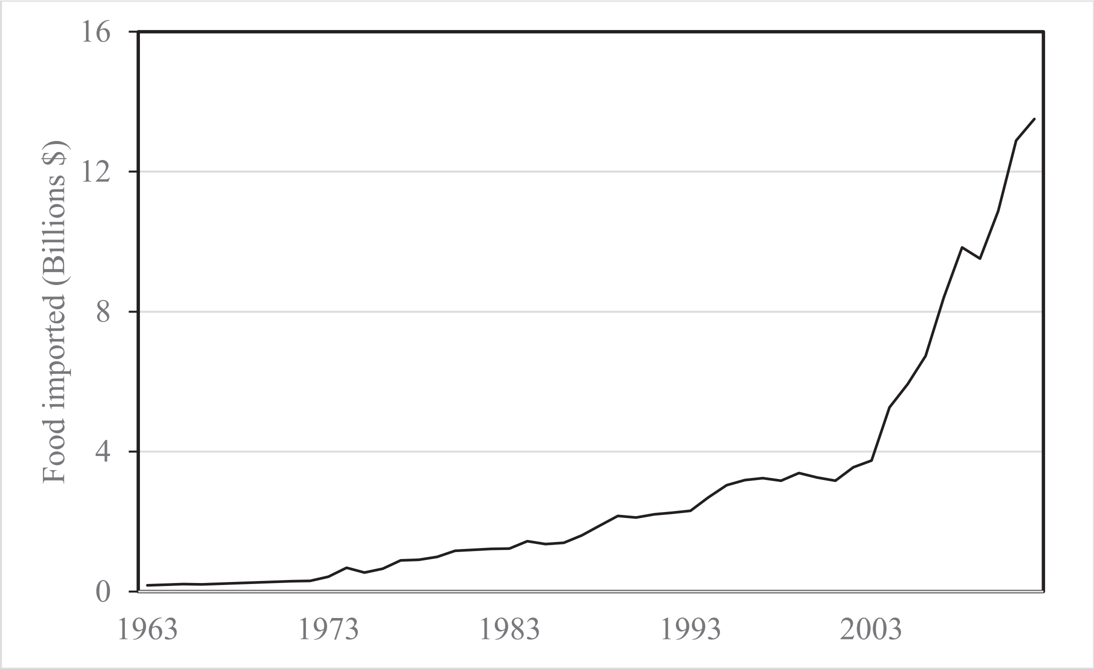


Figure 6.1: Increased imports of food to Australia coinciding with changes in water management.

Secondly, the capital growth rate was used to model the rate of employment in the agriculture industry. Futher study is needed to model the level of capital accumulation contributed by different sources (i.e government funds, foreign direct investment, loans from the World Bank, etc). This should be extended to make captial endogenous in the model.

In this study, the basin's economy was assumed to follow the same trend as the economy outside it. This simplistic assumption can be relaxed in the future by including: an economic sub-model that estimates production from the various industries in the basin as well as outside it; capital formation; and the gross basin product. All these points entail additional complexity to the model to improve how it should work in the real world.

Water withdrawals from the river for agriculture purposes have been modelled based on fixed water use per hectare, which in reality is influenced by the types of crops grown and the climatic conditions. Further research is recommended and it should include those factors in the modeling to improve the model simulation and predictions. This study used the concept of fish species richness (FSR) (Yoshikawa et al., 2014), as a proxy for environmental health, to evaluate the ecosystem's health in river basins. It depends on the annual flow in the river. It does not consider the seasonal variation of flow in the river nor does it consider the status of wetlands explicitly. Research on a more representative indicator of ecosystem services is needed.

When water allocation to agriculture was subjected to limitations in the mid-1990s, it was observed that farmers along the Murrumbidgee River moved from water intensive crops (i.e. rice) to less water intensive crops (i.e. grapes). Their motivation was to maximize their production and income in the face of cuts to water. It is recommended to include an endogenous crop diversification model to increase the predictability of future adaptive capacity of agriculture community.

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