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Systems thinking and modelling for sustainable water resources management and agricultural development in the Volta River Basin, West Africa

Julius Harrison Kotir

MRes, Environment and Development
MA, International Development Management
BA, Sound Production Technology

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The School of Earth and Environmental Sciences (SEES)

Abstract

It is well established that the conventional approaches to understanding and managing natural resource systems such as the traditional linear-reductionist and mechanistic approach founded on a positivistic understanding of science do not provide a sufficient framework for understanding the dynamic complexity and growing uncertainties inherent in most environmental systems. Dynamic complexity arises because such systems are: tightly coupled (components or drivers of the system interact with one another); governed by feedback; nonlinear; history dependent (making a choice precludes other options and determines the destiny); adaptive (decision rules change over time); counterintuitive (cause and effect are distant in time and space); and policy resistant. Despite the recognition of these complexities, there is still a lack of dynamic models that adequately integrate various physical, social, and economic factors and feedback processes that determine the current and future dynamics of most Social-ecological systems such as water resources management systems. There is, therefore, the need for an integrated system dynamics simulation model that adequately captures the non-linear interactions and feedback effects between the key system drivers to improve our understanding of the dynamic behaviour of water resource systems and evaluate the effects of different policy and management scenarios.

The overall aim of this research was to develop computer-based integrated conceptual, dynamic and simulation models that can be used to support decision-making for sustainable water resources management and agricultural development in the Volta River Basin in West Africa. To this end, a systems-based/systems thinking approach was used as the theoretical framework. Systems dynamics approach grounded in the relativistic, holistic/pragmatist philosophical or methodological paradigm provided an appropriate modelling tool to capture the relationships between the key system variables and their dynamic behaviour over time. Overall, a three-tied research plan (mixed methods approach) was employed. A comprehensive literature review, structured expert judgement/surveys and interviews were used to explore and identify the key system drivers, factors, and processes that influence the sustainability of the river basin system. A participatory modelling approach was employed where the system expert stakeholders from academia, NGOs, government, and private consultants were engaged in developing an integrated qualitative conceptual model that described the causal systemic feedback processes operating between the biophysical, environmental, and socio-economic drivers of the system. Based on the conceptual model, a formal quantitative simulation model was then developed using a system dynamics simulation approach, allowing different policy scenarios and strategies to be identified and tested. Besides the baseline or business as usual scenario, three additional policy scenarios were designed and simulated to explore

alternative futures, including investment in water infrastructure, an anticipation of water scarcity or dry conditions, and land or cropland expansion.

The results of the conceptual model showed that the feedback structure of the Volta River Basin is governed by of 21 feedback loops comprising: 14 reinforcing (positive) feedback loops and seven balancing (negative) feedback loops, indicating the complexity and dynamics of the system. These feedback loops revolve around the issues available ground and surface water resources, climate variability and change, population growth, soil fertility, crop yield, and poverty level. These feedback loops were quantified and simulated over a 50-year period (2000-2050) to understand the dynamic behaviour of the system. The results of the BAU scenario showed that agricultural water demand, water availability, crop yields, and net farm income increased until a peak is reached in the mid-2030, after which they remain in a state of equilibrium for the rest of the simulation period. Besides the baseline model run or Business as Usual (BAU) scenario, three additional policy scenarios were designed and simulated to explore alternative futures, including the development of water infrastructure (Scenario1), land or cropland expansion (scenario 2), and water scarcity or dry conditions (worse case, Scenario 3). Results from simulating a range of policy scenarios indicate that development of water resource infrastructure (e.g., construction of additional reservoirs or dams) is the best policy scenario that can contribute to sustainable water resource management and agricultural development within the basin.

Overall, the results of this study enabled a better understanding of the feedback structure and dynamics behaviour of the Volta River Basin water resource system under conditions of environmental and socio-economic change. Theoretically, the research contributes to the advancement of systems approach, including understanding interconnectivity and complexity, which until recently, has been dominated by the linear reductionist approaches. Practically, this research provides stakeholders and managers, from local farmers and NGOs, to policy makers with decision support tools in the form of an integrated conceptual and the simulation models for the sustainable management of water resource system at the basin scale. Methodologically, this is one of the few studies to apply systems thinking and system dynamics as a modelling tool to understand the dynamics of water resource management system in Africa, and, therefore, makes a significant contribution and sparks new research in this regard.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Publications during candidature

Peer-reviewed papers

Kotir, H.J., Brown, G., Marshall, N. and Johnston, R (2017). Drivers of change and sustainability in linked Human- Environmental systems: A case study of the Volta River Basin, West Africa. *Society & Natural Resources.* http://dx.doi.org/10.1080/08941920.2017.1290182

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Kotir, H.J, Smith, C., Brown, G., Marshall, N. and Johnston, R. (2016). A System Dynamics Simulation Model for Sustainable Water Resources Management and Agricultural Development in the Volta River Basin, Ghana. *Science of the Total Environment* 573, 444–457. http://dx.doi.org/10.1016/j.scitotenv.2016.08.081

Publications included in this thesis

This thesis contains three jointly authored papers (all fully published in international reputable journals). These papers are reproduced in full as chapters of this thesis (i.e., chapters 5, 6, and 7). I conducted most of the work in these papers including, conceptualising the work, designing the research, collecting data, analysing and interpreting data and writing the papers. The contributions of the co-authors are indicated below.

Kotir, H.J., Brown, G., Marshall, N. and Johnston, R (2017). Drivers of change and sustainability in linked Human- Environmental systems: A case study of the Volta River Basin, West Africa. *Society & Natural Resources.* DOI: http://dx.doi.org/10.1080/08941920.2017.1290182. (*Incorporated as chapter 5).*

Contributor	Statement of contribution
J.H. Kotir (Candidate)	Research design/conceptualisation (90%)
	Data analysis/interpretation (100%)
	Write/edit paper (80%)
Brown, G	Research design/conceptualisation (4%)

Contributor	Statement of contribution
	Write/edit paper (8%)
Marshall, N	Research design/conceptualisation (4%)
	Write/edit paper (6%)
Johnston, R	Research design/conceptualisation (2%)
	Write/edit paper (6%)

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Contributor	Statement of contribution
Kotir, H.J. (Candidate)	Research design/conceptualisation (90%)
	Data collection (100%)
	Data analysis/interpretation (80%)
	Write/edit paper (80%)
Brown, G	Data analysis/interpretation (20%)
	Write/edit paper (4%)
Marshall, N	Research design/conceptualisation (4%)
	Write/edit paper (6%)
Johnston, R.	Research design/conceptualisation (2%)
	Write/edit paper (4%)

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Contributor	Statement of contribution
Kotir, H.J. (Candidate)	Research design/conceptualisation (90%)
	Data collection (100%)
	Data analysis/interpretation (80%)
	Write/edit paper (80%)
Smith, C.	Simulation model development (20%)

	Write/edit paper (10%)
Brown, G	Research design/conceptualisation (4%)
	Write/edit paper (4%)
Marshall, N.	Research design/conceptualisation (2%)
	Write/edit paper (2%)
Johnston, R.	Research design/conceptualisation (2%)
	Write/edit paper (2%)

Contributions by others to the thesis

Chapter 1 – This chapter was solely written by the candidate with editorial assistance from Greg Brown, Nadine Marshall, and Ron Johnstone.

Chapter 2 – This chapter was solely written by the candidate with editorial assistance from Greg Brown, Nadine Marshall, and Ron Johnstone.

Chapter 3 – This chapter was solely written by the candidate with editorial assistance from Greg Brown, Nadine Marshall, and Ron Johnstone.

Chapter 4 – This chapter was solely written by the candidate with editorial assistance from Greg Brown, Nadine Marshall, and Ron Johnstone.

Chapter 5– This chapter is a replication of the paper entitled: *Drivers of change and sustainability in linked Human- Environmental systems: A case study of the Volta River Basin, West Africa.* The candidate conceived the idea for the chapter and collected all data with the help of research assistants. The candidate undertook the process of data analysis, interpretation, analysis, and results write. The candidate wrote the remaining manuscript with editorial assistance from Greg Brown, Nadine Marshall, and Ron Johnstone.

Chapter 6 – This chapter is a replication of the paper entitled: *Systemic feedback modelling for sustainable water resources management and agricultural development: an application of participatory modelling approach in the Volta River Basin.* The candidate conceived the idea for the chapter and conducted the fieldwork/participatory modelling workshop with the help of the system stakeholders. The candidate solely modified and models and wrote the manuscript with editorial assistance from Greg Brown, Nadine Marshall, and Ron Johnstone.

Chapter 7 – This chapter is a replication of the paper: *A System Dynamics Simulation Model for Sustainable Water Resources Management and Agricultural Development in the Volta River Basin,*

Ghana. The candidate conceived the idea for the chapter and collected the historical data. The candidate undertook the designed of the simulation models with the help of Dr Carl Smith and A/Prof. Ron Johnstone. The candidate wrote the manuscript with editorial assistance from Greg Brown, Nadine Marshall, and Ron Johnstone.

Chapter 8 – This chapter was solely written by the candidate with editorial assistance from Greg Brown, Nadine Marshall, and Ron Johnstone.

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Keywords

Africa; Agricultural Systems modelling; Drivers of Change; Participatory Modelling; River Basin; Social-Ecological System; System Dynamics Modelling; Systems Thinking; Volta River Basin; Integrated Water Resource management.

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FoR code: 0502, Environmental Science and Management, 100%

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List of Figures

List of Abbreviations used in the thesis

BAU   Business as Usual

CLD   Causal Loop Diagramme

CSIRO   Commonwealth Scientific and Industrial Organisation

FAO   Food and Agricultural Organisation

GIS   Geographical information system

GoG   Government of Ghana

GPRS   Ghana Poverty Reduction Strategy

HES   Human-Environmental System

IPPC   Intergovernmental Panel on Climate Change

Km^2 Square Kilometres

Km^3 Cubic Kilometres

MCM   Million per cubic metre

MOFA   Ministry of Food and Agriculture

MWRWH Ministry of Water Resources, Works and Housing

NGO   Non-governmental Organisation

SD   Systems Dynamics

SDM   System Dynamics Model

SES   Social-Ecological System

SFD   Stock and Flow Diagramme

SONA   State of Nation Address

SSA   Sub-Saharan Africa

UN   United Nations

UNEP   United Nations Environment Programme

VRA   Volta River Authority

VRB   Volta River Basin

VRBCM   Volta River Basin Conceptual Model

VRB-SDM Volta River Basin System Dynamics Model

CHAPTER 1: GENERAL INTRODUCTION AND THE RESEARCH PROBLEM

1.1. General Background – Global Change and Drivers of System Change

Variability and global change are realities of the Earth system and during the past few decades, there has been growing evidence that planetary-scale changes are occurring rapidly (Liu et al., 2015b; Steffen et al., 2005, 2015; Schimel et al., 2015). Indeed, change is one of the few reliable phenomena in coupled social-environmental systems (SES) (Adger, 2003). The critical feature of these global changes is described as 'directional', because it is characterised by a constant pattern over time (Chapin et al., 2009). They occur in both biophysical and socio-economic systems, and manifest across all levels – from local to global (Petschel-Held et al., 2005). Global change processes have dramatic effects and consequences for SES on which human communities depend. However, how societies respond to these changes can equally affect many managed natural resource management systems. To build a clear understanding, Anastasopoulou et al. (2009) argued that it is imperative to recognise the "agents or drivers" of those changes, which are a fundamental part of human existence.

The fundamental agents of environmental change that are external to a particular system can be considered as drivers of that change (e.g., climate change and socioeconomic change, national or international policy (Rounsevell et al., 2010). Drivers of change represent either the past, current or future conditions that modify the environment (Anastasopoulou et al., 2009; Rounsevell et al., 2010). Although some changes are caused by natural processes, it is widely argued that human activities (e.g., agriculture and the burning of fossil fuels) are the underlying forces driving change (Crutzen and Steffen, 2003; Steffen et al., 2005; Oldfield et al., 2014). During the past two centuries, anthropogenic actions have induced significant changes in many environmental systems (Steffen et al. 2005, 2015). According to Vallejo (2009, p. 13), "as early as the fourth century BC, Plato persuasively described extensive and insightful human impacts on forests: Hills that were once covered by forests and produced abundant pasture now produce only food for bees." The Sahara Desert was also described as a landscape of lakes and forest 7,000 years ago (Brown and Crawford, 2009). Several change phenomena are also caused by globalisation, described as the 'compression of space and time scales concerning the flows of information, people, goods and services' (Berkes, 2008). These processes and activities give rise to the phenomenon of global change (Steffen et al., 2005).

The influence of humans on the global environmental system is so profound and persistent that the Nobel Laureate Paul Crutzen observed that we are now in a geological age called the *Anthropocene* (Crutzen, 2003). Indeed, it is widely recognized that sustainability is the theme of our times and represents the greatest challenge in the *Anthropocene* (Wu, 2013). While the concept *Anthropocene* is manifested in the nature, scale, and magnitude of human activities in the world, its societal significance rests on how we can take advantages of the changes to inform future decision choices and actions (Bai et al., 2015). Indeed, understanding the *Anthropocene* calls for systematic thinking concerning the future, as both drivers and the concomitant consequences of human activities intensify towards an unsustainable trajectory (Steffen et al., 2015; Bai et al., 2015).

Against the backdrop of changing environmental and socio-economic conditions, decision-makers are confronted with the situation of whether to act reactively or proactively. Often, they consider these changes and challenges as simple problems. Occasionally, however, the change is large and complex, thereby limiting their ability to design sustainable solutions to address them. If this happens, decision-makers find ourselves to be facing an enormous problem, which can lead to far-reaching consequences for life support systems. Thus, the issue of rapid change has raised concern among scientists that several of the SESs present today could collapse by the end of the 21st century (Ostrom, 2007). The situation has, therefore, necessitated a focus on the identification of key drivers of change and the resulting system dynamics to consider if it is possible that existing societies will be able to avoid their own decline or demise (Polhill et al., 2016; Schimel et al., 2015). Consequently, there is an increase in socio-economic and environmental system analysis and modelling studies that seek to gain an understanding of the trends and drivers of change in natural resource systems in the context of a changing earth system. These generally aim to improve the theory and strategic management of problems inherent social-ecological systems (SESs). Thus, understanding the problem of global change and the associated drivers of change in social-ecological systems are urgent and relevant focus of this study. Further, given the increasing multiplicity of drivers of change associated with global change, there is a pressing need to develop an improved understanding of the interactive effects of multiple drivers, factors, and processes to better understand their responses to a changing environment.

The issue of global change and the associated drivers have resulted in fundamental transformations of many SESs such as River Basin systems around the world, including the Volta River Basin (VRB), which provides the case study context for this study. The VRB is an important trans-boundary river system (or 'catchment') in West Africa. As one of the 60 river basins in Africa, it supports the production of food, fibre, hydropower, and other products that are vital to West Africa's economy and the livelihoods of 25 million people who depend on the availability of the

water that flows through the river basin system. During the last four to five decades, demographic pressures, land use change, high rainfall variability, climate change, and the increased competition for land and water have combined temporally and spatially to affect sustainable water resource management and agricultural development within the river basin (Gordon and Amatekpor, 1999; Douxchamps et al., 2012). There is tension between the aspirations of socio-economic development and environmental sustainability. However, the management of any water resource system can be a challenging and difficult because of the complexities arising from the functioning of hydrological cycles and biological systems (Antunes et al., 2009). This is exacerbated when multiple stakeholder 'perspectives, interest, values and concerns regarding the use of water for human-related purposes (Antunes et al., 2009; Simonovic, 2009; Pahl-Wostl et al., 2012).

As is often the case in many SES or environmental systems, the most common approach to addressing problems in water resource systems is to adopt a linear, reductionist, analytical approach where the focus is on only one or a few factors or parts of the system, and to accept that those explanations can only be partial (Thompson et al., 2007; Simonovic, 2009; Pahl-Wostl et al., 2012; Liu et al., 2015b). However, the problems in most SESs, such as water resources systems are *systemic*, which means that biophysical and social systems are tightly interconnected and interdependent and cannot be understood in isolation (Simonovic, 2009; Pahl-Wostl et al., 2011, 2012; Gain and Giupponi, 2015). They cannot be comprehended within the fragmented methodology characteristic of academic discipline and government agencies. As Capra (1982, 1996) emphasised, such an approach will not resolve any of our difficulties, but will tend to shift them around in a complex web of social and environmental relations.

Indeed, a number of scholars have argued that conventional approaches to understanding and managing natural resource systems such as *equilibrium-centred, linear reductionist approaches*, *linear cause-effect methodologies* or a *command-and-control paradigm* (founded on positivistic understanding of science), do not provide a sufficient framework for understanding the dynamics and complexities inherent in most SESs (Van den Belt, 2004; Thompson and Scoones, 2009; Pahl-Wostl et al., 2011; Levin et al., 2013; Liu et al., 2015b; Sivapalan et al., 2015). This is because, many current sustainability problems and challenges are closely linked in ways that challenges conventional linear causality (Hjorth and Bagheri, 2006; Sterman, 2012). Conventional approaches have been critiqued because they provide quick fixes to sustainability problems, but the intended solutions often result in unexpected, and in some cases, disastrous, delayed consequences (Wang et al., 2011; Sterman, 2012). According to Bai et al. (2015), while a disciplinary and reductionist approach is crucial in promoting and understanding science, it has shown to be inadequate in

addressing complex societal issues characterised by uncertainties, multiple interrelationships between social and natural systems, and diverse spatio-temporal scales, overlaid with profound socio-cultural influences.

Further, conventional approaches that emphasise the importance of specific variables can de-emphasize the essential elements of SESs, including nonlinear events and change, emergent properties, and unanticipated system behaviour (Young et al., 2006; Pahl-Wostl et al., 2011; Schoon and Cox, 2012; Levin et al., 2013). Levin et al. (2013) argued that simple linear and reductionist thinking misrepresents how SESs function because they ignore fundamental characteristics of the underlying systems. Similarly, Kay et al. (1999) observed that dominant approaches on which much of the advice was given to decision and policy makers are based, have limited applicability. Likewise, reaffirming several scholars (e.g., Walker and Salt, 2006), Pollard and du Toit (2008, p. 672) underscored "that conventional linear thinking has not only failed to chart a sustainable path, but in many cases, it has actually contributed to the problem." Moreover, and perhaps more fundamentally, feedback effects and non-linear dynamics governing every environmental system have been identified as crucial attributes that influence systems resilience and sustainability through interaction (Pollard and du Toit, 2011; Cinner et al. 2011; Levin et at., 2013; Liu et al., 2015b; Steffen et al., 2015). However, not much attention has been given to understanding significant non-linear feedbacks effects that characterise the behaviour of many complex environmental systems (Kittinger et al., 2012; Schlüter et al., 2012; Sterman, 2012; Levin et al., 2013; Sivapalan et al., 2015). Yet, the recognition of those feedback processes, particularly in a water resource system is essential for improved quantitative and/or qualitative understanding of the long-term behaviour of complex water resource systems (Gohari et al., 2013; Sivapalan et al., 2015). Indeed, feedback processes have been understood to occur if changes in a particular part of a system to initiate changes in other aspects, which consequently, influences the part that initially started the change process (Hannon and Ruth, 2001).

1.2. Developing the Research Problem and Question

The problems in the management of natural resources or social-ecological systems, as described above, are currently prevalent in many river basin systems in the developing world, such as the Volta River Basin (VRB), West Africa. The Volta River Basin is one of the largest and most important river basins in Africa. It has a rich ensemble of various ecosystem goods and services, many of them are of global significance (UNEP-GEF Volta Project, 2013; Mul et al., 2015; Williams et al., 2016). Water resources play a pivotal role in the promotion of environmental

enhancement, economic growth, and poverty reduction in all the riparian countries of the basin (Lemoalle, 2009; Sood et al., 2013; UNEP-GEF Volta Project, 2013; Mul et al., 2015). However, since the 1980s, the sustainability and water resources management in the basin has been hampered by a plethora of challenges and rapid changes, including rapid population and urbanisation, land use change, growing demand for food; increasing demand for water for agriculture, domestic, and industries; high reliance on biofuels for energy; and rapid growth in livestock numbers (Barry et al., 2005; Lemoalle, 2009; Douxchamps et al., 2012; Gorden et al., 2013; UNEP-GEF Volta Project, 2013; Kolavalli and Williams, 2016).

In addition, poorly managed development, weak governance and institutional arrangements further complicate approaches to solving water problems of the basin (UNEP Volta Project, 2013). Further, new challenges related to climate change are expected to increase both the spatial and temporal unpredictability of rainfall and water availability to meet human needs (McCartney et al., 2012; Sood et al., 2013; Awotwi et al., 2015; Amisigo et al., 2014; Roudier et al. 2014). In the midst of these challenges, extensive rain-fed agriculture remains the dominant practice throughout the basin; but this is not able to meet the increasing food demands, leading to the importation of cereals such as rice, wheat, and maize (Willaims et al., 2016). Moreover, extensive agriculture leads to serious and often unanticipated socio-economic and environmental consequences.

Taken together, these problems are expected to exacerbate as standards of living grow, mining becomes extensive, and human activities are diversified (UNEP-GEF Volta Project, 2013). In fact, this situation is already leading to severe environmental degradation and frequent water shortages, which in turn, is resulting in declining agricultural productivity in terms of crop yields, dwindling incomes, and consequently, rising poverty levels among the inhabitants of the basin (Terrasson et al., 2009, Mul et al., 2015; Kolavalli and Williams, 2016; Williams et al., 2016). The increasing demands on the resources have resulted in intense competition among stakeholders, sectors, and countries (van de Giesen et al. 2001; Goa and Margolies, 2009; Mul et al., 2015). Indeed, there are profound environmental and socio-economic uncertainties associated with the current and future water supply and demand for various purposes in the Volta River Basin, particularly for agriculture, which is the main economic activity and determinant of regional development.

To solve the numerous problems, various traditional management approaches have been pursued since the 1960s, including soil and water conservation techniques through large scale projects, river diversion storages, small-scale irrigation, and small reservoirs, with the view to mitigating the water problem and enhancing food security and economic growth (CGIAR, 2013; Douxchamps et al.,

2012; Williams et al., 2016). Also, although most of the basin's inhabitants actually depend on agriculture and traditional livelihoods, most of the current and planned water-development projects for the Volta basin countries focus on the construction of large scale hydropower schemes such as the Akosombo in Ghana or the Bagré dam in Burkina Faso, essentially to mobilise water primarily for hydropower generation. This is particularly the case in Ghana, as evidenced by the recent completion of another large scale hydroelectric dam on the Bui Gorge. Many of these large-scale projects and initiatives are usually designed and funded based on the advice of foreign consultants and international development partners, who, in turn, have based their thinking on conventional engineering solutions. While these projects resulted in some technical solutions, many studies have concluded that their actual impact on livelihood security and poverty alleviation is minimal and contentious (Batterbury and Warren 2001; CGIAR, 2013; Douxchamps et al., 2012).

Indeed, in a review of the management strategies and approaches in the basin, Douxchamps et al. (2012, p. 17) drawing from Liniger and Critchley (2007) categorically attributed the failures of these water-related interventions to a number of factors: "they are planned in a relatively top-down manner, with experts as exclusive actors; projects were too shorts with "silver bullet" solutions; farmers preferences, values, and traditions were not taken into account (i.e., non-participatory); marketing of inputs and outputs were ignored; lack of corporations and alliances; and dearth of integrated and systematic analysis of measures and impact." Further, several studies and reports indicate that the development of decision support tools in the form of management models linked to the broader challenges of the basin continues to focus mainly on the hydrological and biophysical changes – the key socio-economic processes are rarely encompassed (de Condappa et al., 2009; Leemhuis et al., 2009; Lemoalle, 2009; UNEP Volta Project, 2013; Kolavalli and Williams, 2016). This, may further exacerbate the failure of many policies and management decisions to achieve enhanced food security, sustainable livelihood, and economic development (Williams et al., 2016).

These aforementioned concerns illustrate that several unsolved water planning and management problems remain in the VRB, and past approaches, based largely on the traditional mechanistic and compartmentalised approaches, no longer seem sufficient. Consequently, recent assessments have suggested that water resources planning and management for present and future generation in the basin, needs to take a holistic and integrated approach, where stakeholder interest and concerns are adequately considered; and both the critical environmental and socio-economic issues and their interrelationships concomitantly captured (Douxchamps et al., 2012; Gordon et al., 2013; UNEP Volta Project, 2013; Mul et al., 2015; Williams et al., 2016). In sum, actions to achieve food security and reduce poverty will have to be based on an *integrated* and *systemic* modelling approach and a collaborative decision-making process. From this perspective, the following important

question thus, arise: How can socioeconomic issues be integrated with biophysical issues to inform river basin planning and management?

The problems discussed and the ensuing question outlined earlier are complex planning and environmental management problems – so called "wicked problems" (Rittel and Webber, 1973). According to Balint et al. (2011, p.2) "a wicked problem is characterised by a high degree of scientific uncertainty and profound disagreement on values." Therefore, dealing with such complex problems requires a scientifically robust approach or analytical tool that embraces complexity. In the past 60 years or so, *systems thinking* or *systems approach* (Forrester, 1958, 1961; Senge, 1990; Sterman, 2000; Richmond and Peterson, 2001) with its concomitant concepts and tools such as feedback, stocks and flows, time delays, and nonlinearity has evolved as one of the most promising approaches to confront this complexity. Detailed discussion of the systems thinking approach is carried out in chapter 3. Nevertheless, to summarise briefly, systems thinking approach is based on the notion that sustainability problems need to be informed by a holistic consideration of the system processes (biophysical, social, and economic), their dynamic interaction, and how they adapt to diverse changes (Levin et al., 2013; Liu et al., 2015b). It challenges us to view the world as a complex system, in which we understand that "you can't just do one thing and that everything is connected to everything else." (Sterman, 2000, p. 4). A systems approach has arisen as natural resource managers have reflected upon the practical implications of being holistic in their analysis of complex environmental systems. In terms of its application and purpose, Laniake et al. (2013, p.8) aptly explained that a "systems approach is necessary to serve the decision makers' needs to understand the working system, compare impacts among decision scenarios, analyse trade-offs among options, ask 'What if?' questions, avoid the creation or transfer of problems in pursuing solutions to the problem at hand, adapt strategies based on future monitoring of the system, and respond to unintended consequences." The application of the systems approach to water resources management problems has been recognized as one of the most significant developments around water resources management (Simonovic, 2009).

As systems thinking framework advances, *modelling* has grown to become a powerful analytical tool for analysing and solving complex problems in many areas of scientific endeavour – thanks to the upturns in available computational power (Barnes, 1995; Silberstein, 2006). Modelling enables individuals to learn and experiment with systems to gain valuable insight into the way systems work, to identify and describe the structural relationships among important system variables, to create system outcomes, and to communicate outcomes in a transparent manner (Simonovic and Fahmy, 1999; Deaton and Winebrake, 2012). In addition to generating an understanding of the

behaviour of systems, models provide a means for testing data, to check for inconsistencies and errors, to fill in missing information, and to exploring alternative scenarios (Silberstein, 2006). According to Kelly et al. (2013), models are built to accomplish five main purposes, including, prediction, forecasting, management and decision-making under uncertainty, for social learning, and for developing system understanding/experimentation. The ultimate aim of model building in water resources management is to support policy analysis and evaluate the consequences of a particular policy option for improved decision-making (Simonovic and Fahmy, 1999; Simonovic, 2009).

In the context of natural resource management such as water resources planning, a systems approach is concerned with pursuing what can be described as an integrated environmental modelling (IEM) agenda, which is inspired by contemporary environmental challenges, policy-decisions, and facilitated by multidisciplinary science and computer capabilities – thus allowing the environment and its relationship to social systems and activities (i.e., social and economic) to be analysed as a complex integral whole (Laniak et al., 2013; Hamilton et al., 2015). A variety of dynamic modelling approaches or modelling tools have been developed and deployed to assist in the holistic and integrated analysis of complex environmental systems. Kelly et al. (2013) provided an excellent review of the five common modelling approaches, pointing out their strengths and weaknesses. These include: *systems dynamics approach, Bayesian networks, coupled component models, agent-based models, and knowledge-based models* (also known as expert systems). Generally, these are particularly effective in describing and gaining an understanding of the behaviour of complex systems in a dynamic and integrated manner.

In this study, a system dynamics modelling (SDM) approach (Forrester, 1958, 1961; Sterman, 2000), which operates in a whole-system fashion using feedback-based object-oriented simulation is applied to explain and gain an insight into the complex behaviour and feedback-effects between the key environmental/biophysical and socio-economic drivers, factors, and processes that determine the current and future dynamics of the Volta River Basin (VRB) water resource system in West Africa. The term 'dynamic' refers to changing over time (Barlas, 2007; Simonovic, 2009). Thus, system dynamics is applied here, because it provides an avenue to gain an insight into the behaviour of complex dynamical systems over time (Sterman, 2000; Simonovic, 2009; Ford, 2010). SDM approach is grounded in control theory and the theory of nonlinear dynamics (Sterman, 2000). It deals with "the time-dependent behaviour of managed systems as a means of describing the system and understanding, through qualitative and quantitative models, how information feedback governs its behaviour, and designing robust information feedback structures and control policies through

simulation and optimization" (Coyle, 1996, p.10). According to Kelly et al. (2013), system dynamics models (even in their conceptual forms) are valuable learning tools that can assist us to increase our understanding of systems, allows modellers and stakeholders to integrate diverse knowledge, and enhance important systems thinking. Following Simonovic (2009, p. 298), SDM approach was considered to be the most appropriate approach for modelling the dynamics in the Volta River basin because of: (1) its ability to address how structural changes in one part of a system might affect the behaviour of the system as a whole; (2) its ability to combine predictive (determining the behaviour of a system under particular input conditions) and learning (discovery of unexpected system behaviour under particular input conditions) functionality); and (3) the active involvement of stakeholders in the modelling process."

Several recent studies have used SDM approach to develop system dynamic and simulation models in various river basins around the world. For instance, SDM approach has been applied in Tunisia to develop an integrated simulation model for the Merguellil catchment (Sušnik et al., 2012); in the Aayandeh-Rud River Basin in Iran to analyse the potential of inter-basin water transfer and current and future water demands (Madani and Mariño, 2009; Gohari et al., 2013); within the Urmia Lake basin in Iran to simulate and examine the main factors which contribute to reduced water level (Hassanzadeh et al., 2012); in Lake Dianchi Yunnan Province in China to assess water quality and management and examine future development scenarios (Liu et al., 2015a); in the Shenzhen River catchment in Southeast China to study the dynamics of socio-economic and water management processes (Qin et al., 2011); within Las Vegas Valley in southern Nevada, USA to simulate and analyse the population dynamics and changing climatic as they affect water resources (Dawadi and Ahmad, 2013). SDM has also been used in the Colorado River Basin to evaluate the effects of climate change on the hydrologic regime and water resources (Dawadi and Ahmad, 2012). Other previous scientific publications that have used the SDM approach to simulated feedback between water use – based on expected population growth and water availability at the River-basin scale include: Xu et al. (2002) for the Yellow River Basin, China; Tidwell et al. (2004) and Passell and Assembly (2003) within the Middle Rio Grande River basin, USA; Langsdale et al. (2007) for the Okanagan basin, Canada and; Ahmad et al. (2009) for the Murrumbidgee River Catchment, Australia.

The diversity of applications of the SDM approach at the river-basin scale has led to an improved understanding of the dynamic behaviour of various river basins as well as to the rapid advancement of the approach. Despite these efforts, there is still a lack of dynamic models that adequately integrate various biophysical, socio-economic factors and feedback mechanisms that determine the

current and future behaviour of river basins/water resources management systems (Green et al., 2011; Sušnik et al., 2012; Johnston and Smakhtin, 2014). In particular, most current studies are predominantly limited to river basins in Europe, North America, and Australasia. Thus, comparative model-based studies based on systems thinking and SDM approach in Sub-Saharan Africa is sparse. Additionally, a global-scale studies have been able to provide adequate insight into the complex dynamics of linked social-ecological systems, particularly at the river basin level (Chang et al., 2013). Further, SDM approach is dichotomised into qualitative conceptual and quantitative/numerical modelling methods and tools (Wolstenholme, 1999; Coyle, 2000; Sterman, 2000). However, recent reviews indicate that most system dynamics applications have not made adequate use of qualitative/conceptual modelling tools (Mirchi et al., 2012; Laniak et al., 2013). Moreover, in many of the existing studies, there were no participation stakeholders in the model development process. Yet, many scientists and experts have concluded that integrating stakeholder knowledge and their intrinsic mental models in environmental management and modelling is crucial, as it adds flexibility to the problem solving process and knowledge diversity, which in turn, helps to minimise model rigidity, accommodates multiple perspectives, promotes social learning, and promotes adaptability in policy decision-making (Voinov and Bousquet, 2010; Videira et al., 2010; Hare, 2011; Krueger et al., 2012; Voinov et al., 2016).

This research, thus, seeks to contribute to bridging the existing knowledge gaps and complement the noteworthy efforts of the prevailing researchers in the context of the Volta River Basin in West Africa, where as described earlier, the problems are complex, yet they are being managed based predominantly on conventional disciplinary, reductionist, and compartmentalized approaches. In doing so, the research is rooted in the systems thinking approach, which provided the theoretical framework and the analytical, methodological, and modelling tools to holistically explore and capture the important processes and their relationships shaping the basin's behaviour over time. Although system dynamics and simulation models can serve as predictive tools (Davies and Simonovic, 2011; Kelly et al., 2013), their application in this study relates to social learning to enhance our understanding of the basin's structure and dynamic behaviour and as it responds to changing socio-economic and environmental conditions and system drivers.

1.3. Research Aim and Objectives

Based on the challenges and the knowledge gaps earlier discussed, the overall aim of this research is to develop a computer-based integrated conceptual, dynamic and simulation model that can be used to support decision-making concerning sustainable water resources planning and management

and agricultural development in the Volta River Basin of Ghana, West Africa. To achieve this aim, three distinct research objectives based on the three research questions stated earlier, were formulated and, subsequently, addressed:

1. To explore and identify the key biophysical and socio-economic drivers and factors that influence sustainable water resource management and agricultural development in the Volta River Basin. This was achieved through a review of the key drivers of change and processes that have been identified as influencing water and agricultural sustainability at the River Basin-scale within developing countries and assessing the relevance of these those drivers using expert structured expert judgements, surveys, and interviews (*Chapter 5 - Paper I*).

2. To develop an integrated qualitative/conceptual system model that captures the systemic feedback loops, processes and structures governing the system behaviour and their implications for current and future water resource management agricultural development. This was achieved by integrating the key system drivers and processes identified in objective 1 and involving the system stakeholders (i.e., via participatory modelling approach) in the conceptual model development process using Causal Loop Diagrams (CLDs) as analytical tools (*Chapter 6 - Paper II*).

3. To develop a formal integrated system dynamics simulation model that allows for different policy scenarios and strategies to be evaluated over time. This was achieved by quantifying and simulating the important feedback loops identified in objective 2 using quantitative historical biophysical and socio-economic data collected from secondary sources with the aid of system dynamics computer-based simulation tool (*Chapter 7 - Paper III*).

It is envisaged that addressing research objective 1 will generate scientific knowledge on the on the current state of the basin and the ongoing socio-economic and environmental processes that influence sustainable water management and agricultural development. This is important because, as Kolavalli and Willaims (2016) argued, these dominant trends in the basin will concurrently lead to new opportunities and complex challenges that will need to be considered in the future formulation and implementation of policy. Answers to research objective 2 will hopefully lead to an improved understanding of the complex non-linear feedback structure and dynamic processes inherent in the river basin system. Finally, addressing objective 3 through dynamic simulation may provide an understanding regarding the dynamic behaviour of the important system variables and their dynamic behaviour over time, allowing the identification of the best policy scenarios and

strategies necessary to achieve long-term sustainable water resource management and agricultural development.

It is important to stress that the model is not developed to capture the physical hydrologic system justifiable by developed world standards. Rather, it was constructed based on the indigenous/traditional knowledge and the mental models of the local stakeholders, considering the prevailing changes in the main socio-economic and environmental conditions and processes in the basin. Nevertheless, the simulation model made use of published scientific data and knowledge of scientists (i.e., scientists with western training) to ensure sufficient rigour and accuracy in the model's function and outputs. In this respect, the model is distinguished from other models by placing emphasis on a balance between scientific and non-scientific knowledge sources (Petschel-Held et al. 2005; Perera et al., 2012). Further, the model is not purely a physically based hydrologic model as in numerous developed models in the basin (e.g., de Condappa et al., 2008), Leemhuis et al., 2009; Jung et al., 2012; Amisigo et al., 2015; Awotwi et al., 2015), neither is it an exclusively socio-economic model. Rather, it is a coupled population-economic-hydrologic dynamic model. Ultimately, the model is developed with the intent to provide an effective, locally relevant approach for the integration of stakeholder values and preferences into a dynamic system framework. The core hypothesis is that, by doing so, the research will provide a significant value for the future uptake of this approach in developing countries such as those in Sub-Saharan Africa.

Methodologically, the research is grounded in the relativistic/holistic and pragmatist (i.e., the *pragmatic realism)* philosophical paradigm. Based on this paradigm, *three-tiered research plan* within a mixed-methods research strategy was deployed comprising: *structured expert judgement/interviews, participatory modelling based on casual loop modelling (diagramming),* and *system dynamics simulation modelling approach.* See chapters 4 for the detail discussion on overall methodology. The specific research design and strategies are, however, detailed in chapters 5, 6, and 7 along with justifications for their used.

1.4. Study Context: The Volta River Basin

The Volta River Basin is the 9th largest in sub-Saharan Africa. It occupies an area of about 400,000Km^2 within the sub-humid to semi-arid West African savanna zone (Figure 1.1). It extends approximately between latitude between latitude $5^0.30$ N–14^0 30 N and between $2^0.00$ E and $5^0.30$ W. The widest stretch is roughly on longitude 50 30 W to 20 00 E; however, it becomes narrower as it enters the sea (the Atlantic Ocean) at the Gulf of Guinea (Barry et al., 2005; Gordon et al., 2013). It is a trans-boundary river basin shared among 6 riparians West African countries: Burkina

Faso, Ghana, and Togo, Benin, Cote d'Ivoire, and Mali, making it an ethnically and culturally diverse basin. Table 1.1 shows the distribution of the area of the basin between the six riparian countries, which are independent in terms of water and other natural resources utilisation and management (Williams et al., 2016). Burkina Faso and Ghana make up approximately 90% of the total area of the basin and occupying a distinctive upstream–downstream formation (Bhaduri et al., 2011). The river itself has a length of approximately 8, 242.8km. A significant portion (about 80%) of the basin is in the Savannah, and has largely a flat landscape, with elevations below 1000m (Oguntunde et al., 2006).
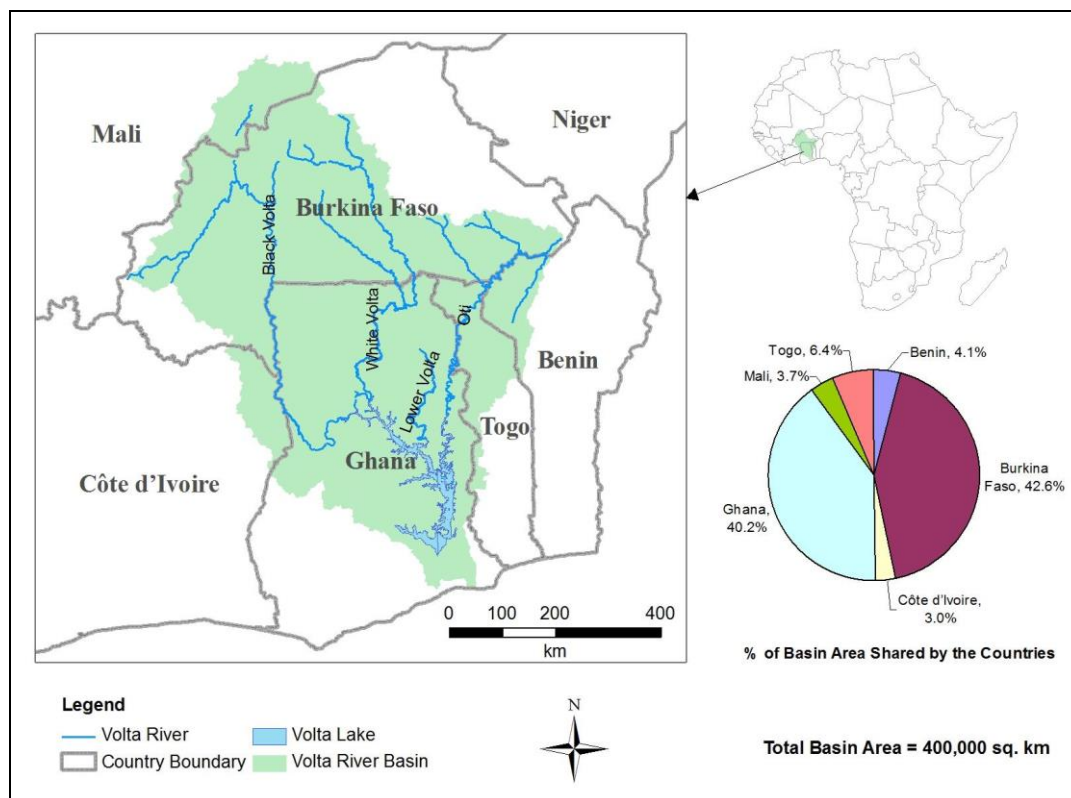
Figure. 1.1. The Volta River Basin showing important political boundaries (Gao and Amy Margolies, 2009)

Table 1.1: The distribution of the area of the basin among the six riparian countries

Country	Area of the Volta River Basin (Km²)	% of Basin	% of Country in the basin
Benin	17,098	4.10	15.2
Burkina Faso	178,000	42.65	63.0
Cote d'Ivoire	12,500	2.99	3.9
Ghana	167,692	40.18	70.0
Mali	15,392	3.69	1.2
Togo	26,700	6.40	47.3
Total	**417,382**	**100%**	

Source: Barry et al. (2005)

The basin is sub-divided into smaller basins belonging to its three major tributaries consisting: Black Volta, the White Volta, and the Oti river basin. The Black Volta drains a land area of about 146,820Km² and donates about 18% of the annual flows to the Volta Lake; the White Volta covers

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an area of 105,540Km^2 and contributes about 20% of the annual flows of the Volta River system; while the Oti river basin drains an area of 71,940Km^2. However, the network of the Volta River System within the area of Ghana occupies approximately 70% of the total land surface of Ghana (Gordon et al., 2013). The basin contributes about 25% of the annual flows in the Volta River system. Surface water is received from both outside and within the country, with about 54% of the flows of the tributaries coming from outside the country of Ghana (Gordon et al., 2013). Mean annual rainfall varies across the basin from approximately 1600mm in the south-eastern section of the basin in Ghana, to as low as 300-700mm/yr in the northern parts of Ghana and Burkina Faso (Barry et al., 2005; Martin and Van De Giesen, 2005; Wagner et al., 2006; Youkhana and Laube, 2006; Gordon et al., 2013). In the Southern part of the basin, there are two rainy seasons with peaks in June/July and September/October, whereas, in the Northern portion, there is only one wet season, from May through November, with peak rainfall occurring in September (Rodgers et al., 2007a).

However, the amount of rainfall generally exhibits extensive spatial and temporal variability, and unreliable precipitation patterns, which make rain-fed agriculture a risky undertaking throughout much of the basin (Rodgers et al., 2007). Thus, river discharge is sensitive to variations in annual rainfall, with a ±10% change in annual rainfall leading to about ±40% change of river discharge (Lemoalle, 2009). Climatic patterns are strongly influenced by the movement of the Inter-Tropical Convergence Zone (ITCZ), which generates unimodal rainy season in the northern part and bimodal distribution in the Southern part, close to the Gulf of Guinea (Youkhana and Laube, 2006; Lemoalle, 2007; Rodgers et al., 2007). The mean annual temperatures in the basin vary from about 27–30°C. Daily temperatures can rise as high as 32–44°C and as low as 15°C in the night (Gordon et al., 2013). Generally, in Ghana, the average temperature rarely goes below 24°C (Barry et al., 2005).

The basin's population stood at 23.8 million in 2010, however, this is expected to reach 56.1 million by 2050 (Williams et al., 2016). The spatial distribution of the population within the basin varies with an average population of about 58 persons/km^2; however, this average masks differences between riparian countries (Kolavalli and Williams, 2016). Over 90% of the Volta River Basin population resides in Ghana and Burkina Faso (Martin and Van De Giesen, 2005). The basin's population is heavily dependent upon the land resources of the region for subsistence agriculture and livestock production. This results in both environmental and economic challenges. The predominant land use types are Guinea Savannah in the southern and Sudan savannah in the northern part (Wagner et al., 2006). Changes in the availability of water across the basin have socioeconomic and cultural impacts (Mul et al., 2015).

A major industrial development of the basin is Akosombo Dam, which plays a vital role in the economy of Ghana, although revenue has been less than expected (Lemoalle, 2009). The Akosombo Dam was constructed in the early 1960s to mainly provide electricity for Ghana and its neighbouring countries, although it delivers supplementary services for irrigation, livestock watering, fishing and domestic purposes (Douxchamps et al., 2012). Its construction led to the formation of the Lake Volta, which, up until the construction of the three gorges dams in China, was considered the largest man-made lake in the world (UNEP Volta Project, 2013). It has a surface area with an area of 8,500 km^2 (i.e., 4% of the total area of Ghana), a shoreline of about 4,800km^2 and a storage capacity of 152 billion km^3 at full supply level (Gordon and Amatekpor, 1999; Andah et al., 2003; Barry et al., 2005). Major water management issues focus on surface water resources. Groundwater is relatively abundant, but it is difficult to mobilise to satisfy the well-being of people. Surface water, thus contributes significantly to livelihoods and food security across the basin. Surface water in the Volta River Basin is subject to three main competing uses, including, agriculture, domestic, and industrial water demands. However, agricultural/irrigation constitutes the major user of water within the basin, particularly in Burkina Faso (Barry et al., 2005; Mul et al., 2015). Generally, irrigation is still very little developed in the Basin, covering less than 0.5% of the cultivated area. There has some production increase in the last decade, but most of the increases came more from an increase in the cropped area than from increased productivity (Lemmoalle, 2009; Kolavalli and Williams, 2016). In general, the agricultural sector development has not kept pace with the Comprehensive Africa Agriculture Programme's (CAAP) 6% goal for African countries (Williams et al., 2016).

Existing infrastructure developments to manage water resources, such as the Akosonbo dam in Ghana and Bagre Dam in Burkina Faso, and many other environmental and demographic factors have already impacted on the hydrological cycle at both upstream and downstream ends of the basin, posing a potential threat to the future sustainability of the resources if not managed appropriately. For example, McCartney et al. (2012) report that following the construction of the Akosombo Dam, there has been a dramatic decline in agricultural productivity along the lake and its tributaries. Similarly, within the upstream area, UNEP Volta Project (2013) noted that 80,000 people were displaced at the time of the dam construction, with a substantial loss of arable lands and forests. In more recent years, floods have been more recurrent, due mainly to the operation and management of dams and reservoirs, which in turn, have led to trans-boundary challenges (Mul et al., 2015). However, water shortages are more common, owing to the reduction in precipitation, drying up of some streams and wells in several communities, decline in river flows, dwindling water tables, a rise in the volume of evapotranspiration (attributable to the construction of thousands

of large and small reservoirs in the basin), which in turn, is caused by climate change, and inefficient use of water resources (Goa and Margolies, 2009; Mul et al., 2015). Several socioeconomic trends also suggest that the demand for, and the pressure on, the basin's natural resources are likely to likely to increase in the coming decades (Gordon et al., 2013; UNEP-GEF Volta Project, 2013; Kolavalli and Williams, 2016).

The two dominant countries in the basin – Ghana and Burkina Faso – both aspire to increase their large reservoir storage, primarily to meet their increasing energy demand by generating hydroelectric power (McCartney et al., 2012). In Ghana, the focus is on hydropower development, while in Burkina Faso, the basin's water resources are considered as a source of irrigation (Andreini, et al., 2001). To date, water resources planners across the basin have not been able to strike a critical the critical balance between water resources and their multiple uses at the national and local levels.

From the foregoing, it is apparent that the challenges facing the Volta River Basin are highly complex and cannot be treated independently from one another. Indeed, the behaviour of the Volta River Basin is typified not by stable equilibria, but by strong non-linearities, in which relatively small changes in an imposing fashion can push the system across a threshold leading to abrupt changes in the critical aspects of the system functioning (Steffen et al., 2004). The main challenge is how to manage the natural resources of the basin to improve food security, reduce poverty and promote economic development, without further degradation of the natural ecosystems for present and future generations (Kolavalli and Williams, 2016). Policy makers in the past have struggled with the problem of estimating water demand with supply uncertainties (Bhaduri et al., 2011; UNEP Volta Project, 2013; Williams et al., 2016). Yet, they are required to anticipate how to adapt management practices and infrastructure development for some future state of their water resource systems (Mul et al., 2015). As Johnson and McCartney (2010) underscored, planning water management and infrastructure requires not only insight into impending needs, but also a good understanding of what already exists and what was, and was not successful in the past. Further, with rapidly increasing demand for water for various purposes demands, water supply will be severely stretched and environmental and socio-economic problems are likely to increase.

According to Kolavalli and Williams (2016), the goal of agricultural policy for the basin since the 1980s has been to feed a rapidly growing population and reduce environmental degradation; however, the policy has been devoid of a comprehensive analysis of the trends being observed and has not responded rapidly enough. This cogent observation calls for an integrated water resources

model linking local livelihood and agriculture production, demographic changes, water supply and demand in the Volta River Basin and how their interaction help to informed policy making and sustainable water resources management. To accomplish this objective, a robust and holistic approach that allows planners and managers to seek sustainable solutions, and make long-term forecasts and projections as needed. Thus, the system dynamics approach based on the notion of systems thinking provides the appropriate approach and methodological tools for such an integrated and robust analysis.

1.5. Boundaries and Scope of the Study

According to Etwart et al. (2009, p. 547), "a system typically comprises elements, borders, relationships among elements and other systems." The drivers of change of any linked SES, such as those in the Volta River Basin operate and interact at diverse hierarchical scales (proximate and underlying) and at distinct spatial scales (i.e., local, regional, national, global) and temporal scales (Nelson et al., 2006; Kittinger et al., 2012). An understanding of the trajectories of these driving forces necessitates a temporal and spatial perspective. Thus, boundary or scalar issues are paramount in complex systems research. In coupled SESs analysis, defining a study area also encompasses selecting a scale/boundary of analysis by drawing artificial boundaries around it (Schröter et al., 2005). These boundaries, consisting of *spatial* scale (e.g., a catchment or region) and *temporal* scale (e.g., over 5 or 50-year period), consist of what may be labelled the 'focal system' (Resilience Alliance, 2010).

In addition to providing a common setting in which all biophysical and socioeconomic processes function (Agarwal et al., 2002), spatial and temporal scales also prescribe the level of detail for the data collection effort (Stoorvogel et al., 2004). The place and time scale selected then becomes the focus of the study, with an understanding that processes at smaller and larger scales, in addition to historical and future trajectory, are crucial for gaining adequate insight into the sustainability of natural resources systems (Schröter et al., 2005). However, the characterisation of the system under study in terms of its spatial and temporal scales (extent and resolution), its boundaries and constituents will rest mainly on the nature of problem, the goal of the study, and the challenges of constraints of procuring the required data (Xu et al., 2002; Ewert et al., 2009), such as the ones discussed above. As with the equilibrium point of view, spatio-temporal resolutions depend on the nature of the challenge (Pendall et al., 2010). It, therefore, follows that the results of any analysis or modelling will depend explicitly on the choice of the study area, context, spatial-temporal scales of the system of interest and the goal of the study.

It must, however, be pointed out that establishing boundaries for complex systems analysis is sometimes a challenging endeavour as there is always an input and output crossing the boundaries of the system (Sevaldson, 2008; Ewert et al., 2009). For example, as one is dealing with an open system, some understanding is unavoidably lost through the neglect of interactions across boundaries (McAllister et al., 2006). Indeed, in the real world, a boundary does not exist, but it is often perceived as a concept, which enables researchers to make sense of reality and will have a major influence on the model design and the ensuing product (Allison, 2003). These caveats, notwithstanding, it is imperative to construct boundaries and scales to focus the analysis, and thus, justify (or exclude) certain issues and levels (Molle, 2007). Also, the establishment of boundaries is necessary for a simpler, more tractable, and more feasible approach (Robinson et al., 1994) to the phenomenon under investigation. As Carpenter et al. (2001) suggest, scaling or boundary issues can be partly be addressed appropriately "bounding" social-ecological systems.

Thus, given the size, the diverse and transboundary nature of the system under study (i.e., The Volta River Basin) and the complexity of the issues confronting it, it would not be feasible to study or model the basin entirely. It is, therefore, necessary to establish boundaries or a scale for the analysis and allow for robust results that are appropriate and useful to managers. Each time a researcher/modeller selects a boundary, she/he is making decisions about what to include in her/his model/analysis and, whether the variables chosen are to be endogenous, exogenous or environmental factors (Allison, 2003, 2006; Pendall et al., 2010). Accordingly, the *temporal* period, also known as 'reference mode of behaviour' in system dynamics parlance (Sterman, 2000; Van den Belt, 2004; Maani and Cavana, 2007;) for this study has been taken as 50 years, starting from the year 2000 through to 2050. The justification for the choice of this time period is that most socio-economic data and information rarely go back further than 50 years, especially in developing countries, while environmental information (e.g., land use/cover, vegetation data) have similar time limitations (Biancalani et al., 2011). Additionally, biophysical data and information (e.g., climate change data) tend to mirror longer term conditions in many natural resources systems (Troyer, 2002). Finally, environmental and socio-economic processes in SES systems evolve over time, so the time scale chosen determines which drivers are identified (McAllister et al., 2006).

On the other hand, the spatial boundary is the Ghana side of the basin and its agro-ecological zones (i.e., the downstream country of the basin), owing to several reasons. First, the focus on this scale is due to pragmatic reasons as well as time and budget constraints. Second, the concentration on this part of the basin was informed by data availability and accessibility, especially gaining access to stakeholders who played a pivotal role in the development of the model. Third, the Ghana part of the basin was selected for the modelling, because the important biophysical and socio-economic

data required for the study are relatively accessible, and partly because from the analytical point of view, the relationship between economic development and water resources management in Ghana seems relatively apparent (Barry et al., 2005). Ghana has the more reliable and more readily available datasets, permitting the systematic analysis across a large river basin. Finally, as compared to the riparian countries, Ghana, the downstream country, has over the years been the more active in terms of the development of major projects that have resulted in significant impact on the basin's water resources and the excessive consumption, utilisation of the water resources (Barry et al., 2005; McCartney et al., 2012; Mul et al., 2015). There are also further ambitious plans by Ghana to build more dams on the Black, Oti, and White Sub-basins, which will potentially have significant impact on the sustainable management of the basin's resources in the coming future (McCartney et al., 2012).

1.6. Outline of the Thesis

As depicted in Figure 1.2, this thesis is structured into 8 chapters that interact to produce a final set of insights and conclusions. Chapter 1 provides the general background introduction, the research problem, the research aim and specific objectives, and a description of the study context − in this case, the Volta River Basin. Chapter 2 reviews traditional approaches to researching and managing natural resource and environmental systems; specifically, the *linear-reductionist thinking, equilibrium centred approach, and command-and-control strategy*). The key argument underpinning this chapter is that, these linear approaches are not sufficient, and if at all, they offer limited answers to questions central to managing and researching complex systems natural resource management systems such as the Volta River basin.

Thus, in chapter 3, the contemporary system- based approaches the *coupled social-ecological system perspective,* and *complex systems thinking approach* − and their conceptual and practical values are discussed and proposed as the theoretical framework for this study. Chapter 4 builds on the preceding chapters and provides an account of the overall research design and the overarching methodology. Chapters 5 to 7 comprise the empirical base of the research presented as individual papers (i.e., journal articles), all of which have been published in international peer-reviewed journals. Specifically, chapter 5 (*paper I*) explored and identified the main biophysical and socio-economic drivers of change within the Volta River Basin, and assessed their relative importance in relation to sustainable water resource management and agricultural development, particularly food and livelihood security, and in general, socioeconomic development.
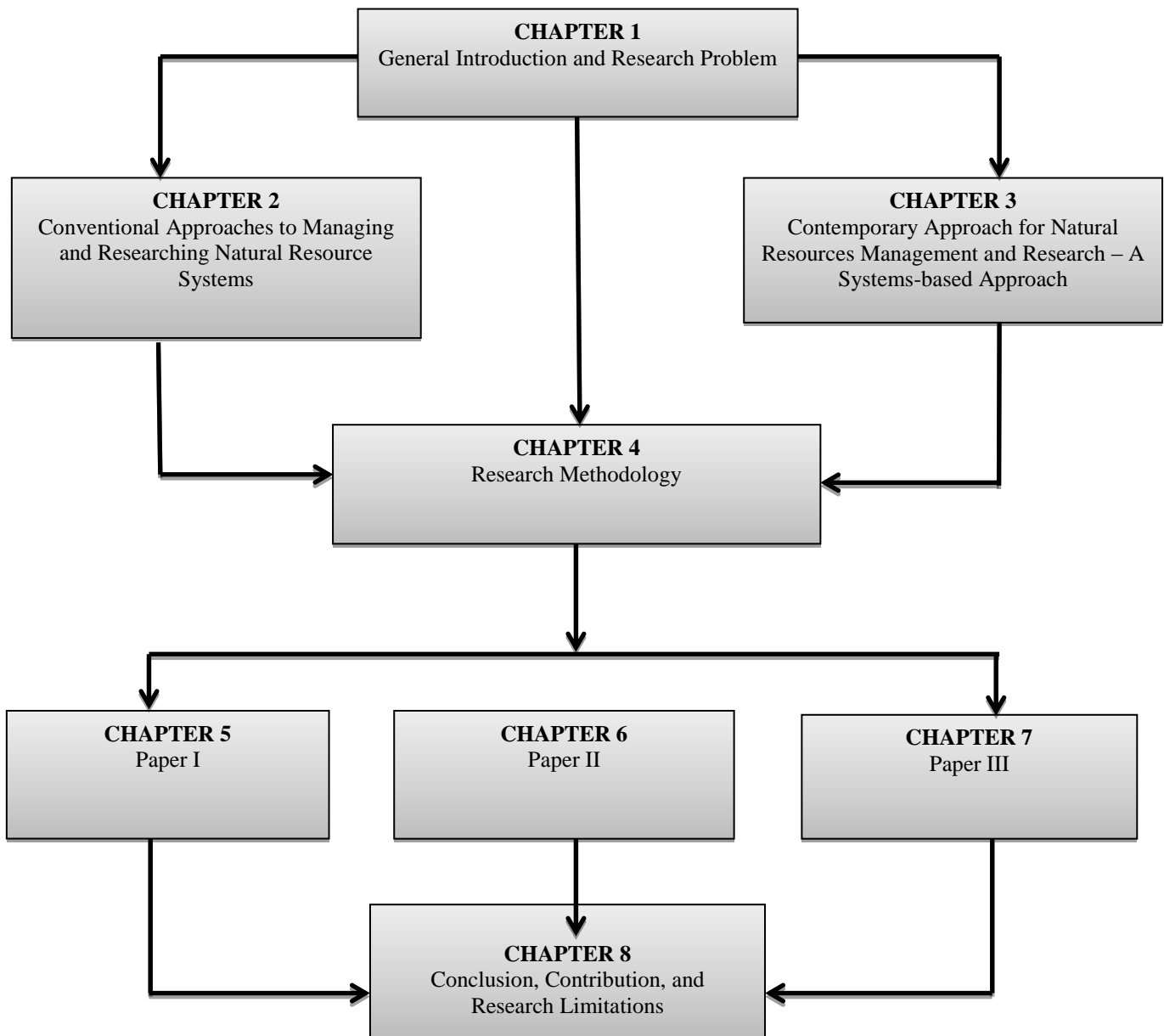
Figure. 1.2: Thesis structure

Chapter 6 (*paper II*) used the drivers identified in chapter 6 to develop a qualitative/conceptual model in the form of a Causal Loop Diagrams (CLDs) showing the feedback structure consisting of the interrelationships between the important biophysical and socioeconomic drivers, factors, and processes governing the dynamics of the basin, with substantial input from the key system stakeholders and decision makers. Chapter 7 (*paper III*) developed an integrated simulation system dynamics model based on the conceptual model to improve our understanding of the behaviour of the river basin system over time. This then allowed for alternative policy scenarios to be evaluated and compared over time. Chapter 8 syntheses the key research findings from the individual chapters and discusses the research contributions, limitations, and opportunities for further research. These are linked back to the three objectives set out herein.

CHAPTER 2: CONVENTIONAL APPROACHES TO MANAGING AND RESEARCHING NATURAL RESOURCE SYSTEMS

2.1. Introduction

In chapter 1, it was briefly argued that the traditional approaches to managing and researching natural resource and environmental systems, as well as the prevailing explanations based on linear-reductionist approaches are inadequate for understanding and addressing the complexity associated with environmental systems, such as the Volta River Basin of Ghana. Following the structure of the thesis, this chapter returns to review and critique some of the conventional approaches in more depth. They include the linear-reductionist thinking, command-and-control approach, and the equilibrium-centred approach. Essentially, these approaches are reviewed here in order expose their limitations in addressing the growing complexity and uncertainty presently faced by water resource managers due to rapid and continuous changes in system drivers. Thus, the review forms the basis to call for a paradigm shift, particularly the adoption of a system-based approach, which has been adopted as the theoretical base for this study.

The chapter begins with a discussion of the meaning of the concept, "scientific paradigm", and the way it operates to shape the research process in totality. This is important because every research is grounded in a philosophical assumptions and commitments that inform the way researchers conceptualise both the nature and purpose of the research enterprise (Thompson, 2007). The chapter then discusses the conventional approaches mentioned above. This is followed by a review of some criticisms launched against these approaches within the literature in relation to water resources and agricultural systems. Based on these criticisms, conclusions are drawn, where the systems thinking is proposed, and subsequently, discussed in detail in chapter 3.

2.2. The Concept of Scientific Paradigm

The previous decades have witnessed a proliferation of the use of the concept, *paradigm*, in association with many subject disciplines. The term is a particularly common and important one in contemporary science and philosophy. It has caught the imagination of scientists and researchers who are keen to lead a change or upturn a dominant paradigm (Pickett et al., 2007). Hence, the concept has become a common term in the daily parlance of scientific research. But like 'niche' and 'community', it is challenging to find a single unequivocal definition for the term (Yunlong and Smit, 1994; Paine, 2005). Nevertheless, some few definitions can be gleaned from the existing

literature. Tilman et al. (2002, p. 9), defined a paradigm as a "worldview, a general perspective, a way of breaking down the complexity of the real world." Similarly, Sparkes (1992) employed the term to suggest the possibility of diverse frameworks or perspectives containing different sets of values, beliefs, and assumptions (cited in Crook and Garratt, 2005). Van Cauwenbergh et al. (2007, p. 75), defined a paradigm as the "constellations of beliefs, values, and concepts that give shape and meaning to the world a person experiences and acts within."

Meanwhile, the whole notion of scientific paradigm was originally used by the philosopher of science, Thomas Kuhn in his 1962 book, *The Structure of Scientific Revolutions* and in his latest edition (Kuhn, 2012). Kuhn described a paradigm as the *worldview*, belief systems, a collection of assumptions and techniques, and exemplars for problem solution held in common by a scientific community (Kuhn, 2012). A plethora of background beliefs regarding the way the world operates are usually, incomplete or fragmented, and are typically not even recognised or appreciated by their proponents (Gladwin et al., 1995). Kuhn's publications (1962/1970), and successions of publications by other scholars (e.g., Kuhn, 1970; Lakatos and Musgrave, 1970; Fuller, 2000; Von Wirén-Lehr, 2001; Swart et al., 2005) provided a distinctive view of the manner scientific research advances (Graham and Dayton, 2002). This appears to have determined the contemporary meaning of scientific paradigm in the twentieth century.

The central argument of Kohn (1962, 1970) is that the 'normal science' many researchers conduct – that is, testing research philosophies identified with Popper (1959) and generally, the positivistic philosophies of science, has not yielded any significant explanation on how disciplines evolved. In the Popperian model, it is argued that knowledge is accumulated within a "formal logical framework", derived from unswerving observations that are sufficiently gathered with a wide range of questions or hypotheses', distinguished by a scientific method, consisting of an evolutionary process of conjectures and refutations (Popper, 1972). However, Kuhn contended this view and delineated science as an idea, which is considerably less integrated as compared to the Popperian model (Kuhn, 1962). He underscored that the way scientists gain knowledge inevitably results in several methodological, philosophical, as well as "social constructs" that assist scientists in their works. Accordingly, Kuhn introduced the concept "paradigm" to describe those constructs. Thus, a 'paradigm' is the fundamental concept that Kuhn employed to advance his arguments. In doing so, he also introduced a related concept – "normal science", which he described as "research firmly based upon one or more past scientific achievements, achievements that a scientific community acknowledges for a time as supplying the foundation for its further practice" (Kuhn, 1970, p. 10).

From these above understandings, it is thus possible to deduce some principal components of scientific paradigm – problem formulation, theory, hypothesis, model development, interpretation, description, and explanation (Pahl-Wostl et al., 2011). A paradigm also includes generalisation along with preferred instruments and methods and further structured by ontological commitments about components and concepts, powered by the faith that nature can be fit into the box of the paradigm via problem solving (Ziegler and Ott, 2011). Paradigms are, thus, important because they provide philosophical and conceptual frameworks or the operational context from which we drive theories, laws and generalisations (Crook and Garratt, 2005; Bell and Morse, 2008; Pahl-Wostl et al., 2011; Scheff et al., 2015). To a certain level of abstraction, paradigms are also theories as well as models. Although less formal, and perhaps not set down as systematic, logical propositions, they are, increasingly, subject to testing and review in the same way that theories are (Pahl-Wostl et al., 2011). Paradigms can be applied to not only to science, but to a specific area of science, but to other forms of knowledge and the ways that people think about the world in general.

Within the confines of water and natural resources management, the modernist or the 'normal science' paradigm sees disturbances as an interference (i.e., white noise) that should immediately be eliminated through management and control (Simonovic, 2009; Pahl-Wostl et al., 2011, 2013; Cook and Bakker, 2012). Nonetheless, Popper's idea of falsification has been embraced by many scientists and used widely by the public in the discussion of the challenges of resource management, particularly the notion of sustainability (Ziegler and Ott, 2011). Within the history of modernist paradigm, there has always been a tension between the dominant *mechanistic* and alternative *organicist* ways of thinking about the world (Sterling, 2003). Hence, as Capra (1996, p.17) observed: "the underlying debate is dichotomised between the *parts* and the *whole."* The prominence given to the *parts* has been described as *mechanistic, reductionist* or *atomic*; while the emphasis on the *whole* is referred to as *holistic, organismic*, or *ecological* (Capra 1996). Mechanistic and reductionist thinking has been the dominant paradigm in science and environmental/natural resources management, which is currently being challenged.

2.3. Traditional Thinking and Approaches to Natural Resources Management

The current and dominant ways of thinking about the management of natural resources, including management within the Volta River Basin of Ghana are rooted in a particular epistemology – i.e., in ways or methods for knowing on the basis of knowledge, which, hitherto, remain largely unchallenged (Sterling, 2003). According to Berkes (2010, p.14) the historical idea concerning 'natural resources management' is intimately associated with the advent of many ideas in political economy and environmental philosophy. These consist of: (1) the looking at humans and the

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environment systems as if they distinct entities, (2) the commodification of nature, (3) the separation of the user of natural resources from the one who manages them, as well as the emergence of the managerial class, (4) the evolution of a tradition of positivist scientific paradigm that believes that the world can be predicted and controlled, and (5) the extensive application of reductionism in scientific inquiry. As stated earlier, in this section, the conventional approaches to natural resource management are reviewed. They include linear-reductionist paradigm; command-and-control approach, and equilibrium centred approach.

2.3.1. Linear-reductionist Paradigm

The conventional human thinking still holds that the world is explainable through 'linear and mechanistic or deterministic thinking model (Hjorth and Bagheri, 2006; Jeffrey and Hawkins, 2008). In other words, the prevailing beliefs are that everything followed precise observable laws and order (Geyer, 2003) and those natural occurrences are fully comprehensible through objective creation and testing of theories (Williams, 2008). The linear causal thinking, upon which our knowledge of nature and insight of major scientific laws rest, believes that certain causes are operating in a collective and linear fashion, which, in turn, leads to a particular event (Hjorth and Bagheri, 2006; Foley, 2014; Liu et al., 2015a). The 'reductionist paradigm' is reflected in these notions and the way scientists, and generally, researchers make sense of a complex world (Cheung, 2008). Reductionist thinking form the foundation for machine-like (mechanistic or deterministic) science, where nature is viewed as clockwork, where individual elements of a system can be assembled and disassembled (Jeffrey and Hawkins, 2008; Hjorth and Bagheri, 2006; Berkes, 2010). Its ideological roots can, thus, be traced to the *conventional normal science* (Lister, 1998; Foley, 2014) that Kuhn talked about.

The origin of reductionist paradigm is traceable to the *Age of Enlightenment*, the emergence of liberal social theory, 'invisible hand' reasoning, and bias towards human dominion over nature that many consider as rooted in Western religion (Daly and Cobb, 1994; Cheung, 2008; Berkes, 2010). However, three famous scientists of the seventieth century; the French Philosopher and Mathematician, Rene Descartes (1596-1650), Galileo Galilei and, subsequently, the English Physicist and Mathematician, Sir Isaac Newton (1642-1727) set the scene (Capra, 1996; Geyer, 2003; Jeffrey and Hawkins, 2008). Galileo excluded quality from science, confining it to the study of phenomena that could be measured and quantified (Capra, 1996). This has been very successful throughout modern science. René Descartes advocated rationalism with the view that the way nature works could be demonstrated through the way a clock functions (Mebratu, 2001; Geyer,

2003). Consequently, Descartes developed the "method of analytical thinking", which entails breaking down complex phenomena into smaller parts, to gain an understanding of the behaviour of its constituent parts (Capra, 1996). He considered his views of nature as the important distinction between two independent and discrete spheres – "that of the mind and that of matter" (Capra, 1996).

Newton, on the other hand, discovered an astounding collection of fundamental laws in his book, *Principia Mathematica* – an effort that eventually became the foundation for all future scientific endeavours (Geyer, 2003). In a classical Newtonian theory, systems are "epistemically closed, static off-line systems", whose hypothetical condition stays static and intact by system dynamics and growth in the runtime of the system (Haag and Kaupenjohann, 2001). These developments were followed by another plethora of discoveries in various fields, including magnetism, electricity, astronomy, and chemistry, thereby providing increased confidence in the value of reason critical to solving scientific problems (Geyer, 2003).

As stated earlier, the proponents of reductionist thinking believe that the behaviour of a system can be discerned in a clockwork manner, through an observation of the behaviour of the individual parts (Geyer, 2003; Cheung, 2008; Jeffrey and Hawkins, 2008; Singh, 2010). Indeed, reductionism is concern about breaking a system into separate elements, analysing the elements, and deriving predictions (Berkes, 2010). Generalisations can be achieved by using this approach, without considering the context of space and time (Berkes, 2010). According to Johnson (1982), "reductionism refers primarily to the effort to explain phenomena at one level of analysis entirely by reference to theoretical principles operating at another level". Usually, but not necessarily, the guiding principles are thought to apply at a more "fundamental" level than the phenomena being explained. Thus, the underlying assumption of reductionist paradigm, which states that the sum of *parts* equals the *whole,* is vital to explaining the behaviour of a system (Jeffrey and Hawkins, 2008). In other words, the *whole* can be understood by the sum of its *parts*, and the goal of science is to recreate reality from the *parts* and produce casual relationships among the parts, usually to explain, guide or predict (Mebratu, 2001; Hjorth and Bagheri, 2006). Reasoning is egoistic, linear, instrumental and rational (Gladwin et al., 1995).

Reductionism thus advocates an additive character of linear cause-effect relationship (Mebratu, 2001; Dent, 2003) and by extension, it encourages linear thinking. Further, the use of reductionism is closely associated with "logical positivism or rationalism", which asserts that the presence of reality is determined by unchallengeable laws founded on common truths (Berkes, 2010). Geyer (2003, p.3) summarised some basic characteristics of reductionist thinking: "(1) it profess order, meaning that particular causes give rise to known consequences at all times and places; (2) it

believe in predictability, implying, once global behaviour is established; the prospect of future events could be predicted by deployment of the required inputs to the model (3) it advocates determinism, which suggests that processes move in an logical and expected direction, with conspicuous beginnings and logical conclusions. Its objective is to provide "a knowable, unified and objective Truth" (Lister, 1998, p.128). Therefore, the duty of science is to unearth these truths and apply them in predicting and controlling nature. Science under this notion is believed to be value-neutral with the scientists viewed to be working in a value-free environment (Norton, 2005; Berkes, 2010). The positivistic-reductionist way of thinking is 'natural, rational, and, perhaps, driven by the generic idea of control operating on local scales' (Singh, 2010).

However, many opponents of reductionist approach argue that you cannot correctly understand a system independent of its settings and contextual factors in which it situates (Clark and Stankey, 2006; Simonovic, 2009; Singh, 2010; Pahl-Wostl et al., 2012). These scholars stressed that natural resource systems, such as water resources are complex, and that a truly complex system cannot be adequately 'captured' or represented from any single perspective as advocated by proponents of reductionism. According to Singh (2010), the reductionist approach fails, when humans begin, or are challenged to think about how to make use of natural resources for the greater good of society (i.e., based on a longer term and wider-scale gain). Hjorth and Bagheri (2006) add that, reductionism as a perspective of 'modern science' is characterised by increased specialisation and, consequently, it has produced numerous knowledge but insufficient insight. Indeed, focusing on individual parts can help illuminate certain aspect about the 'whole', they fall short in explaining the full problem (Hjorth and Bagheri, 2006; Jeffrey and Hawkins, 2008; Cumming, 2011). This is because they also make many assumptions about the constancy of causal relationships, the prevalence of linear relationships, and the structure of the focused system (Cumming, 2011).

2.3.2. Command-and-Control Approach

Many of the large river systems around the world, including the Volta River basin are highly regulated with the numerous physical flow control and storage structures as well as a range of water sharing rules and regulations (Welsh et al., 2013; Johnston and Smakhtin, 2014). Indeed, as the human population rises and available natural resources become scarce, there are increased pressure and efforts to control those resources to maximise its products, minimise the threats, and consequently, to realise the expected outcomes (Holling and Meffe, 1996; Chaffin et al., 2016). In situation where the actions of people, institutions or nature goes contrary to the conventional wisdom, norms, desires or expectations of society, command and control are established to move such institutions, and/or the ecosystems, to a steady, and possibly, to predictable state (Rogers et al.,

2000). This notion of 'control' and 'management' is viewed as the panacea to the challenges of deep-rooted environmental and social problems (Holling and Meffe, 1996; Luke, 1997; Luke, 2002). According to Berkes (2010, p.34), the term "management', suggests 'domination of nature, efficiency, social, and ecological simplification, and expert-knows-best, command-and-control approaches." Pahl-Wostl et al. (2011, p. 840).) defined a management paradigm as a constellation of fundamental believes with respect to the nature of the system to be managed, the objectives of controlling the system and the ways in which these objectives are accomplished. Both Berkes and Pahl-Wosl et al (2011), illustration is evinced in artefacts, including technical infrastructure, planning approaches, regulations, engineering practices, and models.

Command-and-control approach assumes that natural resource systems will respond as predicted (Van den Belt, 2004; Hammer, 2015). It is the common term from the prescriptive and interventionist traditionally used in natural resource management before the inception of integrated natural resources management (Allison, 2003; Chaffin et al., 2016). This conventional wisdom has dominated natural resource management for decades. It allows for certainty and emphasis 'hierarchical, top-down decision-making, and risk aversion irrespective of the outcome' (Knight and Meffe, 1997). It is founded on expert knowledge, which aims to control nature, viewing people as if they were independent from the environment (Berkes, 2003). Management, therefore, defines the primary use of the managed system (Chapin et al., 2009; Chaffin et al., 2016).

Command-and-control policies were the approaches used in an appropriate way in response to the symptoms of natural degradation in agricultural landscapes (Allison, 2003). Usually, control is exercised from the centre, following a rigid protocol for the achievement of established objectives. Command and control believes that management interventions can be optimised and their impact, in principle, be fully calculated (Berkes, 2010; Pahl-Wostl et al., 2013). This is enabled by segregation of the system to be controlled by different individual elements (Pahl-Wostl et al., 2011, 2013). Uncertainties are either relegated to the background or analysed quantitatively through the development of norms. The ultimate goal of the command-and-control approach is the elimination or the reduction of the natural range of environmental variability or the removal of disturbances in natural resource system properties and processes (Holling and Meffe, 1996; Rogers et al., 2000; Folke, 2003; Chapin et al., 2009). However, once the 'natural variation in a system is reduced, it loses its resilience and its capacity to respond, following natural or human disturbances (Rogers et al., 2000).

Because the natural world was viewed as ordered, segmented, and mechanistic, with linear, cause-and-effect relationships, it was not surprising that agencies compartmentalized themselves into

specialties that employed a command-and-control mentality to manage resources (Knight and Meffe, 1997). However, as Berkes (2003) alludes, our evolving thinking on ecosystem-based management suggests that these assumptions often fail, because our capacity to truly predict behaviour of ecosystems is not advanced. Natural resource systems are not static (Chapin et al., 2006). Indeed, while they view the complex and dynamic nature of environmental systems, managers usually strive to achieve sustainability through externally imposed regulations, aiming to reduce the likelihood of events that are viewed as environmentally or economically undesirable (e.g., floods, pest outbreaks, and fire (De Leo and Levin, 1997; Chaffin et al., 2016). Figure 2.1 illustrates the basic attitude of mind underlying current paradigm in environmental and natural resources management.
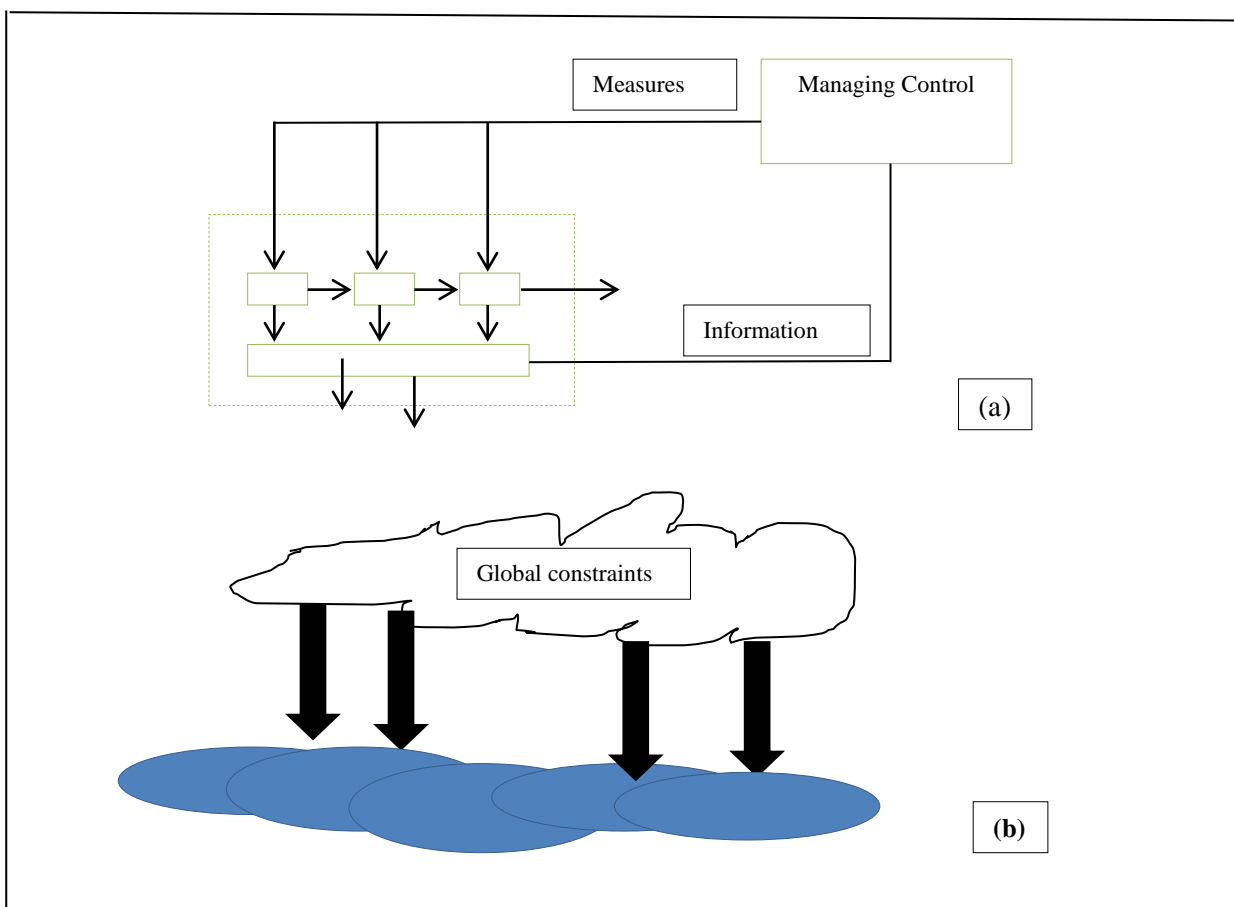
Figure 2.1: Schemes of Environmental "Management". **(a)** Current strategies where a human control panel, perceived as external, attempts to direct an ecosystem or even the global system towards a desired goal. **(b)** Ecosystems (clear shaded cloud) and human systems (light blue shaded cloud) closely interwoven in what can be called a human ecological system that organises itself towards a common goal within material constraints (Adapted from Palh-Wostl, 1995)

The metaphor in figure 2.1b indicates a type of mutual management and co-existence between natural and human systems (Pahl-Wostl, 1995). A recurrent, and possibly, widely known product of command and control in natural resources management context is the reduction of the variety of natural changes of systems structure, function, or both, aimed at increasing their predictability or stability. These changes evolve across time or space. Holling and Meffe (1996) suggested that the

command-and-control approach, when extended to address problems in natural resource systems without careful consideration, often leads to unexpected and adverse impact.

2.3.3. Steady-State Equilibrium Centred Approach

In the physical world, it is believed that a mechanical system is at rest if the forces acting on it are in an equilibrium state (Gunderson et al., 2002). This idea is reflected in the notion of 'balance of nature' or 'equilibrium' paradigm, which argues that nature exists in a perpetual equilibrium state that may not be altered or disturbed (Mbatu, 2010). Notions of 'balance of nature' or 'equilibrium' and non-equilibrium in nature is rooted in the traditions of Western cultures (e.g., Ancient Greek, medieval Christian, and eighteenth century rationalist thoughts) (Botkin, 1990; Worster, 1993; Mbatu, 2010). Their application in natural resources management can be traced back to population and community ecology (Pickett et al., 2007; Ochola et al., 2011).

Darwin's concept of natural selection fostered a flourishing evolutionary ecology searching the explanations for species properties in the optimisation of life strategies to gain maximum fitness. Natural selection and maximum fitness are, therefore, closely tied to the concept of a stable equilibrium state. The latter is needed for competitive exclusion to become efficient and for optimisation strategies to be useful (Pahl-Wostl, 1995). Equilibrium has been defined variously in the literature. In environmental systems, Phillips (2004, p. 370) referred to a state of equilibrium or as a steady-state, as a situation in which little fluctuations may ensue around a constant mean condition. Stability, the conventional generalization that there is an inherent 'balance' or equilibrium in nature, is linked to successional theory: as systems become more diverse during succession, it is believed that they become more stable (Lister, 1998). These ideas have grown as exemplified by their applications in resource economics, social and cultural anthropology, water resource systems, range ecology, land use policy and law etc (Ochola et al., 2011). Like the reductionist and command-and-control paradigms, the equilibrium centred approach assumes that a stable or a single state of a system exists and that all we have to do is to guide a system there with appropriate policies and strategies (Van den Belt, 2004; Chapin et al., 2009). Such a viewpoint directs attention to the equilibrium and near equilibrium conditions (Holling, 1994).

The fundamental assumptions of the equilibrium paradigm are that natural resource systems (1) are basically closed systems, (2) are self-regulating, (3) display a stable point or stable cycle equilibria, (4) have deterministic dynamics, (5) are virtually free of disturbance, and (6) are independent of human influences (Botkin, 1990; Turner et al., 1993; Pickett et al., 2007; Ochola et al., 2011). Further, Holling (1994, p. 600) points out some essential characteristics of this view: it directs

attention to not only constancy in time, but also, spatial homogeneity and linear causation; it leads to equilibrium theories and to empirical measures of reliability that stressed averaging changes in time and averaging 'graininess' in space; it represents a policy world of a benign nature where trials and mistakes of any scale can be made with recovery assured once the disturbance is eliminated.

However, many authors (e.g., Gunderson and Holling, 2002; Gunderson and Pritchard, 2002; Philips, 2003; Heise, 2008; Kricher, 2009) absolutely does not accept a balance of nature paradigm. They contend that nature or environmental systems are rarely close to equilibrium, nor has it ever been at any period in Earth's history. This contention has proliferated in the last 80 years (Scoones, 1999), although it is not sufficiently recognised in many environmental and natural resource assessments (Reice, 1994). According to Kricher (1999), nature has no 'balance' that must be attained, and that nature works on its own terms and that human beings, as part of nature cannot claim to be a determining factor in the natural workings of nature. In his famous textbook of 1930, Elton noted that the balance of nature theory does not exist and possibly never was (Scoones, 1999). Fifty years later, Connell and Sousa (1983, p.789) arrived at a similar conclusion stating: "If a balance of nature exists, it has proved extremely challenging to establish." The debate concerning equilibrium comes partly, from the varying definitions and criteria deployed by investigators and, in part from questions regarding whether, it is reliable to explain the presence of an equilibrium state (Turner et al., 1993).

Meanwhile, the characteristics that have been employed to study equilibrium can be put into two broad categories: *persistence* (i.e., simple non-extinction) and *constancy* (i.e., no change or minimal fluctuation in numbers, densities, or relative proportions) (Turner et al., 1993). The idea of shifting mosaic steady-state has been challenging to measure empirically, but it has been applied in other systems. Consequently, the last few decades have witnessed a dramatic transformation in the debate and re-conceptualization of natural resource systems. Two changes in resources management led to the abandonment of the equilibrium paradigm (Pickett et al., 2007). First, the emergence of a large amount of empirical evidence that visibly and ultimately challenged the underlying assumptions successfully. Second, scientists have been able to view their systems at different, often larger scales that were previously thought via much of the first half of the discipline history. Indeed, all natural environmental systems change over time, implying that it is challenging to determine a normal state for communities whose quantifiable resources are in constant flux, either because of natural disturbance or due to internal ecological dynamics (De Leo and Levin, 1997; Walker, 1999).

Alternative to the equilibrium is the non-equilibrium perspective, which describes the decoupling of the plant and herbivore relations from resource variability (Schlüter et al., 2012). Non-equilibrium

advocates multiple equilibria states: 'nature engineered' and 'nature resilient' and an evolutionary view that highlights organizational change and surprises generated by such change (Holling, 1994). The former emphasises variability, spatial heterogeneity and non-linear causation, the existence of more than one stable state (Holling, 1994; Ochola et al., 2011). A non-equilibrium perspective embraces the complexity of systems and encourages more flexible and dynamic adaptive responses to change (Scoones, 2004), The idea emerged from the recognition that most systems are simultaneously subjected to a number of disturbances) influenced by factors, such as fragmentation of forests, fire, environmental catastrophes (e.g. droughts, floods, wind storms) or by biotic structure and processes in environmental systems (Pickett et al., 2007; Ochola et al., 2011).

The myriad of factors that influence ecosystem dynamics may be studied in homogeneous physical entities of a River Basin system such as the Volta River Basin. Existing advancements in the science within environmental systems support the importance of past disturbances and external forces in determining the direction of environmental change (Ochola et al., 2011). Moreover, disturbance may take place across a wide range of temporal and spatial scales (De Leo and Levin, 1997). Conferring Heise (2003), the scale of change cannot be understood in its entirety if focusing only on local life forms and systems, and such a narrow focus can lead to misperceptions about nature's enduring evolution. Theoretically, equilibrium dynamics related to defined temporal and spatial scales are examples of problems studies outside the larger temporal contexts (Ochola et al., 2011).

The equilibrium-centred approach is also embedded within the notion of fixed carrying capacities, steady-state resource dynamics, and maximum sustainable yield (Schlüter et al., 2012, 2014). Likewise, neoclassical economics have been based upon general equilibrium theory with steady flows of resources into the economic system and flows of wastes out of the system. The policies that result from such worldviews generally attempt to regulate systems to reduce variability and thereby maximize output (Ludwig, 1996). However, as we shall see in the next section, a growing number of authors (e.g. Holling, 1995) believe that such policies are 'doomed' to fail.

Despite such concerns, however, the science of natural resource management, during this century, has been based on equilibrium ideas, which presume stasis, homeostatic regulation, and stable equilibrium points or cycles (Paul-Wostl, 1995, Scoones, 1999). Furthermore, despite the different paradigm shifts that has occurred over some millennia, the idea of balance in nature rests in the *popular* and the *scientific* mindset (Mbatu, 2010). The idea is still the dominant paradigm in the world upon which much of environmentalism is based. Indeed, Sullivan (2010) underscored that the belief in a "balance in nature" flourishes in our "exploitative and capitalistic culture."

2.4. Critiques of the Conventional Approaches

Many of the challenges confronting water resources management, such as the Volta River Basin are conceptualised based on the assumptions of the prevailing approaches discussed the preceding sections. These approaches often direct attention solely on 'myopic optimisation' and benefits of productivity instead of the ability to enhance long-term sustainable management (Berkes et al., 2003; Rammel et al., 2007; Liu et al., 2015b). This is particularly prevalent in water resource management systems (Simonovic, 2009; Pahl-Wostl et al., 2011,2013; Johnston and Kummu, 2012; Johnston and Smakhtin, 2014; Sahin et al., 2016). According to Pahl-Wostl (2012), water systems are less amendable to external control. During the past several decades, the science of ecology, ecosystem and natural resources management has been changing from a "balance-of-nature paradigm" to a "dynamic ecosystem paradigm", with significant developments in the understanding of the inherent complexities and uncertainties (Berkes, 2010). This is triggered by the widespread and growing recognition that the current models and practices in resource and environmental management are in many cases not leading to sustainability (Simonovic, 2009; Pahl-Wostl et al., 2013; Liu et al., 2015b; Sahin et al., 2016; Krueger et al., 2016). This is especially the case for the growing numbers of poor people in the developing world. Some scholars point this to human 'short-sightedness and greed', and questioned whether resources could ever be managed in a sustainable manner (Ludwig et al., 1993).

One critique emphasised that such approaches had failed to see environmental systems as part of a larger socio-economic and political context and hence ignored the crucial role of the key drivers that were not environmental in nature (Berkes and Folke, 1998; Walker et al., 2012). Others attribute it to the general failure of science to recognise the linkages between disciplines (e.g. systems) through the persistent endorsement of silo approaches (Pollard and du Toit, 2011; Sahin et al., 2016). Yet, the increasing majority, attribute this to the application of conventional scientific method based on a *Linear-Newtonian model/normal science paradigm* to inform management, regardless of changes in the socio-economic, political and natural environment (Berkes, 2010; Pollard and du Toit, 2011; Schlüter et al., 2012). As a result, conventional natural resource models have come under scrutiny and sustained criticism in recent years (e.g., Berkes, 2010). In this section, I review the range of critical literature that have developed to challenge those conventional notions of 'natural resources' management', practice and research as advanced by several scholars.

One of the leading critics of the conventional models has come from Canadian ecologist, Crawford Stanley Holling. In his numerous of assessment of natural and managed behaviour of ecological systems, (Holling, 1987, 1994); Holling (1995) used a series of real-world examples to demonstrate how management activities based on command-and-control strategy and equilibrium centred

approach have led to unintended problems for both natural ecosystems and human well-being in the form of declining resources, social and economic conflicts, and losses of biodiversity. He provided several examples of this pathology in resources management. They include; the salmon fisheries in North America; and the conversion of the semi-arid savanna ecosystem to productive cattle grazing lands in the Sahel zone of Africa, southern and East Africa, the southern USA, northern India and Australia. In many of his studies, Holling demonstrated successful, but narrow attempts to manage and control ecological variables (e.g., pests, water quantity, and animal populations) have always led to less resilient ecosystems, more inflexible management institutions and more helpless societies. In place of command and control approaches, he advocated that adaptive management, which combines experimentation and integrated, flexible policies in a learning perspective will enable us to escape this pathology. In their subsequent commentary, Holling and Meffe (1996) conclude that much of the traditional paradigm for managing resource and environmental systems may be contributing to problems, rather than the solutions.

Within the context of water and agricultural systems Bawden (1991) argued that "the language of reductionism and positivism" does not sit comfortably with the complex and dynamic processes connected to the search for sustainable management. He asserts that much of the advancements made in terms of agricultural production in many parts of the world is simply being attained at the expense of long-term degradation of its biophysical and socio-cultural environments. Born and Sonzogni (1995, p.168) also note that management approaches of this type are mostly reactive, disjointed, and far narrow or limited purpose with ineffectual or unsatisfactory, often undesired, management outcomes." Consequently, Bawden (1991) went on to suggest the rejection of the 'old paradigm' of agricultural science for the new – "a paradigm that can accommodate complexity, uncertainty, and even chaos, both as aspects of the world itself and of the way we humans construe meanings of it" (p. 2363). In addition, Bawden proposed "a shift in thinking from the influence of the Age of Productivity to that of the new Age of Persistence" (p. 2363).

During the past decade or so, the literature broadens significantly, with an increasing number of researchers joining in the criticism of the prevailing approaches, This reinforced the debate and the push for an alternative paradigm or way of thinking. For example, in his critical review of the old models, Berkes (2010, p.13) argued that the traditional methods of natural resources management are "problematic", and possibly, outdated, due to the "baggage' they carry" or their historical background. He contends that the term 'management', which brings with it the domination of nature, efficiency, social-ecological simplification, and expert-knows-best, command-and-control strategies, needs be revised and attention laid on ecosystem stewardship (p.34). He emphasised that such a shift is required to deal with complex adaptive systems, characterised by cross-scale effects,

self-organization, non-linear behaviour and threshold effects. In this sense, there is the need to re-conceptualise the management of natural resource systems and a system-based approach offers the best alternative, because of its ability to embrace continual change, and maintain capacity for renewal in dynamic environment rather than focus on stable states (Gunderson, 2003; Berkes, 2003, 2010).

Du-Toit et al. (2003) on their part challenged the significance of these models that have permeated agricultural practice and development in South Africa. They assert that such approaches, characteristics of the "modernity project", and based on the methods of Newton's empiricism and Descartes rationalism, will not achieve sustainable living, owing to their rigidity and complete disregard for change, which an important phenomenon in human society (p. 6). A similar line of argument is provided by Thompson and Scoones (2009). Explicitly, they criticised the dominant perspective in conventional agriculture and development programmes, which assume a stable and an almost indeterminately, resilient environment, where resource flow may be controlled, and nature would return to an equilibrium state once human stressors are eliminated. In their view, such static, equilibrium-centred perspectives do not offer sufficient understanding into the dynamic nature of food and water systems, particularly in a time of global economic and environmental change, in which factors such as population growth, climate change, land use change shifts all impact on the livelihood of people in the developing world. They attributed this to the inability of such 'modernist' strategies to address "complexity, diversity, uncertainty and non-equilibrium states." To achieve long-term sustainability especially in developing countries, they concurred with Berkes et al. (2003) and Smit and Wandel (2006) and proposed a change policy strategy that aims to maintain the usual way of doing things, to embrace analytical approaches and practices that enhance the capacity of food and water systems to respond to change and uncertainties (Thompson and Scoones, 2009).

Indeed, uncertainties and related mechanism (feedbacks) are inherent in many natural resource systems. This makes it a challenge to understand the behaviour of natural systems as advocated by the conventional models. As many authors (e.g., Fulton et al., 2011; Levin et al., 2013; Schluter et al., 2014) have pointed out, 'system uncertainties' and 'decision stakes' are significantly higher, thus, approaches derived from an assumed capacity to predict probabilistic responses to the management of exogenous processes such as climate change offer limited solutions. Uncertainty, however, does not operate as a source of unwanted conflict between scientists, policy-makers and citizens. Rather, it becomes a crucial aspect of the process as a vehicle for gaining insight into complexity, which produces information necessary for theory development, experimentation and decision-making that may not have been part of the original thought (Frame and Brown, 2008).

Nevertheless, Gallopin et al. (2001) stressed that fundamental uncertainty is manifesting numerous ways: by our limited understanding of human and environmental processes; by the "intrinsic indeterminism" regarding the complex dynamical systems (concerning natural, human-made, and human constituents; and by a broad range of human choices and goals. In their view, it is, therefore, not coincident that in several important cases, the very success of the traditional "compartmentalised" approaches have led to the exacerbation of the environmental and development problems they addressed. In this sense, they argue that the prevailing mindset is showing critical limitations with regards to environmental and socio-economic sustainability. From this perspective, Walker et al. (2002) contend that these types of uncertainty hamper the value of approaches necessary for scientific inquiry and management of developing regions and societies. Consequently, Walker et al. suggested that we shift attention on trying "control" these uncertainties to a focus on "learning" to live within systems.

Learning is understood to be a social process where engagement, communication, and dialogue offer the platform for reflecting on and responding to feedback in a manner that is open to change and that ensures creative and innovative responses to an ever-evolving environment (Pollard et al., 2009). Moreover, a system that can experience events, reflect on them, and therefore, learn, is implied to be responsive and capable of adapting to changes that are inherently part of complex systems" (Pollard et al., 2009, p. 21). Further, Walker (2005) underlined that "current best practice", employed in many parts of the world to manage environmental systems are not sustainable, because they are leading to unintended and unwelcome results. He advanced that the prevailing paradigm for resource use and development is still dictated by the command-and-control approach (deterministic and viewing natural systems as highly controllable) that presaged the initial advancement of the contemporary methods of natural resources management. Pointing to the case in the Goulburn-Broken (G-B) catchment in Australia's Murray-Darling Basin, Walker concludes that "the mindset of the early developers of agriculture in the region was one of command-and-control philosophy" (p.78).

Indeed, the Murray-Darling Basin is, probably, a typical example of Australia's natural resource management problem, as the management approach has resulted in 95% of its river basins being degraded (Gell et al., 2009). The Murray lakes and lagoons are also under severe stressed, due to a plethora of socio-economic and environmental drivers of change (Dearing et al., 2010). Consequently, Walker (2005, p.79) concluded that command-and-control approach to management that has been used to address sustainable development issues in the region and around the world is problematic because four flawed assumptions: (1) too much attention placed on average conditions (instead of extreme events), fixed (and short) time frames and fixed spatial scales (instead of

multiple nested levels; (2) a belief that challenges from different sectors in these systems do not interact, when in fact interacting sectors are a key feature of their dynamics; (3) an expectation that change will be incremental and linear, when it is frequently non-linear and often lurching; (4) an assumption that getting the system into, and then keeping it in, some particular state will maximise yield (broadly speaking) from the resource base, indefinitely; there is, however, no sustainable "optimal" state of an ecosystem, a social system, or the world; it is an unattainable goal." In his view, the major challenge to addressing the situation is to reorient the thinking of the policy-makers and managers, which he claims to have been conditioned to work towards finding 'partial solutions'. However, incomplete solutions, he stressed, do not last. He concludes that the complexity and dynamics of environmental system preclude deterministic policies and advocates for more integrated approach, which assume that social-ecological systems behave as complex adaptive systems with alternate system regimes. A complementary perspective to this critique is provided by Allison and Hobbs (2006) who suggest that the inability various attempts to find solutions to the persistent problem of increasing salinity in the Western Australia agricultural region are due in large part to a failure to adopt an epistemology based on post-normal science paradigm. They maintained that natural resource degradation in the region was considered as a problem for science, far removed from its socio-economic and historical context.

Another criticism levelled at the conventional approaches comes from Mayumi and Giampietro (2006) and Ludwig (2001). According to Mayumi and Giampietro (2006), there will always be 'non-equivalent descriptive domains and non-reducible models', indeterminacy, multiple causations, and an open and expanding information space. These factors provide insights into the numerous shortcomings that the experts are unable to predict. They conclude that the role of science for sustainability should be about participation and mutual learning rather than making blueprints. Remarkably, Ludwig (2001) arrives at the same conclusion, but stressed the limitations with respect to expert knowledge in environmental problem solving. He emphasised that the current environmental problems (e.g., climate change and biodiversity loss), cannot be solved by conventional management, unless there is a fundamental shift in approaches. Because 'there are no experts in problematic issues, neither can there be any Ludwig (2001, p.763) proposed a revaluation of our existing thinking, which have remained unchallenged: 'economism' (i.e., attaching excessive importance to economic values as compared to others); 'scientism' (understanding that science is distinctively capable of unravelling virtually every societal problem), and "technocracy" (i.e., believe that policy solutions can be accomplished by relying exclusively on technological innovation). Given that many of our complex environmental problems are 'wicked problems' he claims that period of traditional management approach has come to an end. Consequently, he

concludes that issues, such as ethics and environmental justice were vitally important, and should be moved to the forefront, and a different type of management approach, grounded on "learning" be promoted.

Others, however, turn their attention to addressing the inherent weaknesses in existing models, because they do more harm to environmental systems than good. For example, Meppem and Bourke (1999) content that conventional conceptualisation of environmental challenges has remained a largely discipline based endeavour that has relied on abstracting the environmental issues from their real-world complexities. They note that dominance of these approaches such as 'instrumental rationalism' has led to a sustained increase in environmental degradation in spite widespread political and social interest in its abatement. For instance, Winz et al. (2009) argued that managing natural resources by command and control reduces natural variation in ecological systems, and results in the loss of biodiversity, declined natural resources, and socioeconomic strife. They conclude that systems thinking and participatory system dynamics offers the best methodology to adequately solving these problems.

Against the backdrop of the preceding discussion, three key points are worth pointing out. First, there is seem to be ample evidence and growing agreement that the current models in resources and environmental management are inconsistent with dynamics and complexity in those systems, including problems in river basin systems, such as the ones under study here. Second, the foregoing advancements suggest that the challenges inherent in natural resource management systems are not purely 'scientific or technical issues', but are embedded in our insufficient understanding of the link between biophysical, social, and economic components of ecosystems. Third, and more essentially, many of the voices in the review are advocating for a *paradigm shift* from the conventional thinking to a considerably a different way of thinking that embraces complexity, feedbacks, non-linear dynamics. This, they believe, can help achieve long-term sustainable goals.

More specifically, the paradigm shift is associated with viewing and conceptualising the world as a coupled social-ecological system (e.g., Berkes and Folke, 1998; Berkes et al., 2003; Redman et al., 2004; Folke et al., 2005; Schlüter et al., 2014) or linked human-environmental system (e.g., Turner et al., 2003; Steffen et al., 2005; Liu et al., 2007; Scholz et al., 2011; Scholz, 2011) in which people and nature or biophysical and socio-economic factors generally interrelate at different spatio-temporal and functional in a resilient and sustained fashion. In sum, the approach is linked with seeing environmental issues as complex and *systemic* problems, which require the adoption of systems thinking or system-based approach to solving them. As Young and Steffen (2009, p.306) underlined, "once we shift our paradigmatic perspective to recognise that nature system is a

complex and dynamic social-ecological system, it is evident that we need to think regarding coupled systems in which change is large-scale, often non-linear, frequently fast, and sometimes irreversible". This recognition is not exclusively an academic or theoretical matter, but also warrants the reconsideration of the role of natural resource managers in the design and implementation of sustainable development policies and practices. It further necessitates the interaction of different disciplinary approaches as part of a broader quest to develop an integrated understanding of human-environmental interaction (Wilson and Bryant, 1997; Welsh et al., 2013; Liu et al., 2015b) towards the long-term goal of sustainable development of water resources systems, such as the Volta River basin, which is the focus of this study.

2.5. Concluding Remarks

In this chapter, the different viewpoints, approaches, and strategies that characterise the conventional way of thinking in managing natural resource management systems are reviewed. They include linear-reductionist thinking, command-and-control management strategy, and the equilibrium centred approach. Most of these traditional approaches stressed equilibrium, stability and reductionist method. They have arisen in the mould of the mechanistic world view prevalent in classical physics. The chapter then reviewed a few critiques launched against such approaches within the context of natural resources management. Most the literature have criticised the old approaches for applying a 'one-size-fits-all' or 'quick-fix' solutions to complex human-environment phenomena as they do not consider the non-linear dynamic, uncertainty, and complexity of natural and human-dominated systems. Many contend that they have produced an array of knowledge, but insufficient understanding of the complexities in natural resources management systems.

These developments called for the adoption of a new and novel scientific and theoretical approach to studying and understanding such complexities and dynamics inherent in natural resource systems. Accordingly, this study advocates and adopts a systems thinking approach, which emphasises holistic analysis and understanding of complex social-ecological systems such as the Volta River basin water resources system. In the next chapter, the systems thinking or systems-based approach is introduced, thoroughly reviewed, and subsequently, proposed as the conceptual and theoretical base for this study.

CHAPTER 3: A CONTEMPORARY APPROACH FOR NATURAL RESOURCES MANAGEMENT AND THE RESEARCH – A SYSTEMS-BASED APPROACH

3.1. Introduction

As demonstrated in the previous chapter, conventional approaches to researching and managing natural resource and environmental systems, founded on simple linear and reductionist, normal science paradigm are inadequate in dealing with the uncertainties, complexities and dynamics inherent in such systems. Thus, to address the research objectives as outlined in chapter 1, this research advocates for an alternative or contemporary approach that shifts the emphasis away from these static and approaches towards an approach that deals with complex dynamic open systems. This kind of thinking or approach is conceptually depicted in Figure 3.1 below.

Figure 3.1: Different ways of thinking: (a) Linear causal thinking; (b) Non-linear causal thinking; causal states and causal relationships are denoted by words and arrows, respectively. Double bars indicate presence of time delay (Adapted from Sterman, 2000)
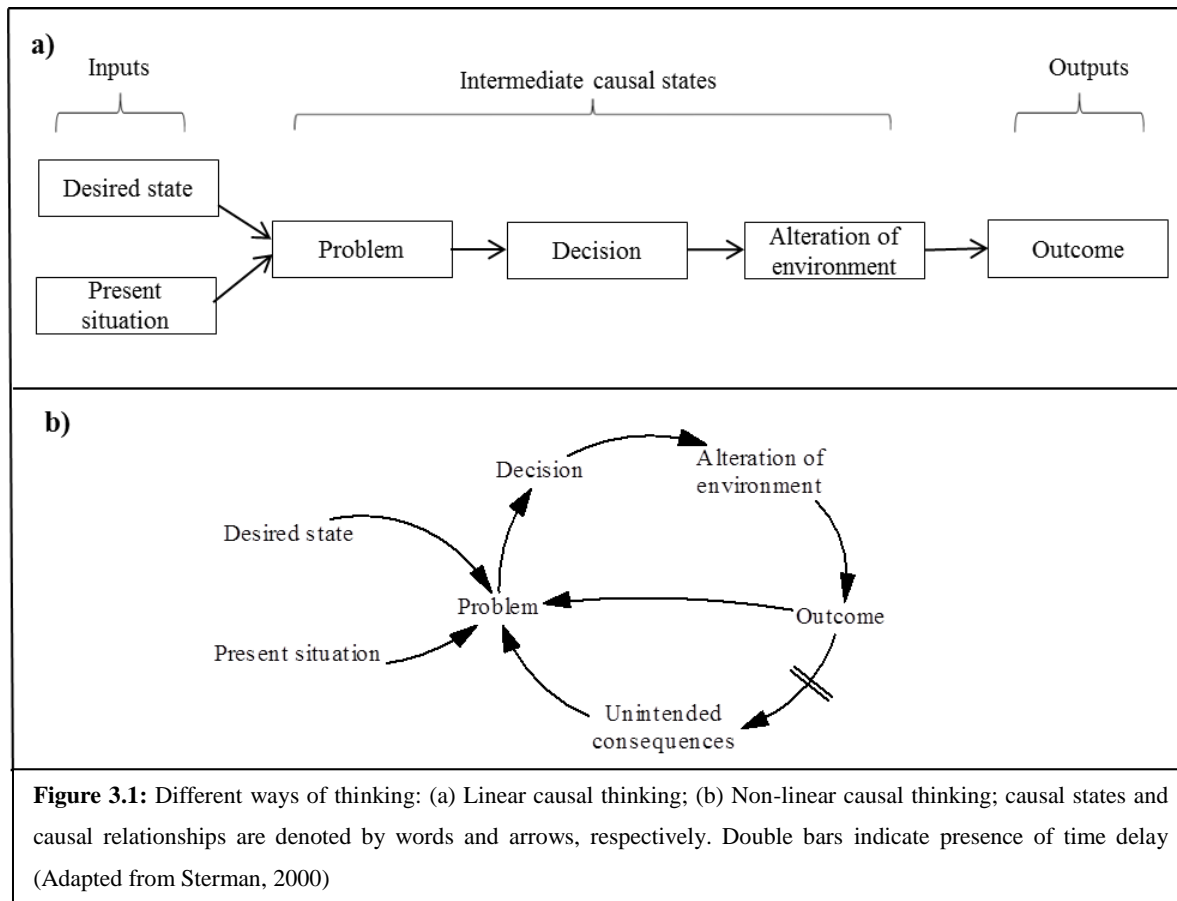
Moving from the conventional kinds of thinking to a contemporary thinking necessitates alternative frameworks and theories to guide the choice of an appropriate analytical focus and tools (Hinkel et al., 2014; McGinnis and Ostrom, 2014). According to McGinnis and Ostrom (2014), frameworks tend to organise diagnostic, descriptive, and prescriptive investigation. A framework is thus, useful

in providing a common suit of potentially relevant variables and their subcomponents to be used in the design of data collection instruments, the conduct of fieldwork, and the analysis of findings about the sustainability of complex social-ecological systems (Ostrom, 2009).   A theory, by contrast, posits specific causal relationships among the essential variables (McGinnis and Ostrom, 2014). Thus, frameworks and theories help structure problems, organise information visually, and mathematically represent relationships among important system variables, and simulate the interactions of system variables over time (Stave, 2015).

Thus, in this chapter, a systems-based approach is proposed as the alternative method of thinking, since it is more suitable in dealing with the complex dynamics of the real world (Senge, 1990; Sterman, 2000). Specifically, two system-based approaches – the Social-ecological system framework (SESF) and complex systems thinking theory, respectively constitute the analytical framework and theoretical foundation on which this study is based. SESF provides a frame to identify the key drivers of change and their dynamic characteristics relevant to the Volta River basin. Systems thinking, on the other hand, provided the theoretical base, tools and methods to investigate and model the interaction and relationship between the main drivers, issues, processes and impacts. Before proceeding to discuss the scientific underpinnings of these approaches, it is vital to make clear, the meaning of the term "system". Following this, the perspective of system-based approach, along with SESF and systems thinking theory are introduced and discussed. An essential aspect of this study is to explore and identify those important factors and processes that drive change and create unsustainable management problems within the Volta River basin (the drivers of change). Accordingly, this chapter concludes with a definition and clarification of the term 'drivers of change' in relation to sustainable natural resources management.

3.2. Understanding the Term 'System'

Following Voinov (2008, p. 6), "a system is a combination of parts that interact and produce some new quality because of their interaction." Similarly, Ewert et al. (2009) delineated that a 'system is typically made of elements, borders, relationships between elements and other systems'. Likewise, Brown et al. (2010) delineate a system simply as "a set of related parts forming a dynamic whole" (p.302). Systems are everywhere. In fact, the earth is made of interconnected systems. Systemic issues manifest every specialised knowledge areas dealing with specific problems (Rousseau, 2014). So, we often talk casually about, a social system, a political system, a production system, a distribution system, an educational system, agricultural system, and water resource system. Each of these systems consists of several parts interrelating in a meaningful manner, to enable the system,

presumably to play its critical role (Barlas, 2007). In dynamical terms, Walker et al. (2012) explained that a system is characterised by its state variables, and it is the relationships between those variables. Thus, in system analysis the emphasis is usually on the relationship between the system components, rather than on specific individual parts and investigating them separately (Darnhofer et al., 2012; Rousseau, 2014). It places emphasises on "interaction, entanglement, dependencies, exchange, connections, relationships, and co-evolution" (Darnhofer et al., 2012).

From the above definitions, three important features of a system can be deduced: (1) systems are made of parts or elements, (2) the parts interact and (3) something new is produced from the interaction. The assemblies of interrelating and co-dependent elements connected by exchanges of energy, matter, and information flow (Costanza, 1996; Barlas, 2007; Voinov, 2008). According to Proust and Newell (2006), to optimise system performance, it is necessary to optimise the way that the parts interact. The pattern of interactions or connections between the constituent elements gives rise to larger wholes (Manson, 2001; Biggs et al., 2010; Collins and Ison, 2010). Thus, words such as 'wholes' and 'interconnected' usually spring to mind with respect to systems (Maani and Cavana, 2007). Further, Chen and Stroup (1993), a system may be described as social, biological physical or symbolic; or it consists of a combination these aspects. The whole-system idea that everything is associated with everything else pervades environmental thought (Stave, 2015). This idea has, subsequently, resulted in the development of a system-based/systems thinking approaches to unravel the inherent complexities therein. It, therefore, follows that the Volta River Basin is a kind of a system, which warrants the application of systems-based approaches to understand it better, and move towards sustainable development.

3.3. Systems-Based Approach

Systems approach is a paradigm concerned with systems and the interrelations among their components (Simonovic, 2009). A systems approach assumes that most of our thinking, experiencing, practices, and institutions are interrelated and interconnected (Senge, 1990; Laszlo and Krippner, 1998). It, therefore, offers a conceptual framework to understand the dynamics these relationships. A systems approach is essential to address the decision makers' requirements to gain an insight into the working system, compare the consequences between alternative scenarios, evaluate trade-offs between decisions, ask "What if?" questions, avoid the development or transfer of problems in terms of finding answers to the challenge in question, implement plans based on future monitoring of the system, and address unanticipated impacts (Laniak et al., 2013). The approach has unearthed innovative developments in studies in water resource management systems

(Simonovic, 2009). A system based approach has led to fundamental discoveries and sustainability actions that are not possible by using conventional disciplinary, reductionist, and compartmentalised approaches (Liu et al., 2015b). Indeed, within the confines of water resource management, many scholars have argued that it is difficult to address the empirical question in sustainable development without taking systems thinking perspective (Mirchi et al., 2012; Pahl-Wostl et al., 2011; Pahl-Wostl et al., 2012; Simonovic, 2009; Welsh et al., 2013).

3.3.1 Social-Ecological System Framework

Until a few decades ago, the disciplinary division of labour and entrenched theoretical assumptions had been restricted to a situation whereby social (human) and the natural environment are investigated independently, so that human-environment interaction appears to be an afterthought and a topic for analysis at some distant point in the future (Berkes et al., 2003; Widlok et al., 2012; Liu et al., 2015b). However, global sustainability challenges have led to the realisation that most natural resource systems embedded in the planetary system, are made of complex, interconnected social, economic, and environmental subsystems (Cornell et al., 2012; Liu et al., 2015b; Steffen et al., 2015). The characteristic of the linkage between the social and environmental components is such that, it is difficult to separate the social component from the biophysical components. This is because these components continually interact and co-evolve overtime, impacting on each other. Further, uncertainty concerning the interconnections and feedbacks between the natural and anthropological drivers of environmental change that probably function at diverse spatial and temporal levels, makes it challenging for humankind to find the best solutions to sustainable livelihoods development (Rounsevell et al., 2010). Uncertainty usually range from insufficient knowledge in relation to the decision-making process of societies, to how future benefits are accounted, to how people learn, or from the processes that are considered crucial for the changing aspects of natural resources (e.g., the reproduction and development of natural resources) (Schlüter et al., 2014).

Consequently, there is a widely-held view that ecosystems and natural resource management systems, in general, should be conceived as coupled social-ecological system (SES) (Berkes et al., 2003; Liu et al., 2007; Ostrom, 2009) or linked human-environmental (H-E) system (Scholz et al., 2011; Scholz, 2011; Turner et al., 2003). This notion of coupled social-ecological system arose from the understanding of the complexity of human–nature interactions in pursuit of both human well-being and global sustainability (Alberti et al., 2011; Costanza et al., 2014; Liu et al., 2015b). In linked human and natural systems, people and nature interrelate mutually, which leads to the

formation of complex feedback loops (Liu et al., 2007). The disciplinary origin of the SESF can be traced to social sciences, specifically, to theories such as collective choice, common-pool resources, and natural resources management, while the human-environmental system framework (HESF) can be tracked back to systems science, decision theory, game theory, and sustainability science (Binder et al., 2013). Generally, these frameworks are based on the premise that that human and nature are inevitably interdependent and should be viewed upon as integrated social–ecological systems (SES) (Berkes et al., 2003; Liu et al., 2007). Unlike the traditional approaches (discussed in chapter 2), which often study and manage the social and natural dimension of complex natural resource systems, these frameworks consider the complex interrelationships and feedback between social and environmental dimensions and analyse simultaneously (Liu et al., 2007; Binder et al., 2013; Liu et al., 2015b).

The SESF was originally developed for application in a relatively distinct area of common-pool resource management situations in which resource users extract resource units from a resource system (McGinnis and Ostrom, 2014). Over time, it has grown to inform thinking about adapting to global environmental change (Foran et al., 2014) and ecology. The SESF and HESF share similar features and are often used interchangeably. Thus, for the purposes of this study, the SESF is used, since it is formulated to treat the social and ecological systems and their dynamics is equal depth (Berkes et al., 2003; Scholz, 2011; Binder et al., 2013).

However, a noteworthy feature of all coupled SES systems is that they co-evolved through time and space as complex adaptive systems (Levin, 1998; Levin et al., 2013), with resource managers a pivotal part of the co-evolution (Walker et al., 2002; Norberg and Cumming, 2008). As complex adaptive systems, they differ from simple systems, in that, they exhibit certain characteristics, including dynamism, unpredictability and uncertainty, non-linearity, emergence, scale, self-organisation, and feedback mechanisms (Levin, 1998; Berkes et al., 2003; Folke, 2006; Norberg and Cumming, 2008; Levin et al., 2013; Bohensky et al., 2015). Coupled SES may be water resource systems, fisheries, pastures, forest ecosystem system, agri-food system, or urban systems. This study views the Volta river basin as a typical coupled SES, and accordingly, adopts the Social-Ecological system framework (SESF) to provide an integrated analysis leading to a better understanding of the system processes (biophysical, socio-economic), their interrelationships, and feedback processes.

Like most SESs, around the world, the Volta River basin is a *tightly coupled system,* meaning that the Social (Human) systems are deeply embedded in natural ecosystems (the environmental

system). The actors (e.g., farmers, policy makers) within the system interrelate profoundly with each other and with the physical environment (e.g., water and forest resources, and the landscape in general). The basin is considered a complex adaptive SES system due to the presence and pressure of uncontrollable variables and multiple drivers of change, such as climate change, chronic water stress, land use change, population growth, and technological change, which are unpredictable. These challenges are usually non-linear in character, cross-scale in space and time and dynamic in nature (Thompson and Scoones, 2009; Levin et al., 2013).

The dynamic nature and presence of a non-linearity implies that the cause-effect relationships between variables are not proportional (Barlas, 2007). Instead, interactions result in an emergent characteristics and behaviours of the system holistically. Nevertheless, the basin is conceived to be *adaptive and evolving* system in response to the changing endogenous and exogenous pressures (Folke and Gunderson, 2006; Schlüter et al., 2014). Furthermore, the basin is *self-organising*, implying that minor, random disturbances are increased and developed through the system's feedback structure, resulting in patterns and behaviours in space and time (Liu et al., 2007; Sterman, 2012). The presence of these characteristics make it difficult for investigators to offer the understandings required to make better decisions concerning the management of complex ecological–economic systems (Costanza and Ruth, 1998; Levin et al., 2013; Liu et al., 2015b). Tackling these challenges means conceptualising the basin as a complex system, with a concentration on gaining an understanding into the system dynamics and critical feedback processes governing those dynamics.

Binder et al. (2013) have provided an important insight into how the social-ecological systems and associated dynamics are conceptualised. The social system is comprised of resource users (actors) and the governance system, which impacts on the actions of the users by establishing rules, as well as monitoring and sanctioning mechanisms. The ecological system, on the other hand, is conceptualised from an anthropocentric standpoint as resource system (e.g., water, forest, and corresponding resource units, e.g., water quantity, tree). In terms of its treatment of the system dynamics, the social system is conceptualised textually by several variables, including "information sharing," "deliberation processes," and "self-organization activities" categorised under the label "interaction." Dynamics in the ecological system are reflected by a suit of variables, such as natural language descriptions of the resource system and resource units, including growth rate, equilibrium properties, and productivity. The framework is explicit; for example, in addressing how combinations of multiple socio-economic and ecological (or biophysical) variables jointly affect sustainable outcomes in complex settings (Binder et al., 2013; Epstein et al., 2013; Schlüter et al., 2014).

The basic elements of any SES framework used in any empirical analysis are variables (Hinkel et al., 2014), also termed drivers of change (Nelson et al., 2006) or driving forces (Geist and Lambin, 2001, 2002). Thus, the SES framework supports the development of models in that it provides: (a) a clear quest for the important variables (or drivers) from both the ecological and social perspectives; and (b) a systematic and comprehensive mechanism of thinking (Schlüter et al., 2014). Also, it offers a framework for selecting the variables required to explain the dynamics in the social and environmental systems and the interaction between them, and recommends the possible variable for specific evaluation (Binder et al., 2013). The drivers of coupled SESs manifest and interact at diverse hierarchical scales (proximate vs. underlying) and at various spatial scales (local, regional, national, global) and temporal scales (Kittinger et al., 2012). According to Hinkel et al. (2014) whenever empirical analysis encompasses many variables, as in typically the case for SESs, it is usually imperative to organise the variables according to their meaning. In this light, this study modified and used the Social-Ecological System framework developed by Chapin et al. (2006) and updated in Carpenter et al. (2009) (see Figure 3.2), as a guide for the detailed investigation of drivers of change, trend and impacts within the Volta River Basin, since it organised the various variables and drivers according to their types and dynamic characteristics.

By framing the Volta River basin as a coupled SES, this study ultimately contributes to a research perspective that integrates human agency and environmental factors in a single explanatory model (Widlok et al., 2012). Despite the paramount value of the SESF to study coupled SESs like the Volta River Basin, it does not provide specific tools to model the relationship between the key system variables, particularly the dynamic feedback mechanisms that is produced because of the complex interactions between the system variables. Therefore, systems thinking theory that comes with its concomitant modelling tools is used as a complementary theory in this study.
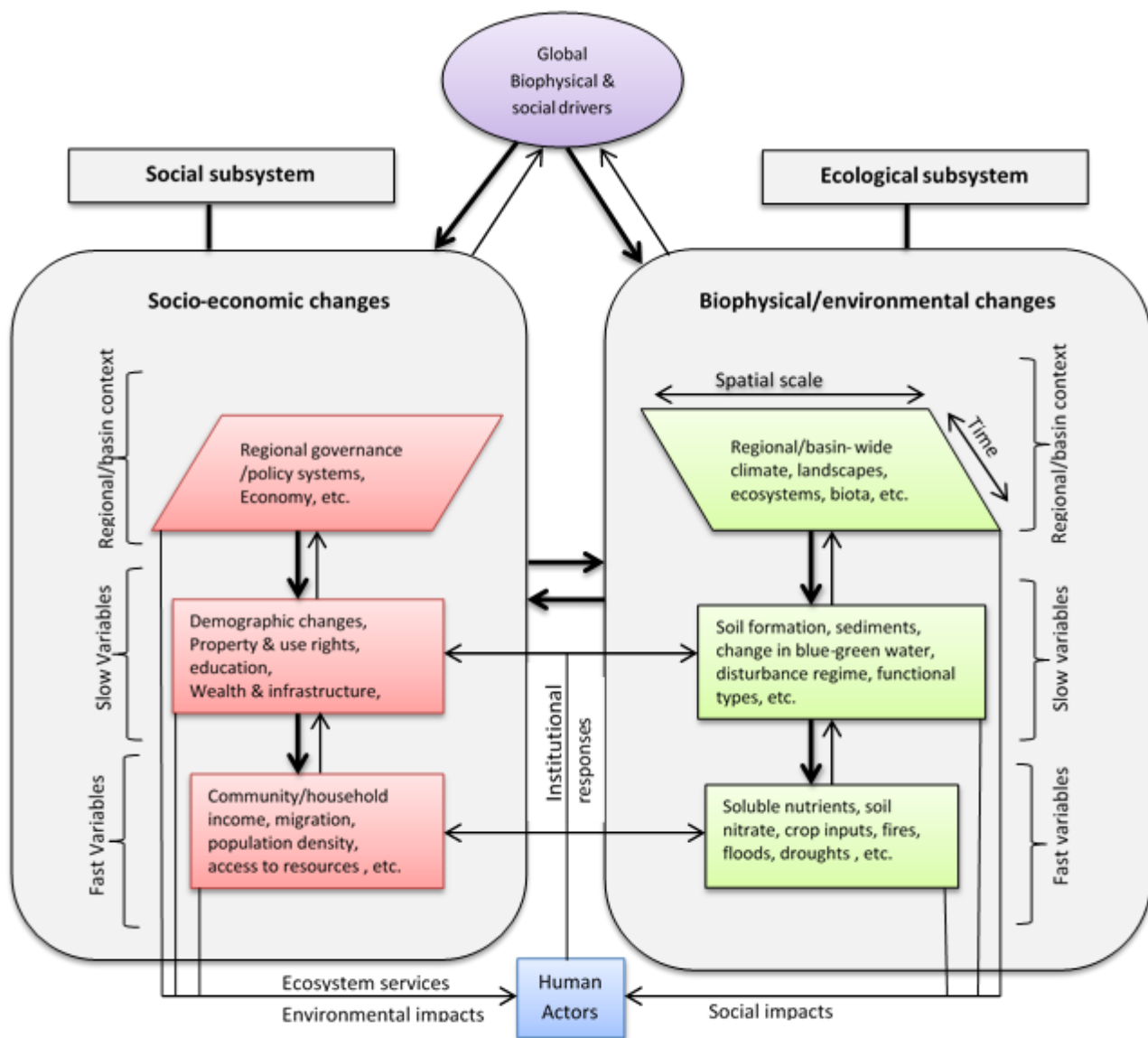
Figure 3.2. Conceptual framework for integrated analysis of coupled social-ecological systems, high linking key issues of space and time scales, social-ecological interactions, dynamics of individual actors and institutional responses (Modified from Carpenter et al., 2009).

3.3.2. Complex Systems Thinking

The idea of complex systems thinking can be traced back to Ludwig von Bertalabffy's General System Theory (GST) (Von Bertalanffy, 1969), and Ervin Laszlo's notion of systems philosophy (Laszlo, 1972). The main contribution of the GST is the concept of 'system', which as stated earlier emphasises internal relations. GST has been proposed as a foundation for the unification of science and subsequently used as one of the major tools guiding the design of large interdisciplinary systems. It draws upon other concepts from new science emerging over the past decades, for example, catastrophe theory, network theory, cybernetics, fractal theory, chaos and complexity theory, non-equilibrium thermodynamics and self-organisation, and *Jaynesian information theory* (Kay et al., 1999; Rousseau, 2014). Systems theory is also synonymous with *complexity theory,*

which preceded the idea of complex adaptive systems (Norberg and Cumming, 2008). The complex adaptive system theory offers a new lens for how to match the behaviour of individual agents with social objectives (Levin et al., 2013.p.117).

Complexity theory has been developed with insights from fields such as physics, genetic biology, and computer science (An, 2012). Collectively, these theories are described as "systems sciences or 'systemics'" (Bunge, 1979, p.1). Terms such as *system, emergence, dynamic, nonlinear, feedback, adaptive,* and *hierarchy are the hallmark of these theories.* The systems sciences encompass various types of mechanisms or dynamical states (e.g., feedback or integration or equilibrium) that play the role of maintaining the wholeness, capability, and stability of systems (Rousseau, 2014). As stated before, because systems are part of every subject domain, the systems science framework offers formal framework that can be applied in different scientific disciplines. Generic systems studies have influenced systemic thinking on sustainable development issues (Darnhofer et al., 2012). Indeed, it is well established that overcoming sustainability problems such as climate change, deforestation, and depletion of fossil fuels to overexploited fisheries, species extinction, and poisons in our food and water require the development of systems thinking (Senge et al., 2008; Sterman, 2012).

The notion of system thinking was proposed to move away from the simplistic dichotomy of pure basic vs. applied research and identify science that could overlap these two viewpoints. It usually seeks to integrate both the fundamental knowledge and utilisation of such knowledge, but does not replace the need for pure basic or applied research. According to Richardson (2011), systems thinking is conceived as the mental effort to uncover endogenous sources of system behaviour. Also, Richmond (1994, p.6) explained: "systems thinking is the art and science of making reliable inferences about behaviour by developing an increasingly deep understanding of underlying structure." Richmond (1993) argues that "doing good systems thinking means operating on at least seven thinking tracks simultaneously." These tracks are *dynamic thinking, closed-loop thinking, generic thinking, structural thinking, operational thinking, continuum thinking* and *scientific thinking*. Also, Barton and Haslett (2007) underscored that understanding systems thinking is bewildered with a wide range of dichotomies each focusing on a particular dimension of systems thinking. These include wholes vs. parts, soft vs. hard systems, open vs.closed systems, synthesis vs. analysis, holism vs. reductionism, and organismic vs. mechanistic. Systems thinking approach has played a crucial role in traditional science since the 1950s (Barton and Haslett, 2007; Sterman, 2012).

The idea of system thinking has the most natural connection to the notion of 'holism' or 'holistic thinking'. Holistic thinking may be described as a science of integration (Thompson et al., 2007; Thompson and Scoones, 2009). Integration as espoused by Jakeman and Letcher (2003) and explored further by Kelly et al. (2013) may consists of: integrated treatment of issues; integration with stakeholders; integration of disciplines; integration of processes; and integration of scales of consideration. Consistent with this, Sterman (2000, 2012) describes systems thinking as the ability to take a 'holistic' view of the world as a complex system. However, a fundamental feature of complex systems thinking is that it rejects the assumptions of linear-reductionist approaches of the traditional scientific method, often viewed as ineffective to address the complex problems and interrelationships found in natural resource management (Costanza, 1996; Hjorth and Bagheri, 2006; Pollard and du Toit, 2011).

Proponents of systems thinking believe that to understand the nature of persistent system problems we face today, linear and mechanistic thinking must be discarded for non-linear and organic thinking, generally referred to as systems thinking (Hjorth and Bagheri, 2006, p.79). Systems thinking provides a multidisciplinary "framework for seeing interrelationships rather than things, for seeing patterns of change rather than static snapshots" (Senge, 1990). As Maani and Cavana (2007, p.2) explained, "system thinking provides an alternative approach to thinking based on the notion of wholes and of interrelationships. It handles unseen complexity, ambiguity and mental models. It provides tools and techniques to uncover complexity and develop long-term solutions to persistent problems. It emphasises holistic understanding of the problem under study, with attention laid on the interactions among the sub-systems governing overall system behaviour (Cavana and Adams, 2010). Thus, as compared to the linear cause-effect relationship or reductionist techniques, systems thinking recognise that the interaction between different elements or entities can lead to a positive or negative outcome for the system (Senge, 1990).

The principle of systems thinking further recognises that a cause can produce more than one outcome (multifinality), while a multitude of causes can also generate an identical effect (equifinality) (Mebratu, 2001). By so doing, it lays emphasises on macro-level processes, including feedback mechanisms that can intensify changes leading to a significant or abrupt shifts in the relevant systems (Young et al., 2006). The approach also enables participatory modelling, and analysis of the system's behavioural trends, essential to the sustainable management of natural resources (Vennix, 1996; Mirchi et al., 2012). Systems thinking offers methods and tools for applying non-linear causal thinking to environmental problem solving (Mirchi et al., 2012).

For the purposes of this study, systems thinking refers specifically to the conceptualization, development, and use of system dynamics models (Kelly, 1998). Dynamic models can serve as useful tools to explore social-ecological interactions (Binder et al., 2013; Levin et al., 2013; Schlüter et al., 2014) at a variety of settings and scales. Schlüter et al. (2014) defined "a dynamic model is defined as a formal, theory- or empirically based, simplified mechanistic representation of the structure and processes of a real-world entity considered relevant to answer a particular question about the development of the system over time." Through mathematical analysis or simulating interconnections between the social and ecological systems, dynamic models enable the analysis of the impacts of important social-ecological feedbacks for management and sustainability (Schlüter et al., 2014). Importantly, the advent of computer-based modelling has assisted modellers and model users in terms of the selection the best modelling approach and tools to analyse and formulate problems, and accordingly make decisions about sustainability issues with stakeholders, which can then drive alternative solution (Bosch et al., 2007).

Conventional modelling approaches that have been variously used to develop models in complex SES systems include: systems dynamics (Forrester, 1958), Bayesian networks (Varis, 2002; Varis and Kuikka, 1999), coupled component models (Delden et al., 2007), agent-based models (Moss et al., 2001), and knowledge-based models (or expert systems). Kelly et al. (2013) have noted five distinctive purposes of using these modelling approaches, including prediction, forecasting, management and decision-making under uncertainty, social learning, and for developing understanding/experimentation. New knowledge of system dynamics and predictability has arisen from the investigation of complex systems, and is developing innovative tools for modelling social-ecological systems (Costanza, 1996; Costanza et al., 2014). In this study, the system dynamic modelling approach is used as it is well suited for facilitating learning and a shared understanding about complex problems in environmental/natural resources systems. This method and how it was applied is described in the methodology chapters 6 and 7.

3.4. Defining and Understanding Drivers of Change

One of the aims of this study is to identify the key drivers and processes within the Volta system and use the information to build a conceptual and system dynamics simulation model that captures their interactions and feedback processes. However, the process of how one might do this is not that clear. Indeed, the first step in system dynamics modelling is the identification of the key issues and variables in the system whose behaviour over time defines the problem (Forrester, 1961; Sterman, 2000; Stave, 2003). Accordingly, it is important to define what this study means by drivers of change.

Over the past decade or so, a significant amount of work has emerged over the issue of drivers of system change (Walker et al., 2012). The definition of a driver is aptly captured in two well-known frameworks – the Drivers-Pressures-State-Impact-Response (DPSIR) framework (Rapport and Friend, 1979); and the Millennium Ecosystem Assessment (MA) framework (MA, 2003, 2005). Within the DPSIR framework drivers are the underlying sources of environmental change that are exogenous to the system or region (e.g., climate and socio-economic change, national and international policy) (MA, 2005). They represent either the past, present or future conditions that lead to changes in the environment (Rounsevell et al., 2010). However, Tzanopoulos et al. (2013) argued that the usage of the term *pressures* in the framework seems to connote an implicit value and places the emphasis on the negative impacts of human activity on environmental systems. Another noted limitation of the DPSIR framework is the dearth of constancy concerning its application to address environmental problems (Maxim et al., 2009; Rounsevell et al., 2010). According to Maxim et al. (2009.p.13), the DPSIR framework appears as "a deterministic and linear 'causal' description of environmental problems, which certainly overlooks the complexity of the environmental and socio-economic systems."

Thus, the definition of a driver captured in the Millennium Ecosystem Assessment framework appears to be one of the broadest and most widely used. In the MA framework, "a driver is any factor that changes an aspect of an ecosystem" (MA, 2003, 2005, p.32). Different types of drivers are also distinguished in the framework: 'direct', and 'indirect drivers' of change. A 'direct driver' unequivocally influences ecosystem processes. 'Direct drivers' are predominantly physical, chemical, and biological, such as climate change, land cover change, air and water pollution, irrigation, use of fertilisers, harvesting, and the introduction of invasive alien species. An 'indirect driver' on the other hand, operates more diffusely, by changing one or more direct drivers. These are mainly demographic, economic, socio-political, scientific and technological, and cultural and religious factors. 'Drivers' within the DPSIR framework are comparable to the 'indirect drivers' in the MA framework, while 'pressures' correspond to the 'direct drivers' of the MA (Rounsevell et al., 2010; Tzanopoulos et al., 2013). 'Direct' and 'indirect drivers' can be respectively be considered as *proximate causes* and *underlying driving forces,* according to Geist and Lambin (2001, 2002). Regarding scale, proximate causes is seen to operate directly at the local level, while, underlying driving forces may manifest directly at the local scale, or indirectly, from the national or even global scale (Geist and Lambin, 2001). The categorisation of drivers based on the scale at which they operate has also been espoused (Hazell and Wood, 2008). However, the distinction between 'direct' and 'indirect drivers' may be difficult to delineate in some cases. For example,

demographic variables can, for example, be direct drivers, but also represent underlying drivers (population growth) (Kolb et al., 2013).

In several other studies, the factors or drivers of change in most ecosystems have also been variously characterised as 'exogenous controls', 'slow' changing variables and 'fast' changing variables (Carpenter and Turner, 2000; Gunderson and Holling, 2002; Gunderson et al., 2002; Walker et al., 2006; Chapin et al., 2009; Huber-Sannwald et al., 2012) or 'slower-acting', long-term drivers of change and 'fast-acting', short term drivers of change (Msangi and Rosegrant, 2011). Exogenous controls are external factors such as regional climate or biota and global market conditions that strongly influence the properties of a system (Chapin et al., 2009). Critical 'slow' changing variables or processes are factors, such as population growth; income growth, soil fertility, household capital wealth among others, tend to act rather slowly and gradually over a lengthy time, and evolve in a somewhat predictable manner with impacts in the long-time period (Carpenter and Turner, 2000; Msangi and Rosegrant, 2011). In contrast, fast-moving variables or drivers of change (e.g. droughts, floods, rainfall variability, soil water content, crop yield, household disposable income, disease and pest outbreaks etc.) are variables that change very rapidly and might have influence on the agricultural system in the short time period (Fernandez et al., 2002; Huber-Sannwald et al., 2006; Msangi and Rosegrant, 2011). Slow moving variables within natural resources systems greatly influence fast changing variables at the same spatial scale (Chapin et al., 2009).

In this study, the MA definition of drivers of change is used as it offers a flexible definition and analysis of drivers (Tzanopoulos et al., 2013). Thus, all types of drivers: direct, indirect, exogenous, endogenous, fast and slow moving drivers or variables from both biophysical and socio-economic domains are considered, since most coupled social-environmental systems are not only affected by one individual driver, but rather a combination of different types of drivers at multiple scales (Chapin et al., 2009; Young and Steffen, 2009; Huber-Sannwald et al., 2012). "Drivers" are sometimes referred to as "variables". Thus, the two terms are used interchangeably. The focus here is to investigate how these drivers change over time and influence the sustainability of the Volta River basin, particularly water availability and sustainable agricultural development.

3.5. Concluding Remarks

In this chapter, the theoretical and conceptual framework comprising; social-ecological system framework and complex systems thinking theory used for the study are discussed. The terms system and drivers of change are also discussed in relation to this study. Together, these approaches

provide a novel framework for investigating and analysing the Volta River Basin water resources system in an integrated and holistic manner, and, as such, do not focus on a comprehensive understanding of individual elements, but on how important aspects contribute to the understanding of the dynamics of the whole system and the impact of the system feedback structure on policy interventions. In the next chapter, the overall research methodology is outlined and discussed.

CHAPTER 4: THE RESEARCH METHODOLOGY

4.1. Introduction

This chapter explores the general research design framework as a broad orientation to the conduct of the research. As Rodela et al. (2012) underlined, "a journey through methodological choices gains specific relevance when it is accompanied by a reflection on practices of knowledge production and validation." Accordingly, the chapter provides detailed information on the philosophical foundations, methodological approaches, research methods, the tools and methods of data collection and analysis that would be employed to address the research aim and objectives, as outlined in chapter 1. The overarching concern is that the approach chosen should be grounded in the philosophical worldviews and rigorous in its operationalization in the pursuit of the goal, recognising that a wide range of considerations and details go into the process of conducting a research.

To this end, the chapter is structured into six main sections. It begins by discussing the main elements of a research design framework in section 4.2, focusing on how the research philosophies/paradigms and methodology, research strategies and methods work together to form the research study. In section 4.3, the framework is used to propose the overall research methodological framework for the overall study. Thus, the case for a mixed-methods approach is proposed, resulting in three-tiered research methods chosen to address each research objective. These include the use of *structured expert judgement technique*, *participatory modelling* based on *casual loop modelling*, and *system dynamics simulation modelling approach*. Also, the justifications and rationale for adopting these research methods are incorporated into the discussion. Section 4.6 summarises the chapter and concludes the discussions.

4.2. Elements of a Research Design Framework

Research design involves 'the process that one can follow to find answers to the research questions' (Hassan and Ghauri, 2014). Over the past few decades, many research design and methodological frameworks have evolved, integrating a variety of impacts and the contemporary scientific knowledge. Several research textbooks and articles suggest that these approaches have become increasingly complex and pluralistic (Sarantakos, 2005; Johnson et al., 2007; Morgan, 2007; Bryman, 2012). The complex nature of the research design process is often shown in well-constructed designs, which ultimately, provide the standards and principles of research practice

(Sarantakos, 2005). These developments are spurred on by the changing social and economic conditions and the advent of computer technologies in the 21st century. The issues further raise questions in relation to known empirical evidence, which, in turn, reveal particular expectations, concerning: (1) the protocols that guide knowledge construction; and (2) validation (i.e., what is considered as evidence) in the processes (Rodela et al., 2012). To assist with the design of an appropriate research strategy to address the aims and objectives of this study, Creswell (2009) and (Greene, 2006) research design frameworks provide a useful guide.

Creswell (2009, p.5) suggested that three important components must be explored in the design of a research strategy. These comprise: (1) philosophical assumptions concerning knowledge claims (described here as *methodological paradigm*); (2) general procedures of research – that is strategies of inquiry (described here as *research strategies*); and (3) the detailed procedures for data collection, analyses and writing – that is methods (interpreted here as *research methods*). Figure 4.1 illustrates this framework.
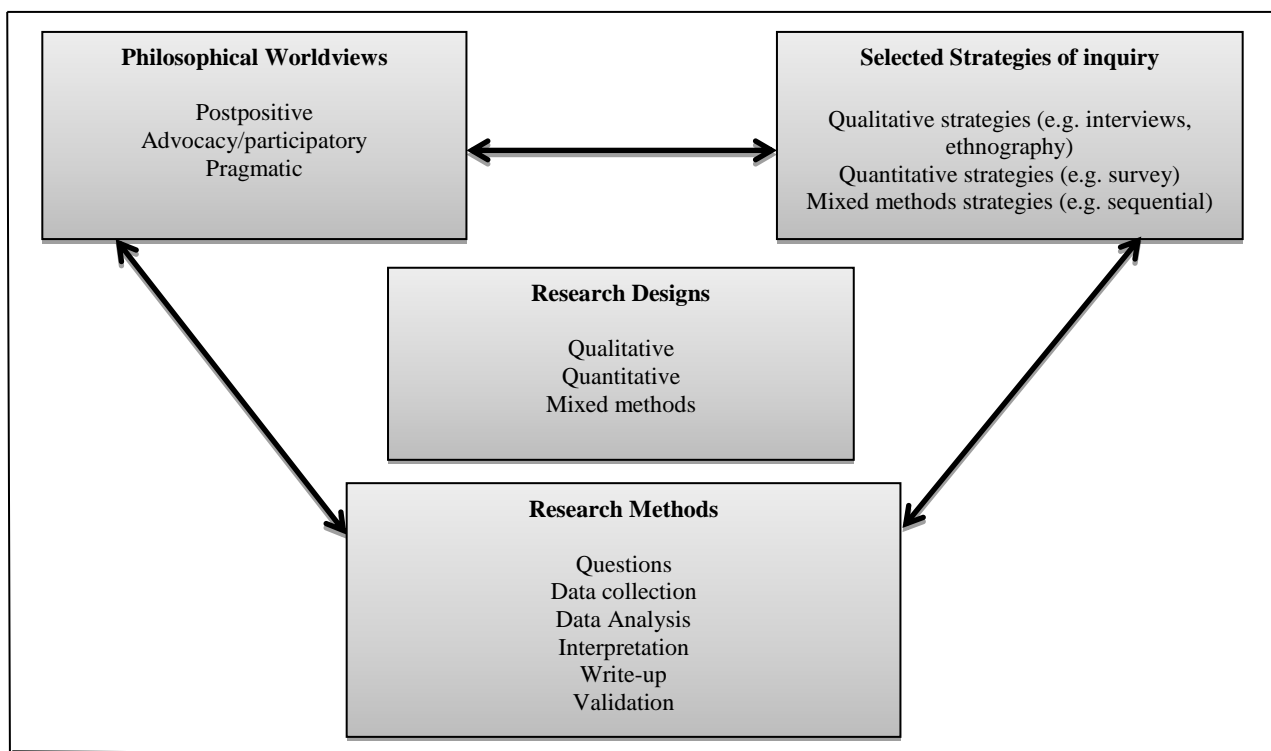
Figure 4.1: A Framework for Research Design - The Interconnection of Worldviews, Strategies of Inquiry, and Research Methods (Adapted from Creswell, 2009, p.5)

Greene (2006) offered a similar framework, but took it a step further. Greene proposed a design strategy, which she labelled *Mixed-Methods Social Inquiry*. Greene decomposed the mixed methods social inquiry or mixed methods methodology (broadly viewed) into four interconnecting, but

nevertheless conceptually distinctive realms: (a*) philosophical assumptions and stances* (i.e., what are the basic philosophical or epistemological assumptions of the methodology?); (b) *inquiry logics* (i.e., what traditionally is called "methodology", and refers to broad inquiry purposes and questions, logic, quality standards, writing forms that guide the researcher's "gaze"), (c) *guidelines for practice* (i.e., detailed actions and tools employed to carry out the research; "the how to" part of research methodology): and (d) *socio-political commitments* (i.e., interests, commitments, and power relations surrounding the location in society in which an inquiry is situated)". In the sections that follow, the elements of these frameworks and their underlying assumptions are reviewed and discussed. The overarching research plan for this study, based on these frameworks is, consequently, proposed.

4.2.1. Research Philosophy and Methodological Paradigms

A research methodology is embedded into issues that are the pillars of the philosophy of science beliefs concerning the nature of the world (*ontology*) and about the nature of social knowledge (*epistemology*) (Greene, 2006, 2008). This perspective also encompasses suppositions related to issues, 'such as *objectivity* and *subjectivity*, the role of context and contingency in social knowing, and the relationship between the *knower* and the *known*' (Greene, 2006, p.93). There are also issues about *methodological paradigm*, which researchers ought to delineate and clarify. Methodological paradigm consists of the rationale and the philosophical assumptions within which a research is carried out (Sarantakos, 2005).

Traditionally, there are two distinct paradigms for doing research – that is *induction* and *deduction* (Gill and Johnson, 2010). Deductive research starts with theory development, hypotheses articulation, operationalising concepts, data collection and analysis, findings, hypothesis confirmation or rejection, and revision of theories. Induction simply reverses the deductive process. Specifically, it begins with the 'data' (e.g., observing the empirical world), obtaining documentary evidence, and then *constructs* meanings out of the information gathered to develop a theory. There are very few research textbooks that have not devoted a whole chapter or a section to the distinguishing features of induction and deduction principles. However, the deductive-inductive dichotomy is viewed as unhelpful (Layder, 1993), false or even misleading (Tuuli, 2009).

Thus, the common philosophy of knowledge: *ontological* (i.e., conception of reality) and *epistemological* (i.e., what should be regarded as knowledge) and their underling viewpoints (Bryman and Bell, 2003) offers an appropriate frame for espousing the philosophical assumptions that guide various research designs (Neuman, 2011; Tuuli, 2009). According to Neuman (2011), all

scientific research is founded on assumptions and principles from these two areas whether a researcher acknowledges them. Neuman (2011) viewed *ontology* as a research philosophy that deals with the nature of being, or what exists; the area of philosophy that asks what reality is and its fundamental categories. *Epistemology*, on the other hand, entails the construction of knowledge, with emphasis on "how we know what we know or what are the most valid ways to reach truth." *Methodology* encompasses "the process of how we seek out new knowledge, the principles of the inquiry and how the inquiry should proceed" (Schwandt, 2007, p. 190). These principles influence how researchers answer research questions in terms of the legitimacy of knowledge (qualitative vs. quantitative, etc.), the legitimacy of methods to produce knowledge (experimentation, induction, hypothesis testing, etc.), and the assumptions embedded in certain conceptualisations of the object of inquiry and specific methodologies that follow (Miller et al., 2008). These distinctions are illustrated in Table 4.1.

Table 4.1: Philosophical foundations of Research (Adapted from Sarantokos, 2005, p. 32)

	Deals with
Ontology	The nature of reality ASK: what is the nature of reality? Is it objective (out there), constructed, subjective? OR BETTER: What does research focus on?
Epistemology	The nature of knowledge ASKs: How do we know what we know? What is the way in which reality is known to us? OR BETTER: What kind of knowledge is research looking for?
Methodology	The nature of research design and method ASKS: How do we gain knowledge about the world? OR BETTER: How is research constructed and conducted?
Research	The execution of research designs

There is an established consensus that research should be carried out under a paradigmatic *framework* (Sarantokos, 2005; Creswell, 2009). Consequently, ontological, epistemological, and methodological concepts of social science research are further 'packaged' in paradigms, which guide daily research inquiry (Sarantokos, 2005). However, paradigms are rarely discussed in most research texts and some research works, and when they do, they are given different prominence and sometimes conflicting definitions. In some research articles and textbooks, paradigms are articulated at the beginning of the text with research design subsequently (e.g., Denzin and Lincoln, 2011; Robson, 2011). Others, however, may make only an ephemeral reference to paradigms at a much later stage or make no mention of it at all (Mackenzie and Knipe, 2006).

In chapter 2 of this study, a scientific paradigm was broadly explained as researchers' beliefs concerning as they produce knowledge, particularly as it relates to the area of natural science studies, as argued by Kuhn (1962/1970). With regards to the conduct of a social science research, a plethora of definitions of paradigms can be gleaned from the scientific literature. Morgan (2007, p.

49) argued "for a version of paradigms as systems of beliefs and practices that influence how researchers select both the questions they study and methods that they use to study them." Paradigm is a general framework for theory and research that encompass basic assumptions, important issues, models of quality research, and methods for finding solutions (Neuman, 2011). Patton (2002) referred to paradigms as guidelines for rational thought concerning research design, measurement, analysis, and personal participation. Guba and Lincoln (1994) on the other hand, explained a paradigm as a collection of basic beliefs that must be incorporated to explain the relationship between variables. Thus, paradigms provide researchers with the needed assumptions and principles to select the suitable methods and techniques to conduct a research.

Several methodological paradigms are also delineated in the literature, including positivist (and post-positivist), constructivist, interpretivist, transformative, emancipatory, critical realism, pragmatism, deconstructivist, advocacy and participatory worldviews (see Mackenzie and Knipe, 2006; Creswell, 2009; Denzin and Lincoln 2005, 2011). Each of these has developed its own principles, assumptions, and methodology (Denzin and Lincoln, 2011). Most importantly, the capacity to focus on these other belief systems provide the needed justification for the different types of research questions and the application of different types of methods to address those questions (Morgan, 2007). In what follows, some commonly cited paradigms in research are briefly discussed.

Positivist (post-positivist paradigm): Although positivist/post-positivism or so-called realist-positivist have been discussed together in some texts (e.g., Mackenzie and Knipe, 2006), two paradigms differ slightly (Denzin and Lincoln, 2011). Positivism paradigm assumes that reality exists independently of a human observer, and that through scientific research, we can build objective, real knowledge (generalisation) about reality (Creswell, 2009; Denzin and Lincoln, 2011). This worldview is also known as scientific methods for doing scientific research (Cresswell, 2009). As scientific methods, they generally seek to test a theory or explain an experience (Mackenzie and Knipe, 2006) "through observation and measurement or to predict and control forces that surround us" (O'Leary, 2004, p.5). Conventional evaluation criteria such as internal and external validity are stressed (Denzin and Lincoln, 2011).

Post-positivist perspective is usually linked to 'hard science', which develops hypothesis and tests them with repeatable and quantifiable experiments. Practitioners of 'hard' science, many of whom are natural scientists are trained to believe that the world they seek to understand has an independent truth that they are discovering in their studies (Douthwaite et al., 2003). Indeed, its proponents assume that once they know external factors, individual reasoning simply follows a

deterministic, machine-like rational logic of decision making (Neuman, 2005). In fact, the principles underlying this perspective run parallel to the linear reductionist approach discussed earlier in chapter 2. It is reductionist in the sense that the goal is to reduce the phenomena into small, discrete sets of ideas to be tested, such as the variables that encompass hypothesis and research questions (Cresswell, 2009). It, therefore, directs attention to 'standardization (i.e., attaining objectivity through the removal of personal judgment) and replicability (made possible in part by standardized and reproducible methods) (Williams and Patterson, 2007). Rigorous and quantitative analysis, and control over variables are the foundation of the associated the scientific methods, with the overall goal of generalisation of the research findings (Rodela et al., 2012). Pure positivism is gradually giving way to post-positivist perspective, which assumes that reality does exist, but that it can never be fully understood, although it can be approximated (Denzin and Lincoln, 2003; Robson, 2002). Post-positivism rests on several methods as a means of incorporating as much reality it can handle (Denzin and Lincoln, 2003). The conventional methods employed by positivist or post-positivist researchers are experimental, quasi-experimental, and survey designs.

Interpretivist/Constructivist paradigm: Interpretivist/Constructivist paradigm: The paradigms interpretivism and social constructivism share similar beliefs and as are often combined and discussed in some texts (Mertens, 2005; Denzin and Lincoln, 2011). Their goal is to foster understanding of the real world rather than on prediction and positive verification. Denzin and Lincoln (2005) are two well-known scholars who have made important contributions to constructivist research approaches. The central assumption of the interpretativist and constructivists paradigm is that there is "in practice neither objective reality nor objective truth in the world" (Sarantakos, 2005, p.13). Rather, reality or knowledge is socially constructed (Denzin and Lincoln, 2005; Sarantakos, 2005), hence, instead of testing assumptions, the researcher serves as an observer looking to identify the different interpretations available, and to gain an insight regarding how these shape one another, and the object of interest (Rodela et al., 2012, p.17). According to Sarantakos (2005), constructing reality imply making accounts of the world around us and gaining understandings through culturally defined and historically situated interpretations and personal experiences. Sarantakos (2005) maintained that the fundamental process that facilitates construction and reconstruction is interpretation (p. 39). The overall goal of a constructivist's researcher is how to mentally grasp and reveal the explanations that different people have concerning the issue. Typical research methods employed include ethnography, grounded theory, hermeneutics, empirical phenomenological research, participatory research and so forth. Quantitative data may be employed in a manner, which assists or deepens the description of qualitative information (Mackenzie and Knipe, 2006).

Critical Research Paradigm: As compared to interpretative research, critical research, tries to engage in naturalistic inquiry (i.e., the study of subjects or objects in their natural environment), and often combine interventions in the design of the study, such as participatory workshops (Rodela et al., 2012).

Pragmatic Worldview: Pragmatists subscribes to the idea that the research question should inform the method(s) used, with the understanding that 'epistemological purity does not get research done' (Onwuegbuzie and Leech, 2005). Like post-positivism, pragmatic paradigm is based on actions, conditions, and consequences instead of past conditions (Cresswell, 2009). Its proponents believe that quantitative techniques cannot be considered positivist, neither can qualitative approaches be viewed as hermeneutic (Refsgaard et al., 2007; Robson, 2011). As such, pragmatists advocate combining methods within a single study (Creswell, 2003). From this perspective, pragmatism liberates the researcher from any mental and practical limitations imposed by the "forced choice" distinction between post-positivism and constructivism (Creswell and Clark, 2007, p.27). Within this paradigm, the research question is paramount and the appropriate data collection and analysis techniques are selected to illuminate on the problem with no philosophical allegiance to any other research paradigm (Mackenzie and Knipe, 2006). It recommends "eclecticism and pluralism" – meaning that different, even conflicting, theories and perspectives can be important; observation, experience and experiments are appropriate forms of gaining and understanding the world and the people in it (Robson, 2011). Pragmatism works without a method or methods and does not discriminate against others; neither does it expect to find consistent causal relations or truths, on the contrary, it seeks to investigate a question, theory, or situation using the best research method (Feilzer, 2010).

Advocacy and participatory worldview: Advocacy/participatory worldview perspective of science was popularised in the 1980s from people who believe that post-positivist principles imposed structural laws and theories that did not benefit marginalised communities in society or problems of social justice that needed to be tackled (Creswell, 2009). Like qualitative research, participatory research places strong emphasis on contextual techniques in order gather qualitative data, with due regards to local knowledge, and "ensures local ownership and control of data collection and analysis" (Chambers, 1997). This type of "ownership and control" is aimed at providing the opportunity for local communities to pursue their own solutions to their problems. Participatory research basically uses different types of participatory techniques to explain problems in a context to outsiders (while considering ethical issues concerning the behaviour, transparency and ownership) (Garbarino and Holland, 2009). In addition, advocacy/participatory worldview argue that research study must not be pursued without political considerations (Creswell, 2009). In doing

this, stakeholder participation in research changes from passive to active. Participatory approaches produce qualitative as well as quantitative information. Participatory numbers may be derived and applied in the context, but have also been taken to scale, most particularly by participatory surveys or by a combination of group-based scoring and ranking activities. Recent calls to blend qualitative methods with quantitative techniques have strongly advocated a pragmatist philosophy (Morgan, 2007; Creswell, 2009).

Post-normal science: A "post-normal" approach to research tends to be issue-driven, policy relevant, trans-disciplinary and emphasises "issue improvement". With regards to the later issues, most modern post-normal researchers deploy action research in their investigations. This implies that the researcher is not confined to a disciplinary area; instead he/she transient boundaries in collaboration with stakeholders in the problem definition, co-learning, knowledge co-production and validation (Rodela et al., 2012). The researcher is exposed to, and recognises the value of different ways of knowing and knowledge that can be used during the research process (Rodela et al., 2012). From this perspective, the post-normal science perspective shares the same characteristic as the advocacy and participatory worldview (discussed above).

Although the above discussion has shown many paradigms, the scientific paradigms that are mostly used in most research are primarily the positivism/post-positivism and constructivism/interpretivism perspectives (Creswell and Clark, 2007). Further, even though these paradigms or worldviews appear to have different features in several important aspects, the notions of interpretative/constructivism, pragmatism, critical, advocacy and participatory worldview and post-normal) tend to have the same characteristics. As acknowledged by many researchers, (e.g., Lincoln et al., 2011; Rodela et al., 2012), they are underpinned by the assumption they diverse explanations of reality (co)exists, and consider qualitative data and case studies rather than hypothesis than can be tested to make generalisations.

The instrumentalist paradigm: The instrumentalist paradigm: The instrumentalist paradigm, it is often presented as anti-realist position, although this is not always the case (Boven, 2009). Within this paradigm, models are only considered as necessary tools to explore complex systems, without making any "realist" claims (Boven, 2009). It is based on the notion that all scientific theories of the past have turned out to be wrong; hence, it is reasonable to assume that prevailing theories will also prove to be false (Boven, 2009; Kleindorfer et al., 1998). Instrumentalist paradigm holds that, the general propositions of a scientific theory or a simulation model are relegated to the role of convenient arrangements (i.e., instruments) that are used to order our observations (Kleindorfer et

al., 1998). Instrumentalism is therefore considered to be the engineering view of environmental modelling (Boven, 2009).

To summarise from the above discussions, it is imperative to understand the relationship between '*research philosophy or assumptions*', '*research methodology*' and *research methods*. Research philosophy or assumptions are statements of things that we cannot directly observe or empirically evaluate (Neuman, 2011). They are basically starting point of any inquiry. Generally, a methodology will develop, either implicitly or explicitly, based on a paradigm with its associated philosophical principles (Mingers and Brocklesby, 1997). The role philosophical assumptions are, therefore, to inform methodologies about the nature of knowledge, or about what is regarded as fact and where knowledge is to be sought. Methodologies, following these instructions, prepare 'packages' of appropriate research designs, to be used by researchers, directing to the specific focus their research activity, and how to recognise and extract knowledge. Thus, research methodology rests on these assumptions (i.e., the foundation of *ontology* and *epistemology*), which, in turn, guides the selection of research designs and instruments (Neuman, 2011; Sarantakos, 2005).

A methodology is, therefore, more than just methods. But many methods sections in much text see it as such. A method is the set of techniques or tools with which data is collected, and as with any tool, methods must be chosen for their ability to address a research question or questions (Boyd et al., 2004; Sarantakos, 2005; Bryman, 2012). A technique is an action that has a well-thought objective purpose within the methodological framework (Mingers and Brocklesby, 1997). Methods are, however, not passive instruments. They – and the specific logic with which they are implemented – provide a structure on empirical systems that have significant implications for the nature of the empirical test (Williams and Patterson, 2007). Therefore, one needs to apply the study of methodology to relate problems in epistemology or ontology – the philosophical assumptions – with issues in research design (i.e., methods and techniques) – rather than separating our thoughts about the nature of knowledge from our efforts to produce it (Morgan, 2007). For example, in this case study of the Volta River Basin, different methods and strategies were deployed to address the research objectives, as outlined in Chapter 1.

4.2.2. Research Strategies and Methods

The various methodological paradigms and philosophies explored in the above sections, would suggest different research strategies/approaches or methods. Generally, two basic research strategies – qualitative and qualitative strategies – have traditionally been used in most research. Consequently, a substantial discussion in research texts has concentrated on distinguishing

qualitative research from the quantitative technique (Morgan, 2007). Recently, mixed-methods research strategy (Johnson and Onwuegbuzie, 2004; Creswell, 2009) or methodological pluralism (Dow, 1997; Norgaard, 1989) have emerged as a third major alternative. Indeed, Johnson et al. (2007) claimed that the research community is currently in "a three methodological or research paradigm world, with quantitative, qualitative, and mixed methods research all thriving and coexisting." Thus, strategies for designing and conducting research will, therefore, vary depending on whether it takes the quantitative, qualitative or mixed-methods route (Neuman, 2005). The important differences between the two research strategies are detailed in the sections that follow.

4.2.2.1. Quantitative Research Approaches and Methods

McLafferty et al. (2010, p.46) define quantitative research as that which primarily involves quantifiable, numeric data and the use of statistics." Hence quantitative approach refers to research designs that involve numerical and objective measurements usually to address questions that hypothesize relationships among variables. The primary aim of this research strategy is to observe accurately and captures details of the empirical world and express what has been found in numbers. The research design is "pre-specified" at the beginning of the research (Robson, 2011). Thus, a quantitative research, usually proceeds as a deductive process – that is, in a straightforward sequence – first conceptualization, next operationalization, and then application of the operational definition or the collection of data (Neuman, 2005). Quantitative research therefore rigorously links abstract ideas to a measurement of procedures that can produce precise information in the form of numbers (p. 204). Objectivity, standardisation (for the sake of control and accuracy), and generalisation of findings are the primary aim (Robson, 2011). Regarding research philosophy, the quantitative research is grounded in the positivist paradigm, a realist/objectivist ontology or the empiricist epistemology (Sarantakos, 2005). Quantitative research is further catigorised into experimental and survey research.

Experiments are also classified into true/classical experiments and quasi-experiments. However, the high level of control needed to assure internal validity often results in very restrictive conditions which make true experiments appear artificial, and thus, lacks external validity. In some circumstances (e.g., evaluation of some social programme or policy), random assignment of subjects to treatment and control groups is not always possible as the treatment group is a 'given'. Nevertheless, experimentation today is highly complemented by well-defined procedures of randomization, statistical control, and statistical analyses (Greene, 2006).

Surveys can take several forms and can include a written questionnaire, which the respondent self-

completes or self-administered by the researcher using face-to-face or a telephone methods. Survey method offers a high amount of data standardisation (Robson, 2011) and provides for transparency and repeatability (O'Leary et al., 2009; Kappel et al., 2012). Moreover, questionnaire method is simple, quick and allowed us to make a direct and meaningful comparison between the technical (scientific) and local knowledge sources. However, surveys have several limitations, including: (1) the researcher not knowing what he/she wants; (2) poor construct validity of measures and; (3) poor external validity when biased samples are used (Mitchell and Jolley, 2001). Robson (2011) also talked about the possibility of social desirability response bias – that is people responding in a manner that portrays them in good light. These drawbacks can, however, be handled through careful planning and design of the survey instrument (Robson, 2011).

4.2.2.2. Qualitative Research Approaches and Methods

Qualitative research emerged because of a reformist movement in the 1970s. Although an accurate definition is somewhat ambiguous (Denzin and Lincoln, 2005), McLafferty et al. (2010, p.46) define qualitative research methods simply as "those approaches that primarily involve the use of non-numeric data, expressed and analysed in words." Compared to the quantitative approach, qualitative methods consist of research designs that explore the meaning, interpretation and the construction of social reality using data mainly in the form of words and ideas rather than numbers. The attention is on inductive logic, meanings, and on the natural context which the research is being conducted (Denzin and Lincoln, 2011; Robson, 2011, Bryman, 2012). Thus, objectivity and generalizability is not sought; rather, the social world is viewed as a creation of the people involved (Robson, 2011). Qualitative research belongs to the constructionist/interpretivist epistemology research paradigm (Sarantakos, 2005; Denzin and Lincoln 2005, 2011). A wide array of qualitative research techniques has been identified in the literature. For instance, Wolcott (2001) identified 19 of such approaches, while Tesch (1990) identified 28. However, the widely discussed and used techniques include: interviewing, participant observation, analysis of documents, ethnography study, phenomenology, hermeneutic, case study, and grounded theory study (see Creswell, 2009; McLafferty et al., 2010; Denzin and Lincoln, 2011; Bryman, 2012; Robson, 2011).

4.2.3. Mixed Methods Research Strategy

Johnson et al. (2007, p.129) defined mixed-methods research broaly as a "research paradigm that (a) partners with the philosophy of pragmatism in one of its forms (left, right, middle); (b) follows the logic of mixed methods research (including the logic of the fundamental principle and any other

useful logics imported from qualitative or quantitative research that are helpful for producing defensible and usable research findings); (c) relies on qualitative and quantitative viewpoints, data collection, analysis, and inference techniques combined, in accordance with the logic of mixed methods research to address one's research question(s); and (d) is cognisant, appreciative, and inclusive of local and broader socio-political realities, resources, and needs." Cresswell (2003) defined mixed-methods research is a research design (or methodology) in which the researcher collects, analyzes, and mixes (integrates or connects) both quantitative and qualitative data in a single study or a multiphase programme of inquiry. Mixed methods as a research strategy is rooted in the pragmatism paradigm (Johnson et al., 2007; Greene, 2008). McLafferty and Onwuegbuzie (2006) have attempted to offer a type of mixed methods, contingency theory by proposing a structural framework that allows for the combination of quantitative and qualitative research strategies and, by extension, provides a philosophical based for mixed methods research. Under their framework, the quantitative and qualitative research paradigms are no longer dichotomous—rather, they are structurally distinct. A continuum of mixed-methods research strategy is illustrated in Figure 4.2.
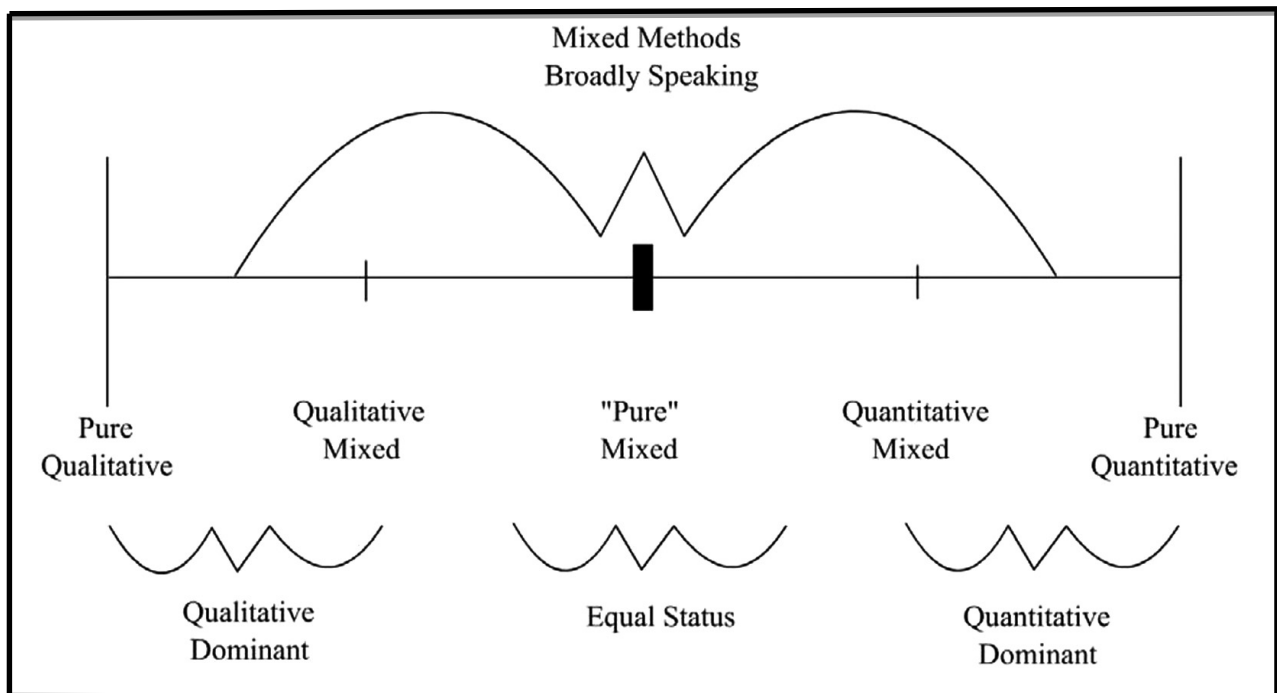
Figure 4.2: integration of the three major research paradigms, including sub-types of mixed research methods (Adapted from Johnson et al., 2007, p.124)

The part around the center of the continuum, *equal status*, is the area of focus anyone who sees himself/herself as a mixed methods researcher. Such researchers believe that qualitative and quantitative data and approaches provide deeper understanding as one considers most, if not all, research questions (Johnson et al., 2007).

4.3. Towards a Research Plan and Design for this Study

The issues reviewed above, suggest that the paradigm debate has changed considerably. Indeed, the focus has shifted to methodological suitability, rather than orthodoxy, methodological originality, instead of rigid adherence to a paradigm, and methodological flexibility, rather than conventionality to a narrow set of principles (Patton, 1997, p. 295). In this light, to design an appropriate research strategy for this study, three questions epitomised below were addressed following Creswell's (2009), Greene (2006), and Tuuli (2009) research frameworks:

a) What knowledge claims are being made? (e.g., objectivism/realism, subjectivism, etc.)

b) What strategies of inquiry are required? (e.g., positivism/quantitative, interpretivism/qualitative, etc.)

c) What methods of data collection and analyses are appropriate? (e.g., interviews, surveys, focus groups, modelling, etc.)

By addressing these questions, a clear research plan emerged and underscored the intertwined nature of the methodological paradigm herein, adopted (i.e., the philosophical assumptions that underpin the study-the why and what) and the resulting research methods (i.e., the tools and techniques for gathering and analysing the data-the how) required to implement the research. The question of knowledge claim involved addressing the assumptions relating to how to learn and what will be learned during the inquiry (i.e. philosophical assumptions). This required being explicit about claims of what knowledge is (*ontology*), how we know it (epistemology), what values go into it (*praxiology*) and how to express it (rhetoric), enabling the processes of studying it (methodology) to be clearly and appropriately articulated (Creswell, 1994).

Given the complex and open nature of the Volta River Basin, as well as the growing complexity of the problems currently faced by decision-makers, it is apparent that a single mode of inquiry will not be sufficient to investigate the research aim and objectives outlined in this study (see Chapter 1). It is, therefore, essentially a question of blending different philosophies/paradigms, epistemologies, research methods, and strategies so that all aspects of the research problem would be adequately addressed. Accordingly, this research was grounded in what (Beven, 2002) described as *pragmatic realism* as its underlying philosophical foundation or methodological paradigm. This paradigm combines elements of instrumentalism, relativism, logical empiricism (or logical positivism), verificationism, critical rationalism, Bayesianism, and pragmatism, while allowing the realist perspective that underlies much of the research and practice of environmental modelling as a central aim (Beven, 2002, 2009). Indeed, pragmatic realism is consistent with the *relativist/holistic philosophy* of science, which underlie the paradigm of systems thinking and system dynamics modelling approach (Sterman, 1984; Forrester, 1968; Barlas and Carpenter, 1990; Barlas, 1996).

The relativist/holistic philosophy view a valid model as one of several potential forms of describing a real situation. Barlas and Carpenter (1990, p. 157) sum aptly sum this up: "no particular representation is superior to others in any absolute sense, although one could prove to be more efficient. No model can claim absolute objectivity, for every model carries with it, the modeler's worldview. Models are neither true nor false, rather, they lie along a continuum of usefulness."

Further, combining different paradigms accords well with the notion of *epistemological pluralism*, which states that, in any research situation, there may be several alternative ways of getting to the truth, and that considering this multiplicity may result in a more fruitful and effective integrated inquiry (Miller et al., 2008). As Liu et al. (2007a) stressed, integrating different philosophies/epistemologies provide a complete understanding of complex social-ecological systems. Moreover, combining different methodologies allows one to accommodate both scientific and indigenous local knowledge that can help one gain deeper insight into complex systems, such as the Volta River Basin.

In terms of the methods or research strategy, this study combines both qualitative and quantitative techniques (i.e., a mixed-methods approach) (Creswell, 2003, 2009, Johnson et al., 2007) was deployed. Qualitative strategy in that unstructured interviews, focus groups and participatory were used to elicit the main drivers, factors and process that determine the dynamics of the basin. This process allowed for the development of a qualitative/conceptual or dynamic hypothesis capturing the feedback structure of the basin. The quantitative aspect of the study is in the process translation of the qualitative model into a quantitative simulation model using quantitative parameters and graphical integration. Indeed, the combination of qualitative and quantitative approaches allows the drawbacks of one technique to be compensated by the counter-balancing strengths of the other (Denzin and Lincoln, 2011), while revealing different empirical truths about the problem being studied. The blending of quantitative and qualitative strategies in social research is reinforced by the strong argument that theory development necessitates 'hard' data for discovery causal relationships and 'soft' data for elucidation this relationship (Creswell, 2009; Denzin and Lincoln, 2011). The combination of both qualitative and quantitative approaches also illustrates a form of methodological pluralism in scientific discovery (Olson et al., 2008), which is often applied in an array of scales (Dow, 1997; Boyd et al., 2004). Methodological pluralism is also referred to as *multimethodology* (Mingers, 1997) or *multistrategy research* (Bryman, 2012).

Methodological pluralism offers several benefits in research designs. Johnson et al. (2007) articulated how the combination of various methods can be useful in the research design, data collection, and data analysis phases of the research process. From this perspective, Johnson et al.

(2007) emphasized that during the data collection phase, quantitative data may be essential in providing baseline data and prevent "elite bias." Also, qualitative information may assist in facilitating the entire data collection process. Likewise, at the design phase, qualitative data may help the quantitative aspect of the research by serving as an instrument for conceptualization. Also, during the data analysis stage, the qualitative data may provide deeper insight on qualitative findings, while the quantitative information may help with the generalisation of the study (Johnson et al., 2007). In the nutshell, the combination of multiple methodological practices, empirical materials, views, and respondent in a single study is best described as an approach that adds rigor, breadth, complexity, richness and depth to the research (Denzin and Lincoln, 2000; Flick, 2007), which ultimately leads to developing a systemic research approach, with one study method dictating the direction and nature of the next (Morse and Chung, 2008).

Moreover, the case for *methodological pluralism* or *mixed methods research* has been advocated by many scholars in environmental and natural resource management discipline (e.g, Norgaard, 1989; Bellamy et al., 2001; Luzadis et al., 2002; Williams and Patterson, 2007; Olson et al., 2008; Gasparatos et al., 2009; Scholz, 2011), particularly as we seek to achieve the objective of integrated natural resource management and address the complexity and uncertainty inherent in many environmental and water resource management systems. It also accords very well with calls for integrated oriented approach (Sayer and Campbell, 2002; Campbell et al., 2006a; Campbell et al., 2006b; Bellamy et al., 2012) in environmental and natural resource management research. This study further attempts to make a stronger case for methodological pluralism in environmental management and sustainability assessments, as it supports the reasoning that methodological pluralism with all its strengths and weaknesses should be invoked when holistic sustainability assessments are needed, and linear reductionist methods are to be complemented (Gasparatos et al., 2009).

4.4. Selected Methods and Approaches for this Study

Based on the preceding discussions, it is the contention of this project that the complexity of the Volta River Basin requires a multiplicity of different approaches to more fully understand it. Within the broader framework of methodological pluralism and mixed-methods strategy adopted here, a three-tiered research plan, comprising; *structured expert judgement technique*, *participatory modelling based on casual loop modelling* (diagramming), and a *system dynamics simulation modelling approach* was adopted. Each method is different in its focus and addressed a specific research objective. To recap, the first research objective sought to explore and identify the key

biophysical and socio-economic drivers of change within the Volta River Basin system. To accomplish this objective, an extensive literature review combined with structured expert judgement technique, and interviews were employed. The second objective was formulated to examine the interrelationships and feedback-effects among the key biophysical/environmental and socio-economic processes and drivers of change at the basin scale. Participatory modelling based on casual loop modelling – that is Causal Loop Diagrams (CLDs) were used as visualisation and analytical system tools to achieve this objective. Finally, the third research objective was designed to simulate the dynamics and behaviour of the system over time. To this end, *system dynamics simulation modelling* approach was applied.

It is important to mention here that because this study took 'a thesis by publication format', the specific design issues that were considered to address the research aim and associated objectives are not provided in this chapter. Rather, they have been detailed in the individual published papers enclosed herein (see chapters 5, 6, and 7). This is to avoid unnecessary repetition. Nevertheless, the logical, procedural sequence that ensured implemented of the three-pronged research strategy is illustrated in Figure 4.3. Following this sequential procedure, the empirical phase of the study started with the identification of the dominant drivers of change and processes within the Volta River Basin (stage 3).

This was followed by the development of qualitative/conceptual model (stage 4), based on information from stage 3 and the intrinsic mental models of the system stakeholders during a participatory modelling workshop. In stage 5, the conceptual model containing the key feedback loops was quantified and simulated using historical data obtained during the fieldwork. At the end of the sequence of the research process/activities, the results and outputs obtained from these 5 activities was then compiled, integrated and cross-validated through triangulation in stage (stage 6). Although the research process encompassing the various activities is depicted graphically as sequential (Figure 4.3), they were, in practice, occurred concurrently or short cycle a few times before moving to other activities. In other words, they were pursued in an iterative manner (Winz et al., 2009). Therefore, some degree of flexibility was allowed within this sequential procedure.

Nevertheless, the chart flow (Figure 4.3) with its associated research activities provides an opportunity at the end of each step and before starting the next one, to assess what is known and what information is missing and should be collected in the next cycle (gap analysis) (McDonagh et al., 2008). But it is important to distinguish these stages conceptually for the clarity of the methodological process, for the organisation, the coordination of the work and for a systematic processing of the research findings (McDonagh et al., 2008). In this way, the methodological

framework is systems base, integrative and distinguished from the traditional methodological approaches (Bellamy et al., 2001).
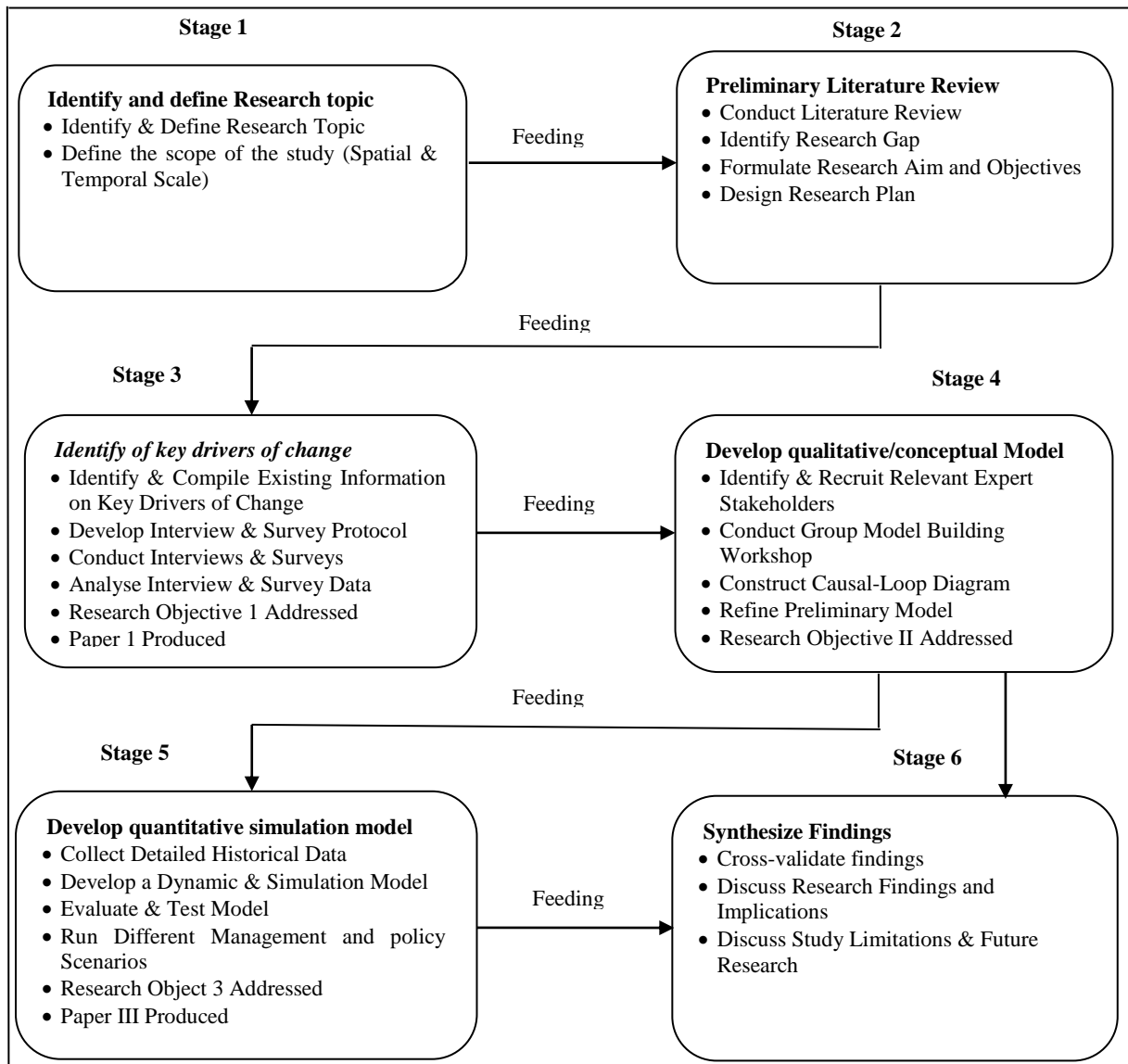
Figure 4.3: Sequential Procedure Comprising Major Activities of the Research

4.5. Concluding Remarks

This chapter presented the overall research methodology and framework for the study. In doing so, the philosophical foundations of a research framework are discussed. A three-tiered research approach comprised: structured expert judgment technique, participatory modelling based on casual loop modelling, and system dynamics simulation modelling approach were employed as the overall research framework for the study. These methods and tools adopted here are closely allied to the theoretical base of this study (i.e., the systems thinking approach) discussed in chapter 3. The

remainder of the thesis consisting of the individual papers demonstrates how the methods and tools selected were applied.

CHAPTER 5: DRIVERS OF CHANGE AND SUSTAINABILITY IN LINKED SOCIAL-ECOLOGICAL SYSTEMS: AN ANALYSIS IN THE VOLTA RIVER BASIN OF GHANA, WEST AFRICA[1]

Julius H. Kotir[1] • Greg Brown[2] • Nadine Marshall[3] • Ron Johnstone[1]

[1]*School of Earth and Environmental Sciences, University of Queensland, Brisbane, QLD, 4072, Australia*

[2]*NRES Department, California Polytechnic State University, San Luis Obispo, CA, 93407, USA*

[3]*CSIRO Land and Water Flagship, James Cook University, Townsville, QLD, 4811, Australia*

Corresponding author: Julius H. Kotir. Email: j.kotir@uq.edu.au

Abstract

Understanding the nature and relative importance of various drivers of change is crucial for sustainable management of natural resources and in prioritising management efforts, allocating limited resources, and understanding cumulative effects. In this paper, we employed structured expert judgements approach to identify, characterise, and assess the relative importance of the key biophysical and socio-economic drivers of change within the Volta River Basin, West Africa. Precipitation variability, water availability, land use change, drought events, and population growth were perceived as most important, while biodiversity loss, social conflicts, pest and disease occurrence, urbanisation, and pollution were viewed as less critical. A majority of these drivers were characterised as "slow" acting processes as compared to rapidly changing drivers. Intra- and inter- expert groups agreement were found to be significant and convergent, indicating the reliability of the results. The implications of these results for sustainable water resources management and agricultural production are discussed.

Key Words: Africa; Agricultural system; coupled human-environmental system; expert judgement; expert opinion; environmental change; River basin; water resources system.

5.1. Introduction

The earth system is undergoing a period of significant, continuous and rapid environmental and socio-economic change — a phenomenon described as global change (Steffen et al., 2015). Global changes, typically anthropogenic in origin, have become significant and pervasive since the mid-twentieth century that despite any concerted efforts to minimise them, the planet is committed to a trajectory where changes are likely to continue or accelerate in the coming decades (Chapin et al., 2009). Global change processes manifest through a wide range of driving forces and factors generally referred to as drivers of change (Petschel-Held et al., 2005; Chapin et al., 2009; Walker et al., 2012). Drivers of change reflect past, present, or future conditions that cause changes to the environment (Rounsevell et al., 2010). They range from environmental to socio-economic and from slow- to fast-moving, direct to indirect, exogenous to endogenous factors and influence outcomes differently in the short and long terms (Chapin et al., 2009; Msangi and Rosegrant, 2011; Walker et al., 2012). Drivers of change thus govern the dynamics, resilience and sustainability of most human-environmental systems (Gunderson and Holling, 2002; Carpenter et al., 2009, Chapin et al., 2009).

In an era of global change, concerted efforts to mobilise scientific information on the various drivers and trends, and strategies to manage them have become increasingly important in natural resource management systems. One such major effort was the global Millennium Ecosystem Assessment (MA, 2005) that provided a comprehensive analysis of the various drivers of change, trends, and indicators in ecosystems. More recent studies have examined drivers of change specific to agriculture and water resources systems (e.g., Hazell and Wood, 2008; Msangi and Rosegrant, 2011; van Vliet et al., 2012; Kumar and van Dam, 2013). However, most of these studies are too global in their perspective, or tend to be heavily focused on Europe, North America, and Australasia. Far less attention has been given to documenting status and trends of the drivers in arid and semi-arid areas in sub-Saharan Africa; despite evidence that Africa is the most vulnerable to the impacts of various drivers of change, particularly climate variability (Farley and Farmer, 2013; Niang et al., 2014). Moreover, a significant portion of environmental change literature and policies focus exclusively on climate as a driver of change (Bennett et al., 2016), yet sustainable development calls for integration of biophysical, economic, institutional, political, social, and technological issues (Berkes et al., 2003; Carpenter et al., 2009; Chapin et al., 2009).

Further, much of the existing literature on drivers of change has failed to distinguish the slower-acting, long-term drivers of change from the faster or rapidly changing ones that can have more influence in the short-term (Msangi and Rosegrant, 2011; Walker et al., 2012). However, such a

distinction is useful, not only in permitting the prioritisation of issues from a policy perspective, but also in distinguishing temporary from long-term issues (Msangi and Rosegrant, 2011). Similarly, separating rapid internal drivers from "slow" acting drivers is crucial to understanding system dynamics, resilience, and sustainability of social-ecological systems (Chapin et al., 2009; Walker et al., 2012). There are multiple drivers of change in any social-ecological system making it difficult to track their changes and associated impacts. Accordingly, there is a need to understand the relative importance of various drivers to prioritize management efforts, allocate limited resources, and understand cumulative effects (Chapin et al., 2009; Hall, 2011). As Hall (2011, p.140) emphasised ''... the relative importance of the various drivers and the pathways through, which they might act must be weighed to help prioritize actions.''

The preceding considerations suggest that our knowledge of drivers of change is incomplete, particularly at the river-basin scale in Africa where their impacts are often more pronounced. Yet, this knowledge, if well-garnered, can enhance our capacity to design strategies to manage these basins sustainably for human well-being as the impacts from global change continue to manifest at all scales. This paper aims to explore and analyse the environmental and socio-economic drivers of change and processes, with a focus on understanding how such changes influence sustainable agriculture development within the Volta River Basin (VRB) of Ghana, West Africa. The specific objectives are as follows: (1) to explore and identify the key environmental and socio-economic trends, processes, and drivers of change within the VRB of Ghana; (2) to assess and characterise those drivers as "slow" or "fast" changing/acting drivers; (3); to indicate the rate of change (i.e., trend) in each driver; and (4) to assess the relative importance of such drivers, as they influence sustainable agricultural development and water availability in the basin.

As Kolavalli and Williams (2016) noted, the goal of agricultural policy for the basin since the 1980s has been to feed a rapidly growing population and reduce environmental degradation; however, the policy has been devoid of a comprehensive analysis of the trends being observed and has not responded rapidly enough. Ultimately, this study is intended to enable and better support policy decisions associated with sustainable agricultural development and water resource management in the semi-arid Volta River basin and other dryland river basins with similar environmental and socio-economic characteristics.

5.1. The Study Area: The Volta River Basin

The Volta River Basin (VRB) is a transboundary basin, which occupies an area of approximately 400,000 Km^2 and runs across six West African countries: Burkina Faso, Ghana, Togo, Benin, Cote

d'Ivoire, and Mali (Fig.1). It has 4 sub-catchments: Black Volta, White Volta, Oti River, and Lower Volta. Average annual rainfall within the basin ranges from 1600mm in the South-Eastern section of the basin in Ghana to about 360mm in the northern part of Burkina Faso (Williams et al., 2016). The basin is also home to approximately 25 million people, more than 70% of whom are involved in small-holder subsistence agriculture. Given the extent of the basin, this study focused on the part of the basin in Ghana of the basin since about 70% of country lies in the basin, providing essential natural resources.
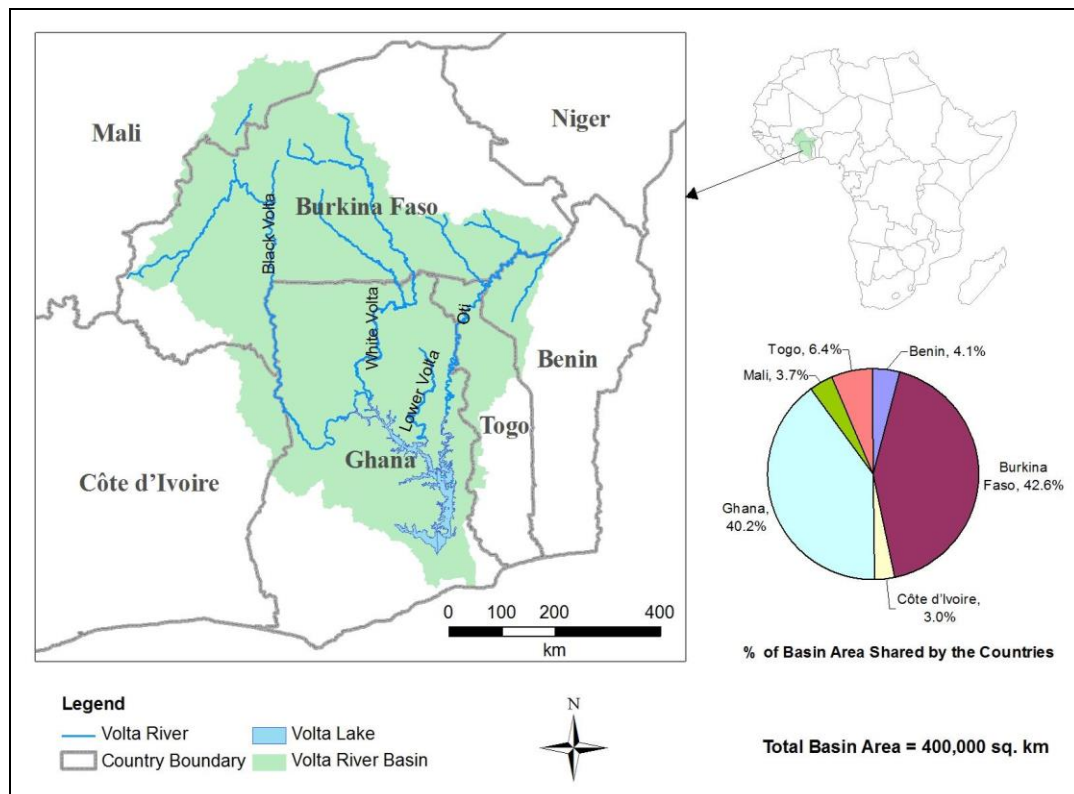
Figure 5.1. The Volta River Basin showing important political boundaries (Adapted from Gao and Margolies, 2009)

5.2. Materials and Methods

5.2.1. Data Sources and Driver Identification Approach

Fundamentally, in this paper, changed is conceived as variations or disturbances in the state, outputs, or structure of ecosystems (MA, 2005). However, to build a clear understanding, Anastasopoulou et al. (2009) argued that it is imperative to identify the agents, or drivers of those changes that are embedded in human society. Accordingly, this paper focuses on those drivers, which are defined as "any natural or human-induced factor that directly or indirectly causes a change in an ecosystem" (after MA, 2005, p.176). This definition impelled the consideration of both

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environmental and socio-economic factors perceived to be undesirable in the context of the VRB of Ghana.

Initially, various drivers of change were identified following an approach employed by Tzanopoulos et al. (2013). Comprehensive literature searches were performed using electronic databases: Google Scholar and Scopus using combinations of the following key words, "agriculture", "change or driver or impact", "ecosystem", "river basin". The reviewed materials included published work from scientific journals, books, and global scientific reports from developed and developing countries that have analysed drivers of change within agricultural and water resources sectors. From these sources, in total, 53 publications were identified and analysed that span local, basin-wide, regional, and global scales. Subsequently, a snowball search procedure was used, that yielded an additional 15 publications, resulting in a total of 68 publications. To capture the current issues, materials that were published in the last 10 years (between 2005 and 2015) were considered.

From the literature, 51 relevant drivers and factors were identified and placed under four categories: biophysical/environmental drivers, economic and technological drivers, socio-demographic drivers, and policy and institutional drivers. To assess the relevance of these drivers to the VRB of Ghana, a one-day workshop was held in the northern regional capital of Ghana (Tamale) on April 11, 2014 with 16 expert stakeholders (i.e., 8 natural scientists and 8 social scientists) who live and work throughout the VRB. The process of selecting the participants was purposive, as it allowed the researcher to target leading researchers, practitioners, and senior policy- makers working in research and academic institutions, government, private firms, NGOs, and local farmers across the basin. In addition to assessing the relevance of the identified drivers to the VRB of Ghana, the workshop participants also indicated the direction of change of the individual drivers. An increasing trend is indicated by ↑, while ↓ indicates a decreasing trend (Figure 5.2).

Subsequently, the drivers were characterised as "fast" or "slow" variables/drivers following Huber-Sannwald et al. (2012). "Slow" changing drivers (V_S) are those factors that tend to act more slowly over time in a somewhat predictable manner with long-term impacts, while fast changing drivers (V_F) are factors that change rapidly in the short term (Chapin et al., 2009; Msangi and Rosegrant, 2011; Walker et al., 2012). Overall, we identified 51 drivers of change comprising: 18 biophysical/environmental drivers; 14 economic and technological drivers; 14 socio-demographic drivers; and five policy and institutional drivers. Drivers were characterised as either "slow" changing/acting drivers of change (n=38), or "fast" changing/acting drivers of change (n=12).

Further, 33 drivers indicate an increasing trend, while 17 drivers portray a decreasing trend (Fig.2). Many of these trends agree with known patterns described in Lemoalle (2009), UNEP-GEF Volta Project (2013), and Kolavalli and Williams (2016), indicating that the model is both robust and important to the social-ecological dynamics in the basin.

Biophysical & Environmental Drivers
Biodiversity loss (V_S) ↑
Change in cropping pattern (V_S) ↑
Change in length of growing season (V_S) ↑
Change in temperature (V_S)↑
Crop yield growth (V_S)↓
Deforestation (V_S)↑
Droughts-intensity & duration (V_F) ↑
Floods-intensity & duration (V_F)↑
Ground & surface water availability (V_S)↓
Land productivity (V_S) ↓
Land use/cover change (V_S)↑
Land/soil degradation (V_S) ↑
Pest & disease occurrence (V_F)↓
Precipitation variability (V_F) ↑
Pollution (V_S)↑
Soil erosion (V_F)↑
Soil fertility (V_S) ↓
Use of fertilizer & pesticides (V_S)↑

Economic & Technological drivers
Access to financial credit (V_F)↓
Agricultural intensification (V_S)↑
Agricultural market access (V_S)↓
Availability of arable land (V_S)↓
Availability of off-farm employment (V_S)↓
Change in consumption patterns (V_S)↑
Change in farm size/structure (V_S)↑
Cost of inputs (V_F)↑
Household income growth (V_S)↓
Infrastructure conditions (V_S)↓
Innovation & technological change (V_S)↑
Labour availability (V_S) ↓
Livelihood & income diversification (V_S) ↑
Small-scale mining (V_F)↑

Socio-demographic drivers
Access to health care (V_S)↓
Change in age structure (V_S)↑
Change in fertility (V_S)↑
Change in mortality (V_S) ↑
Change in traditional values
  & practices(V_S)↑
Education level (V_S)↑
In/out migration (V_F)↑
Inequality (gender, age class) (V_S)↑
Land Abandonment (V_F)↑
Population density (V_S)↑
Population growth (V_S) ↑
Poverty level (V_S)↑
Social Conflicts (V_F)↓
Urbanisation (V_S)↑

Policy & Institutional Drivers
Availability of extension services (V_S) ↓
Availability of R&D funding (V_F)↓
Level of investment (V_S)↓
Production subsidies (V_F)↓
Property rights issues (V_S)↑

Figure 5.2: A simplified Model of Drivers of Change identified in the Volta River Basin and their interactions. V_S denotes "slow changing variables", while V_F denotes "fast changing variables". ↑ indicates increasing trend in the driver, while ↓ indicates decreasing trend.

To determine the relative importance of these drivers of change, a *structured expert judgement technique* was employed (Meyer and Booker, 2001; Perera et al., 2012; Drescher et al., 2013). As noted by Turner (2015), sustainable water resources will need to be conserved and traded through changes in public policy that will involve scientific experts as well as laypersons. Thus, this study

considered two groups of experts: scientific/technical experts, and local experts in the assessment of drivers of change.

5.2.2. Selection of Technical Experts

For the purposes of this study, technical experts comprised of knowledgeable practitioners and researchers (Perera et al., 2012; Drescher et al., 2013) with extensive experience in agriculture and water resources related issues. As a register of qualified technical experts was unavailable in the VRB, the paper used a study design that combines multiple expert identification techniques including, web-based searches and professional networks directories (Drescher et al., 2013) to develop a sampling frame containing a pool of potential experts. This pool of experts was then supplemented using 'chain referral', in which the experts that were identified recommended other potential experts (Meyer and Booker, 2001). To minimise sampling bias and the marginalisation of other potential experts, a purposive sampling technique was used to select a group of experts from the pool based on their qualifications, reputation and publication record in the area, professional standing, prolonged experience, and peer recognition (Meyer and Booker, 2001; Martin et al., 2012; Drescher et al., 2013).

According to Martin et al. (2012), few experts reach the highest levels of competence in less than a decade in a domain. Thus, individuals who have worked across the VRB of Ghana for more than 10 years with technical expertise in water, soil, environmental science, rural geography, agricultural studies, agricultural economics, rural sociology and political science were considered. Also, considerable efforts were made to include individuals working in relevant research and academic institutions, government, private firms, and non-governmental organisations (NGOs) within the VRB of Ghana. Therefore, the selection of technical experts was designed to ensure that a range of cognate natural and social science backgrounds as well as persons from diverse institutions would be represented (Fish et al., 2009). The goal here was to avoid the dominance of one expert group, and hence, minimise possible institutional, locational, and disciplinary biases in the respondent pool.

Through the processes described above, a total of 117 experts were contacted by email and phone, and invited to participate in the study. Overall, 42 technical experts agreed to participate in the survey, resulting in a response rate of 35.9%. The reasons provided for non-participation ranged from limited time (n=38) to lack of interest in the study (n=22). Others simply identified themselves as non-experts (n=15) and did not consider themselves knowledgeable enough to participate in the study.

5.2.3. Selection of Local Experts

The sampling approach to selecting local experts followed "systematically gathering peer recommendations" – an analogue to snowball sampling or chain referral technique – as implemented by Davis and Wagner (2003). Local experts were defined as elderly farmers and land managers within the VRB in accordance with attributes set by Davis and Wagner (2003). Accordingly, one selection criterion was that individuals must be more than 40 years old.

In doing so, the study purposively identified 18 local farmer-based organisations and associations from 10 districts across the three Northern regions of Ghana within the VRB: Northern, Upper East, and Upper West regions. It focused on these regions because most the population in these regions are smallholder farmers directly engaged with VRB water resources. The members of these groups ranged from 14 to 43 members, including both men and women. Across these groups, 142 potential local experts (all smallholder farmers) to participate in the survey were invited. Of these, 49 local experts agreed to participate, yielding a participation rate of 35.5%. Those who did not participate were simply constrained by time.

5.2.4. The Elicitation (Survey) Instrument

In total, 91 experts comprising: 42 technical experts and 49 local experts were engaged in this study. While this sample maybe relatively small, the sampling process ensured that it contains persons with 'well-contextualized, synoptic knowledge' (Drescher et al., 2013) and in-depth understanding of the VRB and its associated challenges. The experts provided judgements based on survey questions focussed on the drivers presented in Figure 5.1. The survey instrument was pre-tested with a sample of 10 experts (five technical experts and five local experts), none of whom was part of the final response pool. The responses indicated that the questions were clearly defined, well understood, and appropriate to the research context.

The final interviews were conducted from May and October 2014 by the first author using face-face style elicitation, as it allowed for more targeted questions and clarification, and therefore, helped to reduce bias due to linguistic uncertainty (Beyer and Booker, 2001; Kuhnert et al., 2010). Interviews were confidential individual-based, and took place at expert's office, farm or home. An elicitation lasted approximately 1 hour and 15 minutes. To account for cross-gender and cross-cultural sensitivities (Nyantakyi and Bezner-Kerr 2015), a female local volunteer was recruited to assist in the process. Depending on the preference of the expert, one of the following languages was used: English, Twi, Dagbani, Dagaare, or Frafra. Some interviews were taped recorded with consent (85 participants); otherwise, extensive hand-written notes were taken (six participants, all of whom

were technical experts). The respondents were not compensated for their time, but rather, the study relied on their good will and interest in the study.

The survey instrument elicitation process consisted of three parts (see Appendix 1). It began by eliciting biographical information about the experts: age, gender, level of education, professional affiliation(s), years of experience in their current job/project, and years of experience within the VRB. In the second part, the interviewers requested the experts to reflect on their knowledge of the 51 drivers/factors in Figure 5.1 and, more specifically, gauge their relative importance relative to sustainable water resources management in agricultural development in the VRB of Ghana. For example, one question was: *"how important do you think precipitation variability is in terms of driving change and influencing water resources management and agricultural development within the VRB of Ghana"?*

A four-point Likert scale was used with anchor points ranging from 1(very important) to 4 (not at all important). Subsequently, we asked the experts to explain their reasoning for each judgement. This provided qualitative comments that were used to contextualise the study and enrich the quantitative data. In making their judgements, the experts were asked to focus on the consequences of these drivers in the last 30 years, as this is noted as the period the basin underwent fundamental changes, exemplified by the mid1980s droughts, which led to severe water scarcity and food shortages (Lemoalle, 2009; Kolavalli and Williams, 2016). In the final part of the process, experts suggested any strategies they believed could mitigate the consequences of these drivers.

To minimise bias associated with overconfidence or conservatism (Meyer and Booker, 2001; Kuhnert et al. 2010), information-sampling theory (Klayman et al., 2006), which includes asking the same questions twice or with different wording throughout the elicitation process (Martin et al., 2012) was used. During the elicitations, it was apparent that the experts were equally knowledgeable about most drivers and, therefore, did not show strong bias towards those issues in their professional domain. It was, however, observed that most experts paid much attention to the consistency of their judgements by referring to their previous answers while answering the questions; they often requested to amend response after they have had time to think about succeeding questions.

5.3. Data Analysis

The judgements and opinions of individual experts were analysed using simple descriptive statistics (unweighted means). Following Scholten et al. (2013), the judgement of each expert was presumed

to carry equal weight and were analysed together. We used the Chi-square (χ^2) goodness-of-fit test to determine whether there was a potential difference between the technical and local expert respondents in gender, age, and level of education. Proportional representation of experts from different organisational affiliations within the technical expert group was tested using one-way ANOVA. The non-parametric Mann–Whitney U – test was used to test whether the ratings of each driver by the technical experts group and local experts group differ. The extent of agreement among individual experts (intra-expert agreement) and inter-expert agreement were quantified using Kendall's Coefficient of Concordance (W) (see Kendall and Smith, 1939).

Inter-expert (or between groups agreement) was measured using Spearman's rho and Kendall's Tau-b correlations coefficients. All statistical analyses were carried out in SPSS version 21.0. Qualitative comments were transcribed and analysed using thematic analysis, as it allowed for the extraction of the core themes that emerged from the interviews (Bryman, 2012). Verbatim quotes were used to support the results and discussion. Finally, published studies were used to confirm or disconfirm the expert knowledge or opinion.

5.4. Results and Discussion

5.4.1. Survey Pool

As shown in Table 5.1, the majority of all respondents (58%), technical experts (62%), and local experts (55%) were male. Further, a majority (63%) of the total sample were aged 50 years and over, with only 3% below the age of 40. Most of the local experts (76%) had no formal education, while 55% of the technical experts had formal education to the postgraduate level. Overall, 59% of total respondents had some form of formal education. The majority of the technical experts were from NGOs (33%) and academic institutions (31%), with only 12% affiliated with private institutions. The technical experts were also highly experienced, with an average tenure in their current job of 12 ± 5.1 years (mean $\pm$ standard deviation) and average tenure in the VRB of approximately 19 ± 3.9 years.

5.4.2. Potential Response Bias

Table 5.1 also reports the results of the chi-square goodness-of-fit test that showed no statistically significant difference between the technical and local experts associated with gender and age. The two expert groups, however, differed significantly in terms of the level of education ($\chi^2 = 80.481$, *df*

= 4, P < 0.01). With regard to the representation of experts from different organisational affiliation within the technical experts group, we found no significant difference ANOVA F($3,38$) = 4.67, $p = .198$).

Table 5.1: Demographics of Survey Respondents

Variable	Technical Experts (n =42)	Local Experts (n = 49)	Total (combined) (N = 91)
Gender			
Male	61.9	55.1	58.2
Female	38.1	44.9	41.8
Chi-square (χ^2) = 430(df = 1, P = .512)	*.430 (df = 1, P = .512)*		
Age (years)			
<40	7.1	0.0	3.3
41 – 50	40.5	28.6	34.1
51 – 60	38.1	40.8	39.6
>61	14.3	30.6	23.1
χ^2	*7.095 (df = 3, P = .069)*		
Educational level			
No Education	0.0	75.5	40.7
School Level Education	2.4	18.4	11.0
Vocational/technical school level	9.5	6.1	7.7
Graduate level	33.3	0.0	15.4
Postgraduate level	54.8	0.0	25.3
χ^2	*80.481 (df = 4, P < .001)*		
Organisational affiliation			
Academic	31.0	-	31.0
State/government	23.8	-	23.8
NGO	33.3	-	33.3
Private institution	11.9	-	11.9
ANOVA (F)	*[a]4.667 (df = 3, P = .198)*		
Average years of experience in current job	12.3 (5.08)	-	-
Average years of experience in the Volta River Basin	18.8 (3.94)	-	-

Note: [a]test for possible difference among respondents within the technical experts group associated with organisational affiliation. Values in parenthesis represent the mean standard deviations (SD) of the corresponding variables. Note that we did not collect data on the variables: organisational affiliation, years of experience in current job and years of experience in the Volta River Basin for the local experts as they do not hold down formal jobs in institutions or organisations.

5.4.3. Relative Importance of Drivers of Change and Trends

To assess the relative importance of these drivers, the unweighted mean scores and the standard deviation for each driver of change were calculated and rank-ordered based on their mean values. The results are shown in Table 5.2. Although the study ensured that a range of cognate natural science and social science backgrounds were represented in the selection of experts, overall, four biophysical drivers (precipitation variability, ground and surface water availability, land use change, drought events) and one socio-demographic driver (population growth) were rated as the top five most important drivers. The result is consistent with previous analysis of the trends in the basin (e.g., UNEP-GEF Volta Project 2013; Mul et al., 2015; Kolavalli and Williams, 2016). Moreover, the experts seem to view all but three of the biophysical drivers (change in cropping pattern, deforestation, and soil erosion) in the same light.

At the opposite end, the five least important drivers included change in consumption pattern, social conflict, pest and disease occurrence, urbanisation, and pollution. An interpretation of these results is that many experts consider the biophysical as the ultimate limiting factors for sustainability in the VRB. It could also be attributed to experts giving higher importance to those issues they have knowledge of. Nevertheless, the findings could well suggest that socioeconomic factors play a subsidiary role and that effective solutions should be targeted at those biophysical drivers. However, given that most environmental changes are closely linked to socio-economic drivers, effective actions would require equal attention to both types of drivers and processes and the feedbacks (Carpenter et al., 2009; Chapin et al., 2009). This is particularly crucial considering repeated calls to view resources systems as coupled social-ecological systems (see Berkes et al. 2003; Liu et al., 2007b; Ostrom, 2009) or linked human-environmental systems (see Turner et al., 2003; Scholz, 2011).

In comparing the findings across the two expert groups, differences were found in the judgement and ratings of the drivers and factors (Table 5.2). For example, population growth, ground and surface water availability, land and soil degradation, and soil erosion were judged and rated highly by the technical experts, but were considered less important by local experts. In contrast, the local experts rated issues related to livelihood security (e.g., access to financial credit, household income growth, crop yield, production subsidies, and livelihood and income diversification, labour availability) very high. This indicates that more attention must be paid to those factors and drivers which either constrain or enhance livelihood security.

Given this insight, the importance of these drivers in livelihood sustainability could be more thoroughly evaluated with local people. However, an interpretation of the differences in ranking between the two expert groups is that people's background, and values had an impact on the expert's opinion of drivers of change. The differences also provide knowledge into how stakeholders perceive and conceptualise change variously. The results suggest that strategies intended to address the consequences of drivers of change must be flexible enough to account for these differences and, most importantly, incorporate the full range of stakeholders.

5.4.4. Variability in Expert Opinion and Judgement

The study examined whether the two expert groups rated the drivers of change differently using the non-parametric Mann-Whitney U test. The results are presented in the last column of Table 5.2. A significant relationship was found in 19 out of the 51 drivers, that is, 37% of drivers (based on $p <$

0.05 and *p < 0.01* two-tailed significance levels). Eleven of the 19 significant drivers were statistically significant at the *p < 0.01* level, and eight significantly differed at the *p < 0.05* level. Five of these significantly different drivers: lack of access to financial credit ($U = 385.00, p < 0.01$), cost of inputs ($U = 630.00, p < 0.01$), crop yield growth ($U = 780.00, p < 0.05$), level of investment ($U = 693.00, p < 0.01$) and production subsidies ($U = 780.50, p < 0.01$) were rated in the top 10 by the local experts. Significant slow drivers such as soil erosion ($U = 826.00, p < 0.05$), deforestation ($U = 790.00, p < 0.05$), population growth ($U = 658.00, p < 0.01$) and population density ($U = 715.00, p < 0.01$) were also rated in the top 10 by the technical expert group. Notably, all policy and institutional drivers except for property rights were significant, while only four of the 18 environmental and biophysical drivers were significant. It is also worth noting that more than half (57%) of the socio-demographic drivers statistically differed and a quarter (25%) of the economic and technological drivers were significant.

5.4.5. Intra-and Inter- Expert Groups Agreement

The concordances and discordances results are summarised in Table 5.3. Estimates of the Kendall coefficient of concordance, W, showed statistically significant concordance among the technical experts ($W = .424, \chi^2 = 576.67, p < 0.01$) and local experts ($W = .534, \chi^2 = 897.61, p < 0.01$). However, there is strong agreement among the local experts than between the technical experts. This may be due to the different areas of expertise and disciplinary traditions among the technical experts, which informs the principle of expert judgement (Fish et al. 2009). Also, the concordance when the two groups were combined was also highly significant ($W = 0.432, \chi^2 = 1174.90, p < 0.01$), indicating a high level of agreement among the experts. The significant correlation coefficients confirm this.

Table 5.2: Mean scores, standard deviation (Std.Dev.), and rank orders for each driver with Mann–Whitney U test between the two expert groups

Driver of Change	Full Sample N = 91			Technical Experts n = 42			Local Experts N = 49			Mann-Whitney U-Test between expert groups[a]
	Mean	Std.Dev	Rank Order	Mean	Std.Dev	Rank Order	Mean	Std.Dev	Rank Order	
Environmental & Biophysical Drivers										
Biodiversity loss (V_S)	3.615	0.489	24	3.619	0.492	16	3.612	0.492	26	1022.00
Change in cropping pattern (V_S)	3.451	0.500	35	3.595	0.497	22	3.323	0.474	39	**752.50***
Change in length of growing season (V_S)	3.462	0.637	34	3.429	0.668	33	3.489	0.617	34	987.00
Change in temperature (V_S)	3.187	0.576	42	3.310	0.517	41	3.082	0.607	44	838.00
Crop yield growth (V_S)	**3.725**	**0.448**	**8**	3.595	0.496	23	3.837	0.373	4	**780.00***
Deforestation (V_S)	3.570	0.580	29	3.714	0.508	10	3.449	0.614	35	**790.00***
Droughts-intensity & duration (V_F)	**3.747**	**0.467**	**5**	3.762	0.431	7	3.714	0.5	14	996.00
Floods-intensity & duration (V_F)	**3.747**	**0.467**	**6**	3.690	0.517	12	3.776	0.421	7	960.50
Ground & surface water availability (V_S)	**3.769**	**0.423**	**2**	3.833	0.377	3	3.714	0.456	15	906.50
Land productivity (V_S)	3.593	0.557	27	3.595	0.544	27	3.592	0.574	27	1022.00
Land use/cover change (V_S)	**3.747**	**0.437**	**4**	3.786	0.415	6	3.714	0.456	13	955.50
Land/soil degradation (V_S)	3.714	0.453	11	3.811	0.397	4	3.633	0.4871	24	847.00
Pest & disease occurrence (V_F)	2.604	0.729	49	2.571	0.831	49	2.633	0.635	48	991.00
Precipitation variability (V_F)	**3.890**	**0.314**	**1**	3.834	0.3771	2	3.939	0.242	2	920.50
Pollution (V_S)	3.122	0.596	51	3.167	0.696	50	3.083	0.498	51	908.00
Soil erosion (V_S)	3.702	0.459	13	3.810	0.398	5	3.612	0.4923	25	**826.00***
Soil fertility (V_S)	3.703	0.458	12	3.714	0.457	11	3.694	0.465	17	1008.00
Use of fertilizer & pesticides (V_S)	3.275	0.667	41	3.262	0.767	42	3.286	0.577	40	1006.00
Economic & Technological drivers										
Access to financial credit(V_F)	3.670	0.472	16	3.333	0.477	39	3.959	0.199	1	**385.00****
Agricultural intensification (V_S)	3.670	0.495	17	3.643	0.485	15	3.694	0.508	16	963.00
Agricultural market access (V_S)	3.671	0.473	15	3.619	0.492	21	3.714	0.456	12	1006.00
Availability of arable land (V_S)	3.560	0.581	30	3.690	0.539	20	3.510	0.616	32	943.50
Availability of off-farm employment (V_S)	3.659	0.499	19	3.595	0.497	26	3.714	0.500	10	894.00
Change in consumption patterns (V_S)	2.978	0.869	47	3.167	0.729	45	2.816	0.95	46	822.00
Change in farm size/structure (V_S)	3.637	0.501	22	3.619	0.539	19	3.653	0.481	20	1010.00
Cost of inputs (V_F)	3.659	0.521	18	3.429	0.590	35	3.857	0.354	3	**630.00****
Household income growth (V_S)	3.714	0.454	**10**	3.667	0.477	13	3.755	0.434	8	938.00
Infrastructure conditions (V_S)	**3.747**	**0.437**	**9**	3.69	0.468	14	3.796	0.407	6	871.50
Innovation & technological change (V_S)	3.110	0.547	45	2.976	0.517	47	3.224	0.55	41	**808.00***
Labour availability (V_S)	3.648	0.524	21	3.571	0.590	28	3.713	0.456	11	917.00
Livelihood & income diversification (V_S)	3.604	0.514	25	3.548	0.504	29	3.653	0.522	21	909.00
Small-scale mining (V_S)	3.341	0.581	38	3.310	0.517	40	3.367	0.636	38	952.00
Socio-demographic Drivers										
Access to health care (V_S)	3.330	0.597	39	3.238	0.617	43	3.408	0.574	36	884.00
Change in age structure (V_S)	3.538	0.564	32	3.524	0.594	32	3.551	0.542	31	1017.00
Change in fertility (V_S)	3.055	0.639	46	3.405	0.497	36	2.755	0.596	47	**500.50****
Change in mortality (V_S)	3.275	0.547	40	3.429	0.501	34	3.184	0.565	42	**813.00****
Change in traditional values & practices(V_S)	3.143	0.708	44	2.714	0.673	48	3.51	0.505	33	**422.00****

Education level (V$_S$)	3.165	0.834	43	3.548	0.632	30	2.837	0.85	45	**547.00****
In/out migration (V$_F$)	3.648	0.503	20	3.619	0.537	17	3.673	0.474	18	989.00
Inequality (e.g., gender, age, class) (V$_S$)	3.396	0.535	36	3.19	0.455	44	3.571	0.54	30	**647.00****
Land Abandonment (V$_F$)	3.626	0.530	23	3.619	0.539	18	3.633	0.528	23	1017.50
Population density (V$_S$)	3.549	0.563	31	3.738	0.445	**9**	3.388	0.606	37	**715.00****
Population growth (V$_S$)	**3.758**	**0.431**	**3**	**3.952**	**0.216**	**1**	3.592	0.497	29	**658.00****
Poverty level (V$_S$)	3.605	0.492	26	3.524	0.506	31	3.673	0.474	19	875.00
Social Conflicts (V$_F$)	2.802	0.991	48	3.071	0.921	46	2.571	0.999	49	**744.00***
Urbanisation (V$_S$)	2.473	0.720	50	2.405	0.735	51	2.531	0.71	50	934.00
Policy & Institutional Drivers										
Availability of extension services(V$_S$)	3.484	0.524	33	3.357	0.485	38	3.592	0.537	28	**780.00***
Availability of R&D funding (V$_F$)	2.823	0.698	37	3.595	0.734	25	2.619	0.660	43	**709.50****
Level of investment (V$_S$)	2.349	0.808	28	2.525	0.735	37	2.196	0.833	9	**693.00****
Production subsidies (V$_F$)	**3.725**	**0.448**	**7**	3.595	0.497	24	3.837	0.373	5	**780.50****
Property rights issues (V$_S$)	3.692	0.464	14	3.738	0.445	**8**	3.653	0.481	22	941.50

Notes: *Drivers are ranked based on their mean scores on a 4-point Likert scale where 1 = Not Important, 2 = Somewhat Important, 3 = Important and 4 = Very Important. Where there was a tie, the standard deviation was used to break the tie.*

Top ten drivers are colour coded. Black (with white numbers) are top ten drivers rated by both technical and local experts. Light grey are top ten drivers rated by the technical experts. Dark grey are top ten drivers rated by the local experts.

[a]Mann-Whitney (*U*) statistics in bold are statistically significant at * P < 0.05; **P< 0 .01 (two tailed).

V$_S$ denotes "slow variables", while V$_F$ denotes "fast variables".

Table 5.3: Intra-expert group agreement measured using Kendall's Coefficient of Concordance (W) and inter-expert group agreement measured using Spearman rho and Kendall's–tau b correlation coefficients (i.e., technical vs. local experts).

Statistic	Technical Experts	Local Experts	Total (combined)
Kendall's Coefficient of Concordance, W	0.424*	0.534*	0.432*
Chi-square (χ^2)	480.15	654.90	929.49
DF	50	50	50
Spearman rank correlation coefficient (Rho)	0.58*		
Kendall's tau-b correlation coefficient (τ)	0.42*		

Note: the test statistics for Kendall's W test is distributed as the classical Chi-squared with k-1 degrees of freedom (DF).
*For p < 0.01

These results imply that some experts may be applying similar standards in judging the importance of the drivers of change (Meyer and Booker, 2001). Such a convergence further indicates some level of consensus and, invariably, increasing confidence in the results. An important conclusion is that when local and technical expert's views on driving forces are systematically elicited and combined, they can generate consistent judgments to inform future agricultural and water policy decisions.

5.5. Characteristics of Drivers of Change

Our results reveal the presence of more 'slow' acting drivers in the VRB than "fast" changing ones (see Figure 5.2 and Table 5.2 above). Gunderson and Holling (2002) argued that the long-term dynamics and sustainability of most social-ecological systems are often driven by three to five key "slow" acting variables or drivers. From this perspective, it could be concluded that the sustainability of the VRB could be determined by the five top, slow changing drivers – population growth, land use/cover change, ground and surface water availability, infrastructure conditions, and land degradation. This implies that water managers and agricultural policy-makers will need to prioritise and manage those slow drivers carefully. However, the rapid changing drivers (e.g., precipitation variability), could be used as early warning indicators of impending damage (Thom et al., 2013).

In this study, factors such as infrastructure conditions, access to information and technology, access to financial credit, household income growth, access to markets, equity issues, skills or educational level, labour availability, and access to health care have all been identified as important drivers of change. However, these factors also determine the resilience and adaptive capacity in environmental systems (Yohe and Tol, 2002), and, therefore, need to be

strengthened. As one local farmer commented, "we will only ever be able to cope with the problems of change if only we have easy access to credit."

5.6. Reasoning Behind Expert Opinion and Judgement

The qualitative reasons behind the quantitative judgements and ratings are as follows. A clear majority of the local experts explained that their judgement and ratings of most were based on the effects that these drivers are having their livelihoods and food security, highlighting progressively declining crop yield and incomes to buttress their point. One local expert sums up this argument:

> "For the last 30 years, we hardly produce enough to food to feed our families and sell for income. We can only attribute this to the unpredictable rainfall, weak water infrastructure, coupled with the rising cost of basic inputs (e.g., fertilizer), and general lack of financial credit and institutional support".

Indeed, a consultation of published sources confirms that, overall, productivity is low, with cereal import dependency ranging from 10 to 50% (Lemoalle, 2009; Terrasson et al., 2009; Kolavalli and Williams, 2016). Regarding the lack of access to credit, most of the technical experts disagreed, explaining that credit is available, but many farmers simply do not repay the loans they collect from the lending bodies. Few, however, acknowledged that the high interest rates, collateral demands and perceived risks to exogenous factors (e.g. weather, pest, and diseases and commodity price fluctuation) by some banks and microfinance companies made it difficult for some farmers to obtain credit. This clarified why several of the local experts rated the provision of production subsidies so highly. An interpretation of these contrasting views is a readjustment of the current lending criteria to meet the unique financial challenges smallholder farmers face.

Notably, the local experts did not deem population growth as a critical issue. For most local respondents, people are valuable assets. Indeed, some noted that the population in their communities had dwindled as many of the youth moved to urban areas in search of better economic opportunities. This, in turn, has led to farm labour shortages and land abandonments in several places. Few technical experts confirmed this situation, deferring to extreme events (floods and droughts) and construction of some hydroelectric projects in some

parts of Ghana (e.g., the Bui Dam) as the drivers of rural depopulation. However, the majority view was that population growth is a generally important driver because it underpins the major changes in the basin, including environmental degradation, changes in water quantity and seasonal flows, and increased competition and demands for land and water resources. Reports indicate that the population across the entire basin has been growing at an average rate of 2.7% per annum, making it one of the fastest in the world (Mul et al., 2015). Further, projections indicate that the basin's population will increase from 23.8 million in 2010 to 56.6 million by 2050 (Kolavalli and Williams, 2016). These evidence and views, real or perceived, seem to support the neo-Malthusian thinking about environmental degradation and resource scarcity as population rises; although some studies in Africa have firmly challenged this assumption (Leach and Fairhead, 2000). Indeed, Lemoalle (2009) reports a correlation between population growth and the expansion of cultivated area over the past 30 years in the VRB.

Among all the expert respondents, precipitation variability was perceived as highly important because it is the major source of water underpinning the economic status of basin's inhabitants who depend on rain-fed agriculture. Also, a recurring theme was the under exploitation of irrigation in the basin, which makes natural rainfall extremely vital. Further, several others argued that the problem of the basin was not the lack of policies, but more to do with a lack of policy implementation. Two comments sum this up:

"As a farmer, if I am asked of anything I need to survive, it would be a reliable rainfall because is it determines whether or not, I will be able to feed my family and earn some income" (Local expert)

"The problem in the Volta River Basin is not lack of water, but institutional failures and weak governance structure. During the droughts of the 1960s and 1970s, the government at the time, constructed a number of small reservoirs to augment agricultural production, but successive governments failed to maintain these structures very well. The problem is compounded by the lack of sufficient political will, corruption and, generally, poor maintenance culture. Consequently, many noble initiatives aimed at enhancing water productivity for agricultural development and poverty reduction have vanished from the national development agenda" (Technical expert).

Indeed, evidence from several studies (e.g., Lemoalle, 2009; UNEP-GEF Volta Project, 2013) indicates that, because of declining precipitation in recent decades, some areas in the South now experience a greatly reduced second wet season compared to historical conditions. Consequently, rain-fed agriculture can only be carried out once instead of twice a year. This buttressed most of the expert's opinion that investments in water storage reservoirs, the provision of supplemental irrigation, and stronger policy implementation are required to meet the goals of food security and environmental sustainability. This is particularly more crucial in the wake of climate change, which observed evidence have shown to be changing at an alarming rate, causing temperature rise, shifting patterns of precipitation, and more extreme events (Awotwi et al., 2015).

When the results are viewed with a gender lens, an interesting but unsurprising finding is noteworthy. Specifically, most of the women pointed to the discrimination against them about access, control, ownership and inheritance of natural resources. Hence, their judgement prioritised drivers, including land availability, gender equality, and property rights issues. A technical female expert, for example, stated that "the basin's resources (e.g., land), while plentiful, are unevenly distributed", and four of her local counterparts lamented about how they lost access to and control of the family lands when their husbands passed on. A majority of the male respondents agreed, but attributed the problem to traditional practices, statutory institutions, and patriarchal land ownership systems, which still prevail in many rural communities across the basin. This observation supports several comments in the literature concerning gender-related problems surrounding resource access in the VRB (e.g., Lemoalle, 2009; Williams et al., 2016). It was a common view that actions promoting changes in cultural values are needed to ensure that women have equitable control of, and access to, all types of natural resources in the basin.

5.7. Conclusions

In this study, an expert judgement-elicitation approach was employed to provide a valuable source of information leading to insightful conclusions about drivers of change, their characteristics, and relative importance concerning water resource management for agricultural development in the VRB of Ghana. 51 drivers of change were found to be most critical to the sustainability of the basin. Among them, 38 drivers (e.g., land use/cover change, soil fertility, biodiversity loss) were characterised as predisposing (slow)

changing/acting drivers of change, while 12 (e.g., precipitation variability, soil erosion, access to financial credit, social conflict) were considered fast changing/acting drivers of change. Further, 33 drivers (e.g., drought intensity and duration, in/out migration, small-scale mining) indicate an increasing trend, while 17 (e.g., crop yield growth, household income growth, level of investment) drivers indicate a decreasing trend.

With regards to their relative importance, the study found four biophysical/environmental drivers (precipitation variability, water availability, land use change, drought events), and one socio-demographic driver (population growth) to be the most important drivers. Intra- and inter- expert group agreement in relation to the importance attached to the drivers were generally moderate and convergent thereby, increasing confidence in the results. Overall, the results can form the basis for decision-making concerning sustainable water resources management and agricultural production in the VRB of Ghana and other basins with similar environmental and socio-economic characteristics.

While this study acknowledges the limitations of this study due to the small sample size, every respondent is an influential expert in a limited network involved in decision-making within the VRB. Also, using quantitative structured expert survey based on published literature and requiring all experts to make decisions based on the same set of issues and the similar scales provides for transparency and repeatability of the study (Moody and Grand, 2012). Further, because the survey and interviews were designed here to cover a variety of themes, and respondents were recruited purposively from diverse backgrounds and disciplines, the study was unable to detect any institutional or disciplinary biases in expert's responses.

It is, however, important to stress that this study specifically focused on the relative importance of drivers of change as perceived my experts. Thus, the role of actors and the basin in driving change, issues of agency as well as the causal relationships and feedback among the individual drivers have not been explored in this chapter. Instead, this has been the focus of chapter 6.

CHAPTER 6: SYSTEMIC FEEDBACK MODELLING FOR SUSTAINABLE WATER RESOURCES MANAGEMENT AND AGRICULTURAL DEVELOPMENT: AN APPLICATION OF PARTICIPATORY MODELLING APPROACH IN THE VOLTA RIVER BASIN[2]

Julius H. Kotir[1] • Greg Brown[2] • Nadine Marshall[3] • Ron Johnstone[1]

[1]*School of Geography, Planning and Environmental Management, University of Queensland, Brisbane, QLD, 4072, Australia*

[2]*NRES Department, California Polytechnic State University, San Luis Obispo, CA, 93407, USA*

[3]*CSIRO Land and Water Flagship, James Cook University, Townsville, QLD, 4811, Australia*

Corresponding author: Julius H. Kotir. Email: j.kotir@uq.edu.au

Abstract

Although our understanding of water resource problems has grown in recent years, our ability to improve decision-making is still limited. Participatory modelling and stakeholder engagement considered an important tool that can facilitate strategic decision-making in environmental/natural resource management systems. This paper presents the participatory and methodological processes involved in the development of an integrated qualitative, conceptual model using causal loops diagrams to assist integrated water resources management and sustainable agricultural development in the Volta River Basin, West Africa. The developed integrated conceptual model facilitates a holistic and shared understanding of the key biophysical and socio-economic factors and processes, and the role the systemic feedbacks play in determining the basin's behaviour. The implication of the results for sustainable water resources management and agricultural development in the Volta River Basin is also given.

6.1. Introduction

In the last two decades, concerns have been raised at the global scale about the need and challenge for sustainable water resource management in an era of rapid global change, and pervasive water and food insecurity (Pahl-Wostl et al., 2013; Girard et al., 2015; Sivapalan, 2015). Although our understanding of water resources problems has grown in recent years, our ability to improve decision-making is still limited (Pahl-Wostl et al., 2011, 2013). New approaches have been exploring the potential of computer modelling methods that allow environmental problems to be considered in a holistic manner with active stakeholder involvement (Videira et al., 2011). More specifically, participatory modelling (PM) and stakeholder engagement is an important tool that can facilitate strategic decision-making in complex environmental/natural resource management systems (Voinov and Bousquet, 2010; Stave, 2010; Laniak et al., 2013; Videira et al., 2014; Voinov et al., 2016). According to Reed et al. (2008) the dynamic and complex nature of environmental issues call for a flexible and transparent decision-making that balances scientific findings with multi-faceted input from a range of stakeholders and decision-makers, many of whom have different values, perspectives, and objectives.

PM is particularly well-suited for the growing emphasis on integrated water resources management that aims to provide an improved understanding of water resources systems while considering biophysical and socio-economic concerns (Voinov and Gaddis, 2008). The involvement of stakeholders in modelling complex systems has grown considerably in the last decade (Beall and Ford, 2010; d'Aquino and Bah, 2014). PM has been designed and implemented in several river basins or watersheds around the world (e.g., Metcalf et al., 2010; Stave, 2010; Beall et al., 2011; Carmona et al., 2013; Hewitt et al., 2014; Robles-Morua et al., 2014; Butler and Adamowski, 2015; Inam et al., 2015; Safavi et al., 2015; Beall and Thornton, 2016). However, a search in Google Scholar, Scopus, and Web of Science revealed that some forms of PM have been used to develop models for land use polices in dryland Sahelian region in Africa (e.g., d'Aquino and Bah, 2013, 2014), but it has only been implemented in one out of the over 60 river basins or watersheds across Africa. The study by Farolfi et al. (2010) used a form of PM (Companion Modelling) to develop multi-agent

models to represent water supply and demand dynamics for the Kat River Valley in South Africa but the models developed did not consider the feedback processes operating between the system components. Simonovic et al. (1997) has also used the system dynamics approach for long-term water resources planning and policy analysis for the Nile River basin in Egypt, but the study is mainly quantitative and more importantly, did not benefit from stakeholder perspectives. Therefore, there is the need to complement quantitative simulations with conceptual or qualitative models that incorporate stakeholder knowledge and perspectives.

Indeed, conceptual modelling has been an important component of PM and of successful application of adaptive management to natural resource problems (Argent et al., 2016). However, system conceptualisation within the integrated environmental modelling community remains limited (Laniak et al., 2013). A review of dynamic modelling in water resources systems indicates that most system dynamics applications have not made adequate use of qualitative modelling tools (Mirchi et al., 2012). However, several studies (e.g., Gupta et al., 2012; Herr et al., 2015; Argent et al., 2016) suggest that qualitative or conceptual modelling provides a means to developing an understanding of a complex system, particularly when there is uncertainty about the system or limitations of quantitative data. Moreover, many of the existing PM studies tend to focus on the modelling process rather than the model itself (Voinov et al., 2014). Consequently, it has been suggested that modellers pay attention to the participatory as well as the modelling process and the model outcomes/outputs (e.g., van den Belt et al., 2010; Voinov and Bousquet, 2010; Videira et al., 2012).

The preceding knowledge gaps need to be filled to improve our understanding and management of environmental/natural resources management. Thus, this paper presents the participatory and methodological processes involved in the development of an integrated qualitative, conceptual model that captures the causal non-linear relationships between the key and multiple biophysical and socio-economic drivers and processes in the Volta River Basin (VRB) in West Africa, highlighting the key or dominant feedback loops. This chapter is based essentially on "conceptual modelling", defined as approach "used in explaining, understanding and exploring different kinds of systems" (Argent et al., 2016, p.114). Conceptual modelling was also strongly advocated as part of the early development of system dynamics (Forrester, 1973).

Following the above considerations, this chapter, thus, set the state for the development of the system dynamics model proposed in this study. A model is defined as a simplification of a real system in relation to some defined problem(s) (Forrester, 1995; Coyle, 2000; Barlas, 2007; Ford, 2010). According to Forrester (1971), all decisions, laws and actions are taken based on models. Models help us simply complex phenomena by eliminating everything we believe is extraneous to what we interested in studying (Ruth and Hannon, 1997). Models help to organise information in a more comprehensible manner (Forrester, 1991). Models are central to our understanding of the world, because they enable us to represent and manipulate real phenomena, then explore the results (Ruth and Hannon, 2012). Models can consist of many types: physical and symbolic (Barlas, 1996; Barlas, 2007). Physical models comprise of "physical objects (such as scaled models of airplanes, submarines, architectural models, models of molecules – symbolic models consist of abstract symbols (such as verbal descriptions, diagrams, graphs, mathematical equations)" (Barlas, 2007, p.4). Models may take a spatial or temporal perspective or a combination of both (Kerr et al., 2011). In recent times, modelling has been used as a tool to integrate knowledge, issues, and stakeholders. A typical model development process generally involves a continuous iteration, questioning, testing, and refinement (Sterman, 2000) before it can be used for decision-making.

Models are built for several purposes including, prediction, forecasting, management and decision-making under uncertainty, for social learning, and for developing system understanding/experimentation (Kelly et al., 2013). The purpose of the model developed in this study is to provide for a better understanding of the feedback structure and dynamic behaviour of the basin, and to provide a knowledge base in the form a decision support tool that would assist water resources management and sustainable agricultural development. The approach adopted herein, focuses on both the model development process and an evaluation of the participatory process as well as the model outcomes/outputs. Thus, this chapter is structured as follows. The study area is already described in chapter 1, and as such, is not repeated here. Section 6.2 provides an overview of participatory modelling approach and the modelling process. The conceptual modelling results are given in Section 6.3. A discussion of the results, implications, and conclusion are provided in Sections 6.4 and 6.5.

6.2. Materials and Methods

6.2.1. Systems Thinking and Participatory System Dynamics Modelling

Systems thinking approach is a science-based approach of making robust inferences concerning the behaviour of a system and developing full insight into the underlying structure of a complex system (Richmond, 1994). Systems thinking deals with unknown complexity, uncertainty, and mental models, thus providing a framework for holistic thinking (Senge, 1990; Sterman, 2000). It offers powerful concepts, tools, and techniques to unravel complexity and create lasting interventions for chronic socio-economic and environmental problems (Simonovic, 2009). These include feedback, stocks and flows, time delays, nonlinearities, which are critical building blocks for effective systems thinking and modelling (Sterman, 2000; 2002). System dynamics modelling (SDM) approach based on the notion of systems thinking (Maani and Cavana, 2007), on the other hand, is a computer-based scientific method for studying and managing complex systems that change over time (Ford, 2010).

SDM was originally developed by Professor Jay W. Forrester at the Massachusetts Institute of Technology (MIT), in the mid-1950s (Forrester, 1961). Forrester's work also led to a more sophisticated world model by Donella and Dennis Meadows. Their classic book: *Limits to Growth* (Meadows et al., 1972) advanced the application of SDM for a wide range of environmental/natural resources and social systems. The approach is grounded in feedback control theory and the modern theory of non-linear dynamics (Sterman, 2000). It stresses the multiloop, multistate, nonlinear character of the feedback systems in which we live (Forrester, 1961). It involves the development of formal models to capture complex system dynamics, and to create an environment for learning and policy design using a feedback perspective (Forrester, 1961; Sterman, 2000; Barlas, 2007).

Fundamentally, SDM rests on the assumption that time delays, nonlinearities, system feedbacks, amplifications, and structural relationships between a system's elements can be more significant in determining aggregate system behaviour than the individual components themselves (Forrester, 1961; Sterman, 2000). Since its development, SDM has been applied to issues ranging from physics to physiology and psychology, from arms races to the war on drugs, from global climate change to organisational change (Sterman, 2000). An extensive review of SDM applications in water resources systems is provided by Winz et al. (2009). As stated in chapter 1, the applicability of SDM approach is largely based on its ability to

capture the feedback-effects of systems and characterise temporal processes (Sterman, 2000). Compared with the conventional simulation or optimisation models, the SDM approach has the advantage of showing how different changes of the fundamental components of the system affect the dynamics of the whole system in the future (Xu et al., 2002). It can capture feedback-effects, time delays, accumulations, and nonlinearities (Sterman, 2000). These model development procedures are designed based on a visualisation process that allows modellers to conceptualise, document, simulate, and analyse models of dynamic systems (Sterman, 2000; Ford, 2010).

There is a consensus among practitioners and modellers that stakeholders can, or should be involved in most steps of environmental modelling (Beall and Ford, 2010; Laniak et al., 2013; Stave, 2015; Voinov et al., 2016). Thus, and as stated above, the main aim of this chapter is to also demonstrate the involvement of stakeholders in the development of the *dynamic hypothesis*, specifically, through the application of participatory modelling (PM) approach. In broad terms, PM consists of the participation of diverse interested stakeholders in a specified modelling process (Vidiera et al., 2011). According to Stave (2010, p. 2766), a "participatory system dynamics modelling is the use of a system dynamics perspective in which stakeholders or clients participate to some degree in different stages of the process, including problem definition, system description, identification of policy levers, model development and/or policy analysis."

The approach is based on the notion that people who reside and work in a system may be better informed about its processes and probably have observed phenomena that would not be captured by scientists (Voinov and Bousquet, 2010). According to Beall and Ford (2010, p.19), "modellers using the science of system dynamics and the art of facilitation in a participatory process can create a nexus of science and social concerns." The PM process leads to one or more types of system models ranging from qualitative, descriptive visual maps or causal loop diagrams that seek to identify the archetype of behaviour, to quantitative spatial and or temporal modelling (Beall and Thornton, 2016). It should be noted that PM shares similar methodological elements with Shared Vision Planning (SVP) – a computer-aided collaborative approach, which has been extensively used for several decades by the US Army Corps of Engineers as a tool to address complex water resources management problems (see Cardwell, et al., 2009; Creighton, 2010).

Many proponents and practitioners of PM approach in environmental decision-making (e.g., Videira et al. 2009, 2012; Stave, 2010; Voinov and Bousquet, 2010; Rockmann et al., 2012; Carmona et al., 2013; Bellocchi et al., 2015; Voinov et al., 2016) have highlighted several benefits of modelling with stakeholders. These include facilitating and structuring discussion between scientists and stakeholders, creating an environment for social learning and co-production of knowledge, building social capital, and increasing the credibility of model outputs and legitimacy of management decisions. While the model building process assists stakeholders to clarify their own mental models and gain deeper insight into vital scientific relationships, jointly developed models also have a great virtue of helping stakeholders with problem definition and evaluation of possible management or policy options (Beall and Ford, 2010). Another great virtue of PM is that it can provide valuable skills to stakeholders, and help to bridge important data or information gaps (Voinov et al., 2016). Also, the involvement of stakeholders in modelling also provides a platform to integrate natural resource science and social issues (Beall and Ford, 2010), as well as scientific and non-scientific/indigenous knowledge (van den Belt, 2004; Voinov and Gaddis, 2008; Hewitt et al., 2014; Stave, 2010; Lippe et al., 2011). Among the numerous advantages, the promotion of social learning, the co-production of knowledge and development of innovative strategies to problems, have possibly been considered the most important outcomes from any participatory process (Videira et al., 2010).

However, several issues, including: (1) the multifarious and conflicting views, values, perspectives, and interests held by stakeholders concerning the problematic issue and how it should be managed and; (2) different disciplinary backgrounds of stakeholders can make the PM process difficult (Hedelin, 2007; Voinov and Bousquet, 2010; Stave, 2010; Hare, 2011; Carr et al., 2015; Voinov et al., 2016). Also, it may be quite expensive to organise, and can be tiring and time-consuming in terms of identifying and bringing expert stakeholders to a joint process of problem solving and model building (Voinov et al., 2016). Despite these drawbacks, it is the many benefits it provides, particularly its ability to involve key stakeholders in the co-construction of dynamic and integrated models, leading to a shared or collective view and understanding of persistent complex management problems (such as those in the Volta River Basin) that justifies its application here. Further, the lack of stakeholder involvement in the planning and decision-making processes in the basin, as expressed in recent studies (e.g., Douxchamps et al., 2012; UNEP Volta Project, 2013) informs the application of the PM approach in this study.

6.2.2. Model Development Process

Generally, the development of a system dynamics model involves a sequence of iterative and interrelated steps (e.g., Randers, 1980, Richardson and Pugh, 1981; Roberts et al., 1983, Wolstenholme, 1990, Stave, 2003; Cavaana and Maani, 2007; Barlas, 2007; Simonovic, 2009; Beall and Ford, 2010; Ford, 2010). There is, however, no standard or best modelling process employed by all system dynamic modellers. Although the specifics differ between processes, there is general agreement on some key steps. In this study, the modelling steps proposed by Sterman (2000) were followed (see Table 6.1): It should be noted, though, that the process is flexible; hence, one does not need to strictly follow the depicted sequence in Table 6.1. Indeed, the process is iterative and, in many cases, imposed by several considerations such as the project context, time, available resources, the needs of the stakeholders, and the preference of the modeller (Beall and Ford, 2010; Beall and Thornton, 2016). Parts of step 1- that is the problem, and the identification of the key variables and concepts are covered in chapters 1 and 5, respectively. Thus, this chapter specifically focused on step 2.

The remainder of the modelling process is addressed in chapter 7, where the *dynamic hypothesis* is translated into a formal computer-based simulation model, allowing alternative policy scenarios to be designed, analysed, and compared. The end-product of the efforts in this chapter is, therefore, a *dynamic hypothesis* or a *conceptual model* – that is a qualitative model in the form of a *causal loop diagram* (CLD), which captured the feedback structure of the VRB, showing the cause-effect relationships and feedback loops between the important variables (Sterman, 2000; Barlas, 2007). A dynamic hypothesis is a 'conceptualisation of the causal relationships, feedback loops, delays, and decision rules that are believed to produce system behaviour' (Kelly et al., 2013, p.164). It is "a working theory of how a particular problem came about" (Sterman, 2000, p. 95).

According to Sedlacko et al. (2014), CLDs are perhaps the most utilised system visualisation and communication or modelling tools for dealing with environmental problems. CLDs based on the principles of systems thinking and system dynamics are powerful tools because they assist in conceptualising how different systems structures and understanding how different variables interconnect. They visually represent the feedback loops among the various components of the system under study (Hassanzadeh et al., 2014). In addition, CLDs can be

used to formulate preliminary causal hypothesis of the problem under study as well as to simplify the illustration of a model (Sterman, 2000; Coyle, 2002).

Table 6.1: Steps of the modelling process (Adapted from Sterman, 2000, p. 86)	
1.Problem Articulation (Boundary selection)	• What is the problem? Why is it a problem? • Theme selection: what are the key variables and concepts one must consider? • Time horizon: How far in the future should one consider? How far back in the past lie the roots of the problem? • Dynamic problem definition (reference modes): what is the historical behaviour of the key concepts and variables? What might their behaviour be in the future?
2.Formulation of Dynamic Hypothesis	• Initial hypothesis generation. What are current theories of the problematic behaviour? • Endogenous focus: Formulate a dynamic hypothesis that explains the dynamic as endogenous consequences of the feedback structure • Mapping: Develop maps of casual structure based on initial hypothesis. Key variables, reference modes, and other available data, using tools such as Model boundary diagrams, Subsystem diagrams, Causal loop diagrams, Stock and flow diagrams, Policy structure diagrams, and other facilitation tools.
3.Formulation of Simulation model	• Specification of structure, decision rules. • Estimation of parameters, behavioural relationships, and initial conditions. • Testing for consistency with purpose and boundary.
4. Testing the model	• Comparison to reference mode: does the model reproduce the problem behaviour adequately for your purpose? • Robustness under extreme conditions: does the model behave realistically when stressed by extreme conditions? • Sensitivity analysis: How does the model behave given uncertainty in parameters, initial conditions, model boundary, and aggregation?
5.Policy Design and Evaluation for improvement	• Scenario specification • Policy design: What new decision rules, strategies, and structures might be tried in the real world? How can they be represented in the model? • "What if" analysis: what are the effects of the policies? • Interaction of policies: do the policies interact? Are there synergies or compensatory responses?

CLDs comprise of words and arrows with appropriate polarity, depicting combinations of positive and/or negative causal relationships. A positive (+) causal relationship indicates that, other things being equal (*Ceteris paribus*), an increase/decrease in model *Variable A* would result in an increase/decrease in model *Variable B*. In other words, the polarities change in the same direction. A negative (-) causal relationship means that an increase/decrease in model *Variable A* will lead to a decrease/increase in model *Variable B* (i.e., the polarities change in opposite direction). A combination of positive and negative causal relationships gives rise to the system's feedback loops. The notion of 'feedback loop' implies that at least two unidirectional cause-effect relationships connect two or more system components, thus, representing circular causalities (Le et al., 2012). Feedback loops can be described as reinforcing (or positive) or balancing (or negative) feedback loops (Sterman, 2000). Positive

feedback loops accelerate change within systems, which can result in a rapid growth or decline (Simonovic, 2009). On the other hand, negative feedback loops counteract or oppose change and display goal seeking behaviour. This type of feedback loop "is characterised by trends of growth-decline or decline-growth (oscillation around the equilibrium point)" (Goheri et al., 2013, p. 27).

CLDs are used as the modelling tools in this study, because of their ability to show cause-effect relationships between a set of variables, issues, and problems that characterise a dynamical system through a simple graphical structure (Sterman, 2000). Also, the ability to model feedback and delay processes present a distinct advantage of CLDs over the other visualisation tools such as Bayesian network modelling for example, which is inherently acyclic, and thus unable to handle feedback structure of systems (Molina et al., 2010; Kelly et al., 2013). In addition, the focus on identifying and modelling feedback loops promotes closed-loop thinking (i.e., thinking in terms of interdependent variables rather than linear and uni-directional relationships) (Richmond, 1993). In addition, CLDs appear to be ideal for problem scoping and model conceptualisation (Videira et al., 2010), which is the case in this chapter. Further, due to their graphical nature, CLDs can easily be understood by non-technical users, thus making it the ideal modelling tool in a participatory setting.

6.2.2.1. Developing the Dynamic Hypothesis/Conceptual – The CLD
As already stated, the following process in this study followed the steps presented in Table 6.1, although it also drew from some examples of participatory modelling processes conducted in environmental systems in recent years (e.g., Videira et al., 2012; Inam et al., 2015) and guidelines suggested by Voinov and Bousquet (2010) and Argent et al. (2016). However, most of the activities took place in a workshop setting. Thus, the participatory aspect in this study was structured into 5 key activities (see Figure 6.1). This comprise: (1) preparatory activities; (2) participatory modelling workshop; (2) mental modelling and construction of the CLDs; (4) digitising the CLDs using Vensim; and (5) evaluation of the PM process and outcomes/outputs. Each stage is further decomposed into several key activities that guided implementation of the overall process. Some may reasonably argue that these specific activities ought not to be reported. However, as Rahmandad and Sterman (2012, p. 397) recently advised, "modellers need to document their work in such a way that it is fully reproducible by others." Seidl (2015) recently re-echoed similar concerns. This level

of documentation and transparency, according to Laniak et al. (2010), is necessary to facilitate quality assurance and peer review.
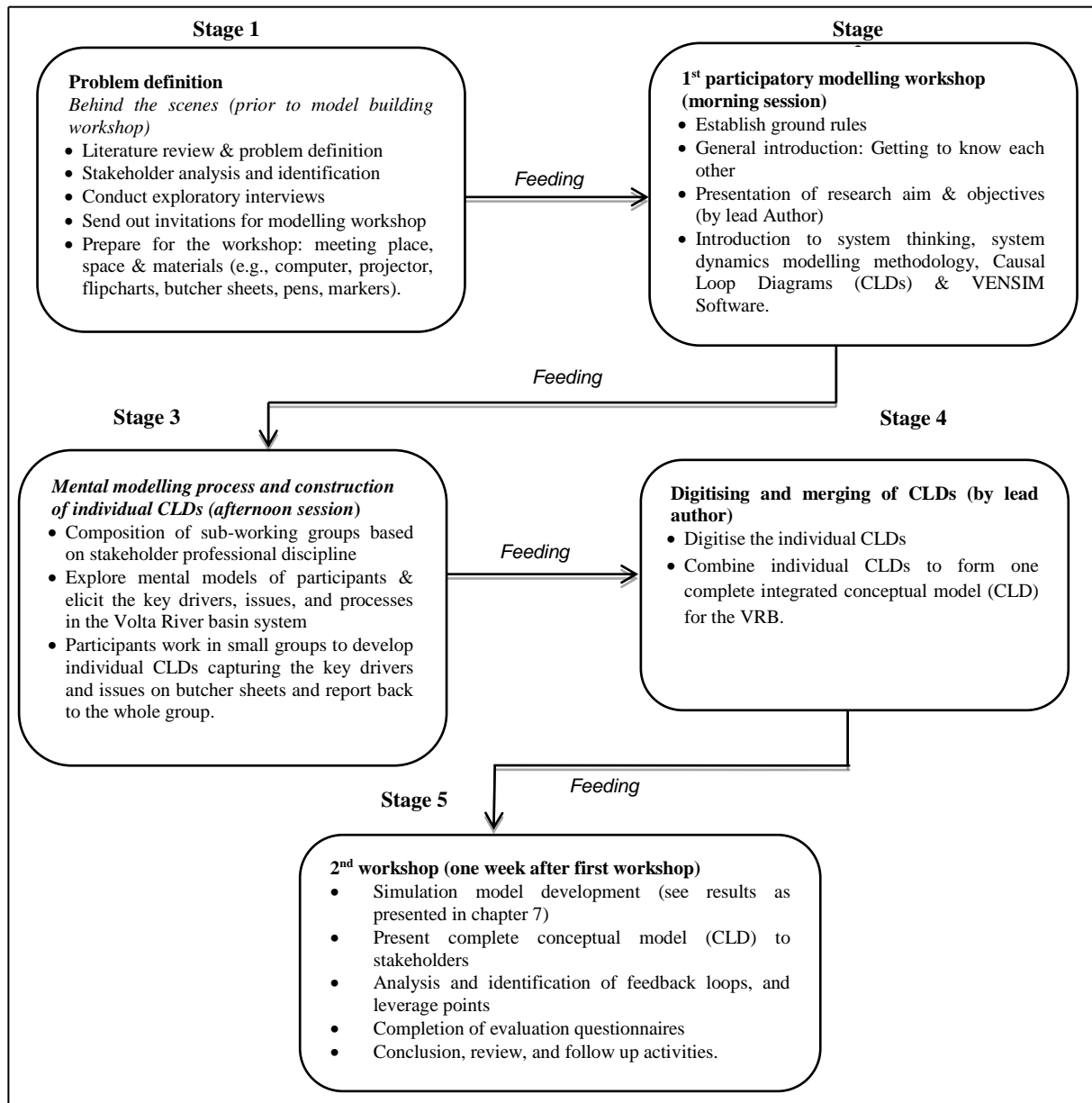

Figure 6.1. Iterative stages of the participatory modelling workshop within the Volta River Basin

6.2.2.1.1. Problem definition

As part of the problem definition, a scoping review was performed to understand the context of the study and its underlying problem issues. Specifically, this task involved literature review, definition of the spatial and temporal scale (i.e., the model boundaries), selection of time horizon, identification of key variables, dynamic problem definition (*reference modes*),

and identification of the stakeholder groups (Sterman, 2000; Ford, 2010). Reference modes consist of a set of graphs and other descriptive data indicating the historical and dynamic behaviour of the main system variables or challenges over time (Sterman, 2000). If possible, there should be accessible (quantitative) historical information and data for the graphs as far back in time as you decide to look ahead (Rander, 2013). They can represent either past or future behaviour of the system (Simonovic, 2009). Nevertheless, reference modes can be drawn in a rough manner without reference to exact observed or time series data (Sterman, 2000; Maani and Cavana, 2007).

An important purpose of generating the reference modes is that they are used as a reference in step 6 to test whether the simulated model outputs adequately replicate the reference modes or observed behaviour of the system (Sterman, 2000; Stave, 2003; Ford, 2010). If they do, then confidence is gained in the performance of model, implying that it can be used for policy design and analysis (Sterman, 2000; Stave, 2003; Barlas, 2007; Ford, 2010). As stated above, the model boundaries and the time horizon have already been defined in chapter 1 – specifically in Section 1.5. Through a combination of literature review and expert stakeholder interviews, the identification of the key variables has also been carried out and, the results, as presented in chapter 5 showed that issues such water availability and demand, population growth, land use change (crop land area), crop yield were deemed to be the critical variables characterising the dynamic problem of the basin. Accordingly, a graph indicating the dynamic pattern and behaviour of these central variables in recent years is depicted in Figure 6.2. They were constructed based on available historical data.

In general, the graph shows total population increased steadily. Agricultural water demand has also increased from 2000; however, it has levelled off since 2007. Cropland area grew rapidly from 2000 to 2006. It then reached equilibrium until 2007, when it began to rise again. Although crop yield slowly trended up, it started to level off since 2010. Moreover, crop yield rise is not fast enough to keep up food demand. Indeed, several studies confirm that current overall agricultural productivity is low, with cereal import dependency ranging from 10 to 50% (Lemoalle, 2009; Terrasson et al., 2009; Kolavalli and Williams, 2016). As a result, projections of future income growth and poverty reduction efforts are more uncertain (UNEP Volta Basin Project, 2013; Williams et al., 2016). The behaviour of these key variables creates an archetypical example of a system with potential for evolving threat, which poses several challenges from the standpoint of production and sustainable

development in the basin. In sum, there is some evidence of a long-term problem with potential unanticipated side effects. If this is to be avoided, managers and decision-makers need a systemic understanding of the issues and problems so that they can respond with the appropriate strategies and solutions. Participatory system dynamics modelling provides such an approach.
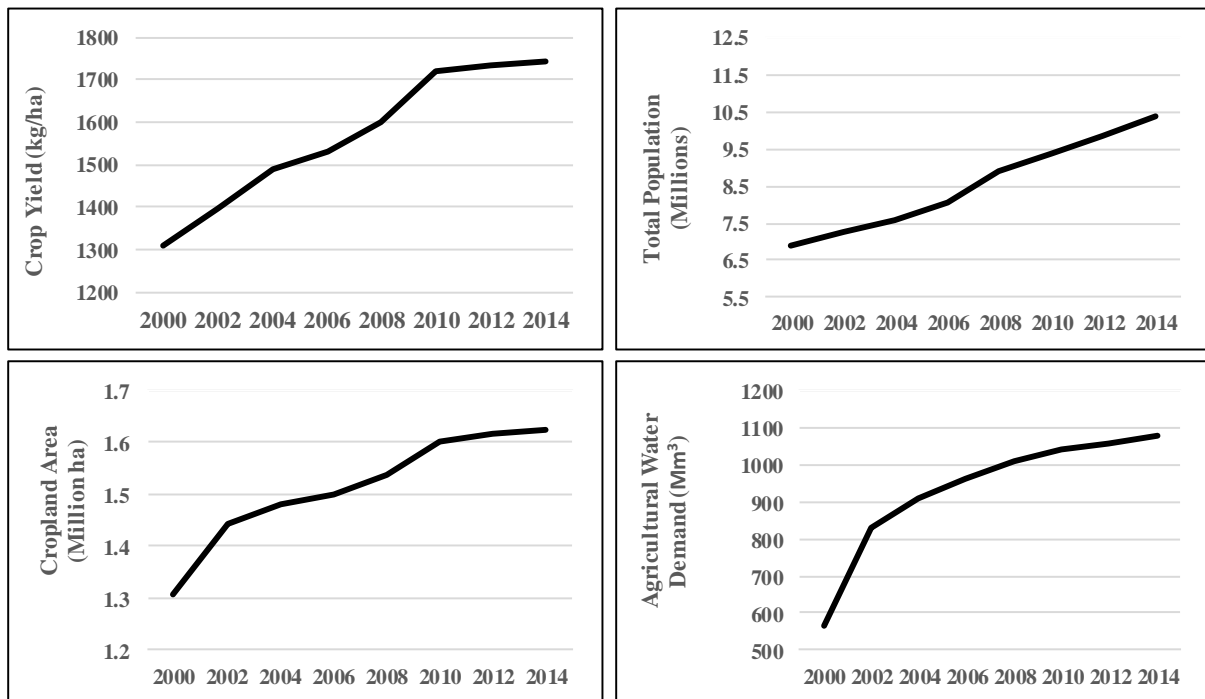

Figure 6.2: Reference modes of key variable of the VRB over 10-year time horizon

6.2.2.1.2. Stakeholder analysis, identification, and invitation

Participation in a PM process 'can never be all-inclusive' (Voinov et al., 2016). Thus, the identification and selection of participants are important regarding the transparency, representativeness, and legitimacy of the PM process (Reed et al., 2009; Mathevet et al., 2014). In general, there is no standard method for identifying and selecting a sample of stakeholders for a PM process (Voinov and Bousquet, 2010; Drescher et al., 2013). According to Voinov and Bousquet (2010), whichever method one adopts, efforts should be made to include different group of stakeholders that represent a diversity of interest and background. As a register of qualified stakeholders was unavailable in the VRB, multiple techniques including, 'snowball sampling' or 'chain referral' (Lewis-Beck et al., 2004), web-based searches, and a review of literature were employment to develop a sampling frame containing a pool of potential stakeholders.

To minimise sampling bias and the marginalisation of stakeholder groups (Reed et al., 2009; Voinov et al., 2016; Drescher et al., 2013), a purposive sampling technique was then used to select a group of stakeholders from the pool based on their professional standing, prolonged years of experience through research or practice (i.e., more than 10 years) and their likely ability to discuss problems of the basin with a strategic basin-wide perspective. The selection process was designed to ensure that a range of stakeholders from the natural science and social science backgrounds (i.e., traditional scientists) and local farmers (i.e., non-traditional scientists) (Perera et al., 2012, as described in chapter 5) were represented. Participants did not need to have any modelling aptitude or experience. Overall, a pool of 44 potential stakeholders were identified and were subsequently contacted via phone and email for a preliminary/exploratory interview.

6.2.2.1.3. Exploratory Interviews

One month prior to the modelling workshop, an exploratory interview was conducted with the 44 selected stakeholders. The exploratory interviews served as a useful tool for building rapport with the stakeholders and explaining the participatory process in more detail before the modelling workshop (Videira et al., 2009, 2011). Furthermore, these interviews permitted us to gather relevant background information about the participants and offered a point of departure for suggesting issues that could be addressed during the workshops (Videira et al., 2009). This background information was essential in deciding who to invite for the model development workshop and also ensuring equal representation in terms of gender, areas of discipline, and expertise. Results from the interviews indicate that six of the participants had an idea of system dynamics modelling but only two had experience in participatory modelling workshop elsewhere in Africa. During the interviews, an invitation was extended to each participant to participate in the modelling workshop.

6.2.2.1.4. The Participatory Modelling Workshop

Out of the 44 stakeholders interviewed and invited, 27 participants from different organisational affiliation reported for the modelling workshop (see table 1). The model building workshop was conducted on June 14th and 21st, 2014 (i.e., in 2 full days). The lead author facilitated the workshop with assistance from an outside consultant (Dr Oscar Yawson) from the University of Cape Coast, Ghana. Together, we kept track of the

exchanges between the participants and helped to explain the modelling process to the participants.

We also ensured that the modelling process followed standard scientific practice and objectivity (Voinov and Bousquet, 2010). We started with an "ice breaker" during which participants got to know each other and the facilitators. After establishing the grounds rules for the day, the participants were given a brief introduction to the general objectives of the research, the principles, methods and objectives of the modelling process, and system dynamics approach in general. We also introduced the participants to the Vensim modelling software version 6.4 from Ventana Systems, Inc. (http://www.ventanasystems.com/) and its function. The introductory session also provided an opportunity for the facilitators to discuss the scope and boundaries established for the study. The reference modes constructed and depicted in Figure 6.2, were also presented to the stakeholders to confirm whether they were logically consistent with their mental models. Overwhelmingly, they confirmed that the trends conformed with their experiences.

Table 6.2: Workshop participants and organisational affiliation (N =27)

Types of organisation represented	Number of participant
Government institutions	7
NGO and civil society	9
Research and academic institutions	4
Private and consulting firms	1
Local farmers and their agents	4
Other	2
Total	**27**

6.2.2.1.5. Mental Modelling Process and Construction of the CLD

Having introduced the participants to modelling process, the rest of the day was devoted to developing the conceptual models (i.e., the CLDs). The workshop participants were placed into one of four groups, based on their research interests representing: the biophysical/environmental sub-sector; the socio-demographic sub-sector, the economic and policy sub-sector. Each group composed of at least 6 members. Stakeholders were asked to reflect on their mental models and brainstorm about the key drivers, issues, factors, and processes affecting the sustainability of the VRB. As the father of system dynamics, Jay W Forrester indicated, the most important source of information, both in quantity and significance for the modeler, is the mental database of individuals (Forrester, 1994). Thus,

focusing on mental models helped the modeller/researcher and the participants understand the different worldviews. The guiding questions that prompted the brainstorming exercise were:

- ✓ *What do you think are the main drivers, factors, and processes that influence water resource management and agricultural development in the Volta River Basin?*
- ✓ *What are the impacts/consequences of the drivers and factors?*
- ✓ *What strategies are required to enhance sustainable water resource management and agricultural development?*

These questions are similar to the main research question used in chapter 5, except that they are unstructured. The ideas that emerged from the mental modelling were collected using flip-charts and post-it notes. Many of the issues, problems, and drivers identified were largely consistent with those identified and described in chapter 5 as part of the problem definition or familiarisation process. Butcher sheets and large sheets of papers were provided to each sub-group to develop their individual CLDs showing the cause-effect relationships between the system drivers and processes. The sub-groups operate mostly in parallel, punctuated by plenary sessions, to enable adequate creativity and divergent thinking concerning the relevant issues throughout the workshop (Metcalf et al., 2010). However, each group selected a *rapporteur* who took notes and reported the results achieved to the whole group in a plenary session. Overall, the model building exercise was straightforward and stakeholders kept amending their CLDs until all members in their groups were satisfied that they had built a simple model representing their mental map in the form of causal linkages. In the end, each group presented their results to the plenary, generating a lively and informative discussion.

6.2.2.1.6. Digitising and Merging Individual CLDs

After the first workshop, all the individual CLDs were digitised and merged by the lead author using Vensim modelling software (http://www.ventanasystems.com/). The merging process started with the most comprehensive model, which in this case was the economic and policy sub-model (Figure 6.4). After one week, the digitised preliminary CLDs and the merged (integrated) model were presented back to the stakeholders during the second workshop for further evaluation, refinement, and validation. During this process, the stakeholders were reminded to focused on the most important factors and processes while striking a balance between model comprehensiveness and simplicity so as avoid creating an unnecessarily complex model that could have a high cost in terms implementation (e.g., high

costs of data input, a lengthy cycle of model development, and difficulty in application by the decision-makers) (Le et al., 2012). For example, it was agreed by all stakeholders to drop 'agricultural production' as variable from the model, and instead use 'crop yield' since they considered this to be more specific and definitive. Stakeholders also agreed to focus on surface resource water availability instead of combined ground and surface water availability as captured in the biophysical/environmental sub-model (Figure 6.3) because it is the first choice to meet all water demands while groundwater is used when surface water supply is not available (Barry et al., 2005).

Because of the stakeholder evaluation, not all factors contained in the individual CLDs (e.g., availability of arable land) made it into the final integrated model (CLD) as there was a consensus among the stakeholders that the basin's problems could be explained without those factors. Finally, the merged/integrated model went through a little more refinement process until all participants were satisfied the developed model had met certain important criteria concerning its realism, flexibility to respond to changing management needs, clarity, ability to reproduce historical patterns, and ability to generate useful insights (Homer and Hirsch, 2006; Jackman et al., 2006; Bellocchi et al., 2015). For example, the clarity of the model, its credibility, and whether it realistically represents the VRB was assessed through thorough visual inspection (Hewitt et al., 2014) of the outputs with the stakeholders to ensure that the key components (such as the description of the variables, the model polarities, the causal relationships, and the resulting feedback loops) were not ambiguous. The model's ability to reproduced historical patterns was inferred by cross-checking the behaviour of certain key variables (e.g., population, crop yield, water demand, and precipitation variability) with observed trends that have been described elsewhere in the literature (e.g., Barry et al., 2005; Lemoalle, 2009; UNEP-GEF Volta Project, 2013).

It is, however, important to mention that the robustness and performance of the model in terms of how accurately it replicates the major behaviour patterns can be comprehensively evaluated once it has been quantified and simulated with reliable observed/historical data (Sterman, 2000; Bellocchi et al., 2015). The simulation model development, stock and flow construction, and parameterisation, started with stakeholders but stakeholders run out time. It was subsequently, refined and completed by the researcher/modeller and evaluated individually by few stakeholders. The formal numerical simulation model of the conceptual model is developed in chapter 7. At the end of the second workshop, an evaluation was

conducted with the stakeholders to solicit their views on the modelling process and the model outputs. Detail results from the evaluation process as well as the insights and lessons learned gained from the process are presented in chapter 8.

6.3. Results

6.3.1. Biophysical/Environmental Sub-model

The CLD representing the biophysical/environmental domain is shown in Figure 6.3. Stakeholders within this domain have identified 20 drivers of change or issues. The model was constructed around the issues of climate change, available surface water, total agricultural production, and crop yield.
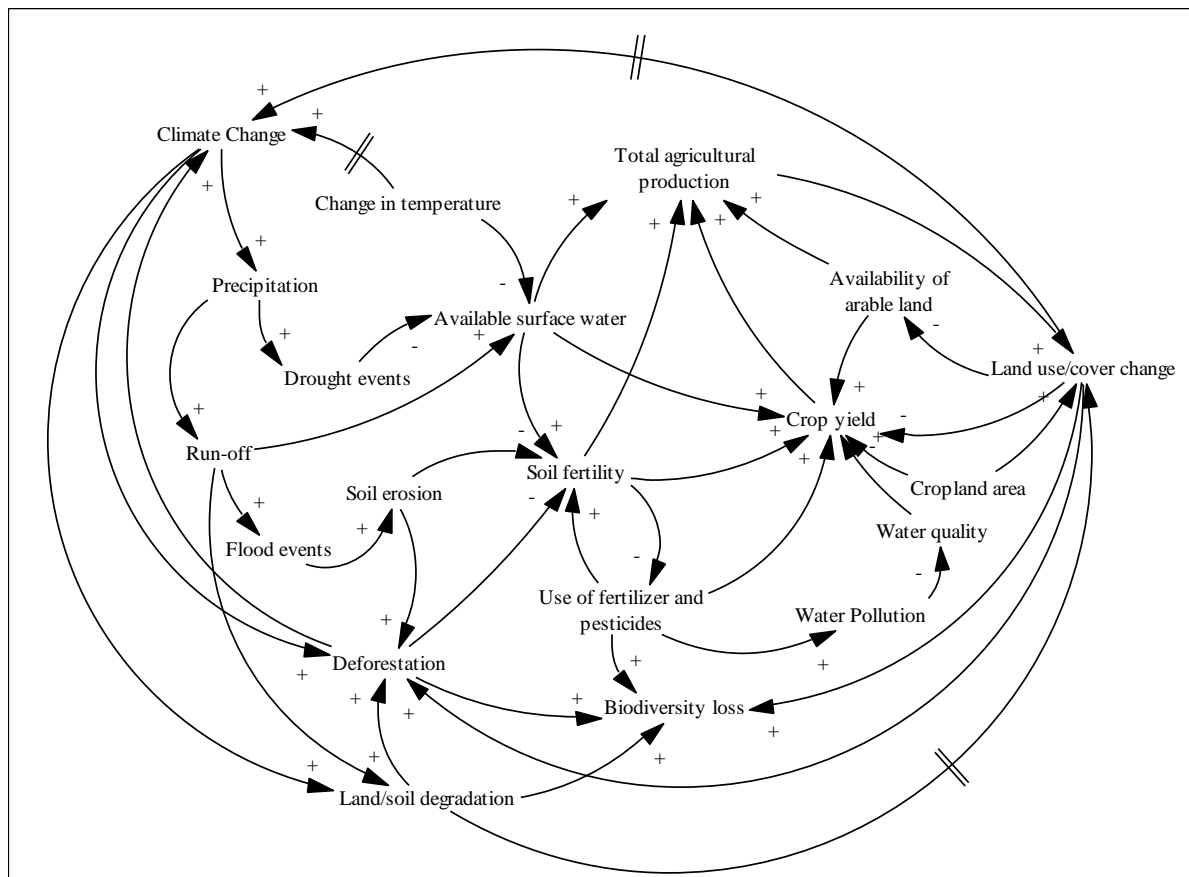
Figure 6.3. CLD of biophysical/environmental sub-model

6.3.2. Economic and Policy Sub-model

The economic and technology sub-model is depicted in Figure 6.4. The model consists of 23 variables. Overall, the economic and policy sub-model appears to be underpinned by five

fundamental drivers and factors: water availability, crop yield, agricultural production, farm income, and use of fertilizer. Compared to the biophysical sub-model, stakeholders in this domain also identified the issues of climate change, land use change, use of fertilizer, agricultural production, crop yield, and water availability as crucial, and thus, incorporated them in their model.
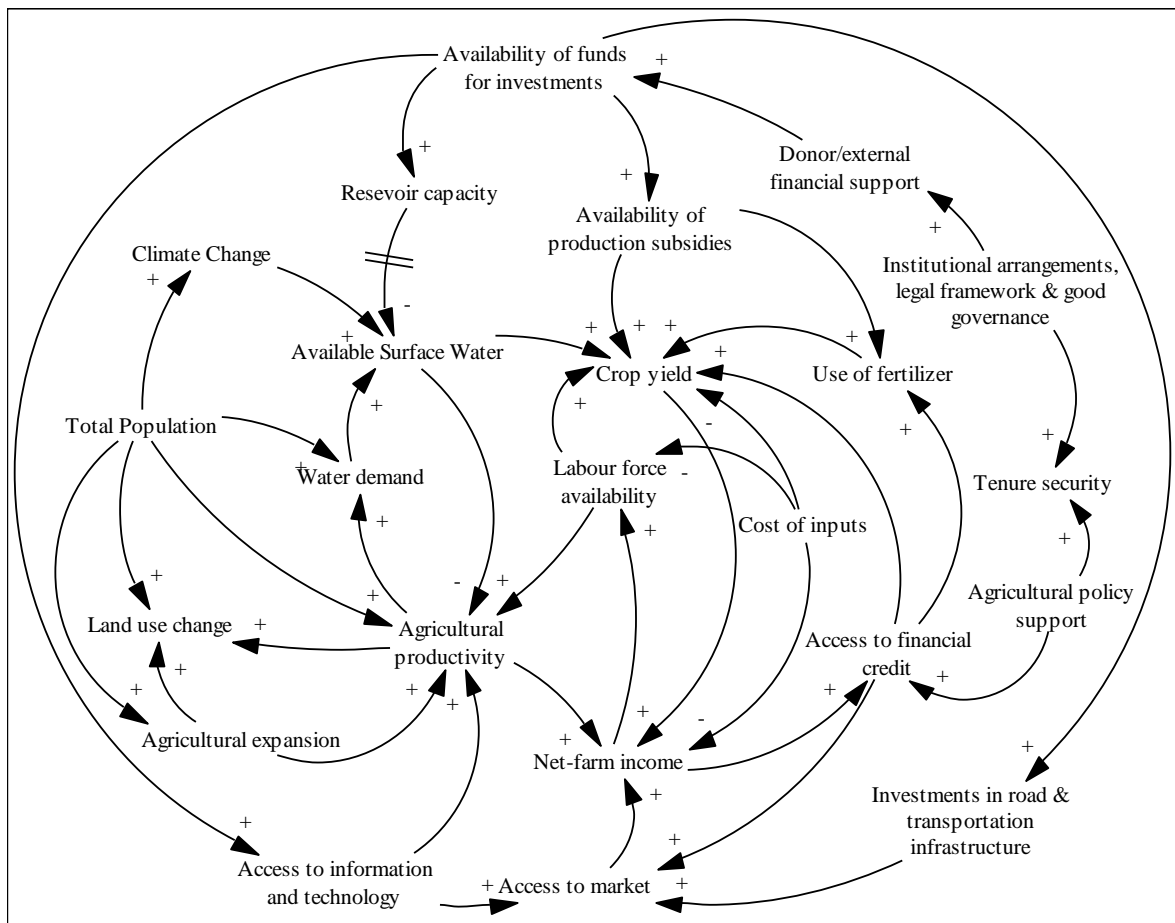
Figure 6.4. CLD of economic and policy sub-model

6.3.3. Socio-demographic sub-model

The CLD representing the socio-demographic sub-sector is depicted in Figure 6.5. Stakeholder in this domain identified 16 drivers or issues. However, the model was built around the issues of total population, food availability, agricultural production, poverty level, malnutrition, and socio-economic marginalisation. Between the socio-demographic group and the economic and policy group, the issues of total population, and tenure security appear to be paramount.
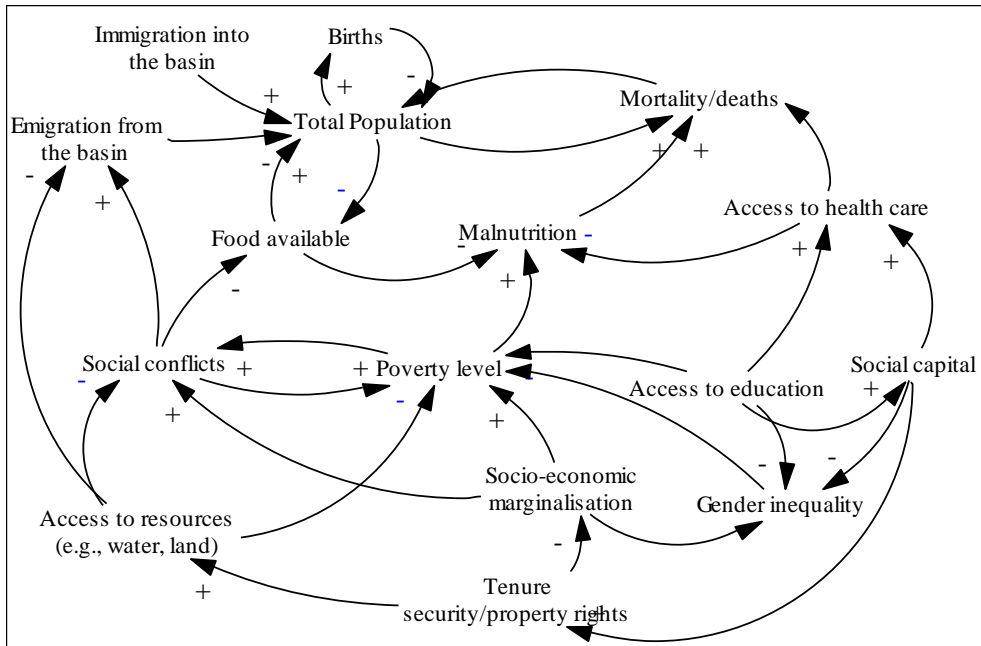
Figure 6.5. CLD of socio-demographic sub-model

6.3.4. Integrated Conceptual System Model

The merged system model (CLD) that integrates the biophysical/environmental, socio-demographic, economic and policy sub-models of the VRB is shown in Figure 6.6. Overall, 46 variables are involved, which are connected to each other by 85 arrows (links). The interconnections produced 21 feedback loops comprising: 14 reinforcing (positive) feedback loops and seven balancing (negative) feedback loops, indicating the complex systemic feedback structure that determines the dynamics behaviour of the basin. Given this complexity, 15 feedback loops (highlighted) are selected for in-depth discussion, because they capture the key structural elements of the conceptual model and have important implications for water resources management and agricultural production.

Loop R1 illustrates the interdependence between total population, labour inputs, crop yield, and available food. According to the mental model of the stakeholders, total population after a delay leads to an increase in labour force, and consequently, crop yield growth. As crop yield increases, it leads to food availability and population growth is reinforced.

Figure 6.6: Integrated Conceptual model of the Volta River Basin. ("+") indicate a positive link; ("–") indicates negative link. (R) denotes a Reinforcing (or positive) loop; (B) denotes a Balancing (or negative) loop. \\ (delay marks) on the arrows denotes time delay perceived to be relevant to the dynamics of the system.

Loop R1 is counteracted by an important balancing loop (loop B1) which illustrates that population pressure will eventually feedback to limit the amount of food available to the population. The model also portrays total population as a direct function of mortality, and emigration from the basin which is determined by social conflicts. Further, total population increases water demand, which causes a reduction in the available surface water resources, which in turn, has a direct influence on crop yield and the process loops forward to influence available food and total population (loop B2).

The conceptual model also illustrates that investment in water infrastructure (e.g., expansion of reservoir capacity) is an important issue to the stakeholders as it is assumed to lead to a more desirable outcome (i.e., surface water availability). Specifically, the more water infrastructure investments, the more available water for various purposes and, consequently, the less water use. On the other hand, increased water demand increases more expansion in reservoir capacity (loop B3). However, expansion of reservoir capacity is also seen as a function of funds for investments, which in turn, is a product of donor/external financial support driven by good institutional arrangements, legal framework, and good governance. However, it is also evidenced that water availability is influenced not only by infrastructure investment but also by the amount of precipitation (rainfall) and changes in surface run-off, which stakeholders conceived as outside their control.

Precipitation is intermittent in the VRB, and the amount of rainfall, when it occurs, depends largely on temperature and climate variability and change (UNEP-GEF Volta Project., 2013; McCartney et al., 2012; Sood et al., 2013; Awotwi et al., 2015). From the perspective of the stakeholders, as climate changes, several direct influences alter precipitation amount, intensity, frequency, and type. High precipitation variability accelerates run-off, and thus, soil erosion. Increased erosion leads to higher rate of land/soil degradation which over time increases the intensity of land use/cover change and consequently climate change is reinforced (loop R9). Also, within the conceptual model, land use/cover change increases the rate of deforestation, and, therefore, land/soil degradation thereby causing more and more land to be used and exploited over time (loop R10). The combined effect of soil erosion and land/soil degradation creates persistent decline in soil fertility (soil nutrient stock), which according to the stakeholders is being augmented by the widespread use of chemical fertilizers. However, the use of fertilizer is determined by access to credit and the availability of production subsidies both of which are functions of steady agricultural policy support. The ripple effect of fertilizer use is the emergence of several positive feedback loops, where its applications increases soil fertility and consequently crop yield.

Crop yield growth leads to increased net-farm income which in turn encourages more use of fertilizer to improve soil quality (loop R3). Also, higher net-farm income means a reduction in poverty levels, and hence, more ability to purchase chemical fertilizer and the process feeds back to affect soil fertility, crop yield, and net-farm income (loop R4). Further, high crop yield and net-farm income imply increase food availability, which then causes a reduction in malnutrition levels, although this trigger yet another reinforcing loop (R2), where more food stimulates higher population growth, which, in turn, influences total labour force and demand for water resources.

Other important feedback loops worth focusing attention on are loops R5, R6, R7, and R8. Together, these loops show the reinforcing effects of market access, net-farm income, and level of education. Within the model, it is hypothesised by the stakeholders that access to market is induced by investment in road and transportation infrastructure, which leads to more net-farm income, less poverty, and further market access (loop R5). Market access also depends on the educational level, and access to information and technology by the population and their interaction with poverty level and access to education result in the formation of two important positive feedback loops (R6 and R7). Finally, the issues of poverty and social conflict and their dynamic feedback effect is aptly recognised and depicted in the conceptual model by the system stakeholders. Specifically, socio-economic marginalisation leads to an increase in poverty levels, which cause a rise in social conflicts (mainly land and chieftaincy disputes). As conflicts rise, poverty is reinforced (Loop R8). It is, however, important to stress that mitigating social conflicts will depend on the strong institutional arrangements, effective legal framework, and good governance (Agyenim, 2011; Mul et al., 2015; Williams et al., 2016).

Overall, the reinforcing feedback loops indicate sources of growth, erosion, and collapse in the system. On the other hand, the balancing feedback loops point to areas of trends of growth-decline or decline-growth (i.e., oscillating around the equilibrium point) (Sterman, 2000; Gohari et al., 2013). They reduce the pressure on the water resources system, and, therefore, contribute to agricultural sustainability within the river basin. In the following sections, the role of systemic feedback effects and leverage points in relation to policy and management are discussed.

6.4. Discussion

6.4.1. Systemic Feedback Effects and Leverage Points

In this paper, a qualitative conceptual model was developed to enhance a shared and holistic understanding and management of water resources and improve agricultural development in the

VRB. The integrated conceptual model developed here differ from other science based-models in that it is not linear, rather, it is cyclical, considering the complex non-linear feedbacks between the critical suite of biophysical, socioeconomic, policy, and institutional processes that determine the structure and behaviour of the basin. The model indicates that the feedback structure of the basin is governed by available ground and surface water resources, climate variability and change, total population, soil fertility, crop yield, and poverty level. However, it is the resulting feedback loops from the interaction among these key drivers and several other factors that are of paramount importance for this study.

Feedback loops govern the dynamic behaviour of the system and are regarded as the main 'engine' of change for the system (Barlas, 2007; Sterman, 2012). Understanding these governing feedback loops can provide insights into the structure and functioning of the basin, and the identification of leverage points for strategic decision-making. The conceptual model shows that the feedback structure and behaviour of the VRB is dominated by positive feedbacks (reinforcing loops) rather than negative feedbacks (balancing loops). These feedback loops reside in the biophysical, socio-demographic, and economic and policy domains within the system. This supports the long-held view that society, economy and natural environment are connected through feedback mechanisms (Liu et al., 2015b; Steffen et al., 2015). The dominant of positive feedbacks indicates that there are more sources of growth, erosion, and collapse in the system, which implies that if management does not take action the system is likely to run "out of control."

From management and policy perspective, the conceptual model and the controlling feedback loops provide hints concerning action (leverage) points to sustainably manage the system. Leverage points are the "right places in a system where small, well-focused actions can sometimes produce significant, enduring improvements" (Senge, 2006, p. 64). According to Meadows (1999) leverage points range from physical elements in the system (e.g., constants and parameters, structure of material stock and flows, time delays), to feedback control interventions (e.g., strengthening balancing loops, weakening reinforcing loops, sharing information between the different parts of the system) to fundamental levers (such as rules of the system, self-organisation of the systems structures, system's goals and paradigm. In the VRB system, leverage points lie in reducing the gain around a positive loop while simultaneously improving the self-correcting abilities of the system (i.e., its resilience). For example, as a strategy, the stakeholders suggested that population growth control has the ability of slow down agricultural land expansion, which is creating the referencing process regarding land use change, deforestation, and land/soil degradation or soil erosion (loops R9 and R10). This could also contribute to weakening some balancing loops (e.g., B5 and B6), which are limiting loops in the conceptual model.

In addition, the stakeholder suggested that population control while investing in water infrastructure (loop B3), such as reservoir development and expansion, could contribute to water resource availability for agricultural production while reducing the pressure on the water resources (water demand). Stakeholders also raised concerns about the increasing problem of land or cropland area, which, as depicted in Figure 6.6, is causing land use change and deforestation. They therefore suggested the implementation cropland expansion and control measures to address it. These proposed strategies have tested as part of the policy design and analysis (step 8) in the simulation model in chapter 7 to determine their effect on various water demands and agricultural productivity.

Another action point identified by the stakeholders is strengthening the institutional arrangements and the governance systems, which the they believe could attract more external funding into the system, thereby improving the balancing loop underpinned by water investments, demand loop and water availability (loop B3). Good governance and institutional arrangements according to our stakeholders could also contribute to reduce the gain around the loop that is reinforcing poverty and social conflicts (loop R8) as well as strengthening tenure security and property rights. Further, as agricultural production is the mainstay of the basin economy (Mul et al., 2015; Williams et al., 2016), the system stakeholders believe sustainable intensification offers a practical leverage point towards the goal of producing more food with less impact on the environment. Finally, the process has demonstrated that stakeholders from diverse backgrounds and knowledge domains can work together to develop an integrated model that contributes to an understanding of the system structure and behaviour. Therefore, the participants agreed that sharing information (i.e., information flow) between different parts of the system and among the system stakeholders is an important leverage point to improve understanding of the system's problems, and consequently, the design of sustainable and integrated strategies to address the challenges.

Taken together, the conceptual model as developed by the system stakeholders illustrates three key points: (1) that the number of factors, drivers, and process and interactions between them is complex and dynamic; (2) that the important feedback processes exist that influence the ability of the system to move towards a sustainable trajectory; and (3) that individual drivers can simultaneously have positive and negative consequences and loops. Therefore, management decisions would benefit from considering the interaction between the different components of the system and the non-linear feedback-effects and dynamics and their implications for water resource management and agricultural production within the basin.

6.4.3. Caveats

The entire modelling process was based on simple cost and time-effective approach, which can be replicated in developing countries. Given the paucity of participatory system dynamics modelling efforts in Africa, this paper could inspire more research on participatory modelling within the basin and beyond. It is, however, important to note that the model outputs (the CLDs) are mental constructs (models) of the VRB system as perceived by the stakeholders who were engaged in the modelling process. As such, the integrated model (CLDs) reflects the biases and assumptions of those stakeholders who were involved in its development. Also, as a conceptual model, it should be a 'dynamic hypothesis' of the structure and functioning (Sterman, 2000; Gupta et al., 2012; Kelly et al., 2013) of the VRB system. As noted by several scholars (e.g., Richardson, 1996; Sterman, 2000), the dynamic behaviour of a complex system cannot be fully understood from a purely causal-descriptive (qualitative) model perspective. Thus, in chapter 7, a numerical simulation of the key feedback loops was performed and alternative long-term policies and management scenarios evaluated and compared.

6.5. Conclusions

The overarching purpose of this study was to develop an integrated qualitative, conceptual system dynamic model that can be used to understand the feedback structure and behaviour of the VRB system as well as a decision support tool to assist sustainable water resources management and agricultural development. Toward this end, a PM approach, based on the principle of system thinking and system dynamics was employed. Within this approach, CLDs were used as system visualisation tools to capture the non-linear causal relationships between the biophysical, socio-economic, social, and policy factors and processes inherent in the basin, resulting in the identification of the key feedback loops and leverage points.

The developed integrated model indicated that the VRB system is governed by several feedback processes, including seven balancing (negative) feedback loops and 14 reinforcing (positive) loops, concluding that the system is dynamically complex. However, positive feedback loops dominate the dynamic behaviour of the basin. Based on the numerous governing feedback loops, several number of leverage points comprising; investment in water infrastructure (e.g., reservoir expansion); land expansion control; population growth control; strengthening the institutional arrangements; and sharing of information among managers of the constituent parts of the system were proposed as key strategies that can help improve the function and sustainability of the basin.

An evaluation of the modelling process and the model outputs/outcomes from the perspective of the stakeholders showed that the process and the resulting model outputs have contributed to a better understanding of the feedback structure and function of the basin. Stakeholders also thought that the developed integrated model is realistic enough to be used it as a simple tool to support making management decisions. However, it is imperative to mention that dynamic behaviour of a complex system such as the VRB cannot be comprehensively assessed based on a qualitative (conceptual) model. As such, in chapter 7, a numerical simulation of the key feedback loops was carried out with observed/historical data and alternative long-term policies and management scenarios evaluated and compared over a desired time horizon.

CHAPTER 7: A SYSTEM DYNAMICS SIMULATION MODEL FOR SUSTAINABLE WATER RESOURCES MANAGEMENT AND AGRICULTURAL DEVELOPMENT IN THE VOLTA RIVER BASIN, GHANA[3]

Abstract

In a rapidly changing water resources system, dynamic models based on the notion of systems thinking can serve as useful analytical tools for scientists and policy-makers to study changes in key system variables over time. In this paper, an integrated system dynamics simulation model was developed using a system dynamics modelling approach to examine the feedback processes and interaction between the population, the water resource, and the agricultural production sub-sectors of the Volta River Basin in West Africa. The objective of the model is to provide a learning tool for policy-makers to improve their understanding of the long-term dynamic behaviour of the basin, and as a decision support tool for exploring plausible policy scenarios necessary for sustainable water resource management and agricultural development. Structural and behavioural pattern tests, and statistical test were used to evaluate and validate the performance of the model. The results showed that the simulated outputs agreed well with the observed reality of the system. A sensitivity analysis also indicated that the model is reliable and robust to uncertainties in the major parameters. Results of the business as usual scenario showed that total population, agricultural, domestic, and industrial water demands will continue to increase over the simulated period. Besides business as usual, three additional policy scenarios were simulated to assess their impact on water demands, crop yield, and net-farm income. These were the development of the water infrastructure (scenario 1), cropland expansion (scenario 2) and dry conditions (scenario 3). The results showed that scenario 1 would provide the maximum benefit to people living in the basin. Overall, the model results could help inform planning and investment decisions within the basin to enhance food security, livelihoods development, socio-economic growth, and sustainable management of natural resources.

Keywords: Agricultural production; feedback loops; system dynamics modelling; River basin; scenarios analysis; systems thinking

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7.1. Introduction

Global water assessments indicate that multiple countries are confronted with water scarcity as a critical problem to socio-economic development. By 2030 more than a third of the world population will be living in river basins that will have to adapt to high water stress, including countries and regions that influence global economic growth (Water Resources Group, 2009). Currently, management at the river-basin scale, particularly in developing countries, has become increasingly challenging due to the complexities arising from the functioning of hydrological cycles, socio-economic factors, diverse stakeholder perspectives, needs, values, and concerns associated with the use of water for various purposes (Gain and Giupponi, 2015; Martin et al., 2016). In particular, complex interactions and dynamic feedbacks between socio-economic and environmental systems make it difficult to understand the potential consequences of decisions (Sterman, 2012; Stave, 2015; Sivapalan, 2015).

System feedbacks have been identified as one of the key attributes that influence sustainability in most human-environmental systems (Levin et al., 2013; Liu et al., 2015b), yet limited attention has been given to feedback processes and long-term dynamics in those systems (Sterman, 2012; Levin et al., 2013; Schlüter et al., 2014).Within water resources management systems, it has been argued that our inability to develop sustainable solutions is grounded in the lack of understanding about the interconnections and dynamics of different sub-systems (Davies and Simonovic, 2011; Sivapalan, 2015). Consequently, many authors have stressed that decision-making in water resources planning and management should be based on a holistic view given the magnitude of complex dynamics, feedback processes, and interdependencies between the socio-economic and biophysical processes (Simonovic, 2009; Davies and Simonovic, 2011; Mirchi and Watkins, 2013; Gohari et al., 2013; Gain and Giupponi, 2015; Liu et al., 2015a; Sivapalan, 2015; Sahin et al., 2016). According to Girard et al. (2015), water planners need to anticipate how to adapt management practices and infra-structure development by developing a systemic approach to depicting the natural and socio-economic factors and processes that determine future dynamics of river basins. Consideration of the combined effects of system dynamics can improve management decisions and reduce the possibilities of adverse side-effects and unintended consequences of policy decisions (Simonovic, 2009; Kelly et al., 2013; Sivapalan, 2015).

In the past few decades, system dynamics modelling (SDM) based on the notion of systems thinking (Forrester, 1961; Sterman, 2000) has emerged as an innovative approach that facilitates a holistic analysis of complex human-environmental systems, such as water resource systems

(Simonovic, 2009). Several recent studies have used the SDM approach to develop system dynamic and simulation models in various river basins or watersheds around the world (see Qin et al., 2011; Sušnik et al., 2012; Dawadi and Ahmad, 2013; Gohari et al., 2013; Mirchi andWatkins, 2013; Niazi et al., 2014; Liu et al., 2015b; Sahin et al., 2016; Chapman and Darby, 2016). The diversity of SMD applications contributed to an improved understanding of the dynamic behaviour of basins, but there is still a need for dynamic models that adequately integrate various physical, social, and economic factors and feedback processes that determine the current and future dynamics of river basins and water resources management systems (Green et al., 2011; Qin et al., 2011; Sušnik et al., 2012). Existing basin-scale models are usually focused on the hydrology of the basin, and economic processes as they relate to agricultural production, while socio-demographic dynamics are rarely included and quantified (Johnston and Kummu, 2012; Johnston and Smakhtin, 2014). Therefore, there is limited knowledge and understanding about the long-term dynamic behaviours of most river basins. Moreover, most SDM are predominantly limited to river basins in Europe, North America, and Australasia. Comparative models and SDM approach in Sub-Saharan Africa are scarce.

This paper presents an integrated system dynamics simulation model in the form a decision support system for the sustainable management of water resource system for the Volta River Basin (VRB) of Ghana. The developed model, hereby referred to as the Volta River Basin System Dynamics (VRB-SD) model, simulates the interaction and feedbacks between the population dynamics, surface water resources, and agricultural production sub-sectors of the basin. While some studies have developed integrated models that provide insights into the basin's hydrological cycle, water use and availability, climate change impacts, and the consequent effects on livelihoods using various climate and hydrologic models (see e.g., Bharati et al., 2008; McCartney et al., 2012; Amisigo et al., 2015; Awotwi et al., 2015) these studies do not consider feedback processes and non-linear dynamic behaviour of the system overtime. Further, these studies are largely based on the traditional linear-reductionist and mechanistic approach, which has been widely considered to be ill-equipped to addressing the problems and complexity inherent in many water resource management systems (Simonovic, 2009; Pahl-Wostl et al., 2011; Mirchi et al., 2012). Recent assessments of the VRB (e.g., McCartney et al., 2012; Mul et al., 2015; Williams et al., 2016) have highlighted the need for an integrated approach that combines the biophysical and socio-economic processes in a strongly coupled manner for future water resources development that will contribute to food security, poverty reduction, and socio-economic development, while Bharati et al. (2008) suggested the need to simulate the dynamics of the basin over a long period of time. Thus, the recognition of feedback processes and interaction between the key system components and

processes, as well as simulation over a long period of time, were fundamental to the development of the VRB-SD model described herein.

A dynamic hypothesis or qualitative conceptual model in the form of CLD of the system under study here was developed and presented in chapter 6. In this chapter, the dynamic hypothesis is translated into a formal simulation model, allowing alternative policy scenarios to be designed, analysed, and compared. Indeed, it has been argued that the behaviour of complex systems cannot be credibly inferred from purely qualitative perspective (Richardson, 1999; Coyle, 2000). Instead, a quantitative simulation model makes behavioural inferences possible. A cardinal point in this "*genre* was that the system dynamics of systems cannot be inferred simply by reasoning from an influence or causal loop diagram and that quantified simulation is the *sine qua non* of policy analysis" (Coyle, 2000, p. 25). The development of a simulation model is necessary because, as Beall and Ford (2010) noted, a simulation model enables the system stakeholders to gain a deeper insight into the dynamics of the problem they have defined with their qualitative or conceptual model. Thus, the specific objectives of this chapter are, thus, to: (1) enhance our understanding of the dynamic behaviour of the VRB system as it responds to changes in the key system drivers over time through simulation; and (2) identify and evaluate the effects of different policy scenarios to support decision-making for sustainable water resources management and agricultural development.

Given the preceding considerations, the key role of the simulation model constructed herein, relates to shared/collective learning and understanding and scenario testing (Davies and Simonovic (2011). Thus, although desirable, accurate prediction of levels and volumes regarding the key system variables is not the primary aim of this chapter. It is also important to stress that the model is not developed to capture the physical hydrologic system justifiable by developed world standards. Rather, it was constructed based on the indigenous/traditional knowledge and the mental models of the local stakeholders, taking into account the prevailing changes in the main socio-economic and environmental conditions and processes in the basin. Nevertheless, the simulation model made use of published scientific data and knowledge of scientists (i.e., scientists with western training) to ensure sufficient rigour and accuracy in the models function and outputs. In this respect, the model is distinguished from other models by placing emphasis on a balance between scientific and non-scientific knowledge sources (Petschel-Held et al. 2005; Perera et al., 2012). Further, the model is not purely a physically based hydrologic model as in numerous developed models in the basin (e.g., de Condappa et al., 2008), Leemhuis et al., 2009; Jung et al., 2012; Amisigo et al., 2015; Awotwi et al., 2015), neither is it an exclusively socio-economic model. Rather, it is a coupled population-

economic-hydrologic dynamic model. Ultimately, the model is developed with the intent to provide an effective, locally relevant approach for the integration of stakeholder values and preferences into a dynamic system framework. The core hypothesis is that, by doing so, the research will provide a significant value for the future uptake of this approach in developing countries such as those in Sub-Saharan Africa.

7.2. The Study Context and Scope

The VRB is located within the sub-humid to semi-arid West African savannah zone (see Figure 1.1 shown earlier in chapter 1), with a surface area of approximately 400,000 km^2. The River Basin is a transboundary watershed shared among six riparian West African countries: Benin, Burkina Faso, Côte d'Ivoire, Ghana, Mali, and Togo. It is the ninth largest basin in Africa and consists of three main sub-basins: the Black Volta, the White Volta, and the Oti river basin all flowing into the Atlantic Ocean. Mean annual rainfall varies across the basin from approximately 1600mm/yr in the South-Eastern section of the basin in Ghana to as low as 300–700 mm/yr in the northern parts of Ghana and Burkina Faso (Barry et al., 2005; Gordon et al., 2013). The major uses of the water in the basin are agricultural (irrigation), domestic, and industrial (hydroelectric power generation) (Mul et al., 2015). Rain-fed with some irrigation and animal husbandry (mixed farming) for subsistence are the principal economic activities for the majority of the largely rural population. Thus, the livelihoods of 25 million people depend on the availability of water that flows through the river basin (Mul et al., 2015; Williams et al., 2016).

While it is recognised that a trans-boundary perspective and an integrative approach, based on the principle of integrated water resources management (IWRM) is optimal in assessing water resources issues in large river basins, several studies have also confirmed that practical realities related to differences between riparian countries in terms of socio-economic development, capacity to manage water resources, infrastructure, political orientation, and institutional as well as legal con- text do hamper the implementation of such an approach (see Biswas, 2008; Medema et al., 2008; Saravanan et al., 2009; Giordano and Shah, 2014). Specific assessments within the VRB (e.g., Barry et al., 2005; Agyenim, 2011; UNEP-GEF Volta Project, 2013) indicate that the absence of effective and operational institutional and legislative mechanisms, inadequate coordination of the implementation of strategies, action plans and regional programmes, inadequate human and financial resources do expressly hinder effective and coordinated development as well as transboundary management of the basin. Moreover, for transboundary river basin such as the VRB, the paucity of data represents a challenge to developing basin-scale models particularly in

developing countries (Johnston and Smakhtin, 2014). As a result, most integrated modelling efforts in large scale river basins focus on the sub-basin scales or portions of the basin (e.g., Dawadi and Ahmad, 2013; Hassanzadeh et al., 2014; Chapman and Darby, 2016).

Taken cognisance of above challenges, the geographical scope of the model is the Ghana portion of the basin to help assess the country's efforts to understanding its internal water resource situation and the potential issues influencing sustainable agricultural production; including potential future behaviours under different strategies being discussed. This scale of focus also meant that suitable and accurate data sets could be obtained in the most efficient and cost-effective manner, and that practical challenges such as those mentioned above did not significantly limit the potential to gain new knowledge and insights that can successfully be implemented. Further, as compared to the riparian countries, Ghana, the downstream country, has over the years been the most active in terms of the development of major projects that have resulted in significant impact on the basin's water resources and the excessive consumption utilisation of the water resources (Barry et al., 2005; de Condappa et al., 2008; Mul et al., 2015). Notable examples include the Akosombo Dam (the Lake Volta), which was completed in 1965 on the main Volta River to provide electricity for Ghana, as well as for export to the other riparian countries, and the Bui Dam, which was completed in 2013 on the Black Volta sub-basin. With an area of 8,500 km^2 and a storage capacity of 148 km^3, the Volta Lake is considered the largest man-made lake in the world by surface area and third in the world by volume. There are also ambitious plans by Ghana to build more dams on the Black, Oti, and White Sub-basins, which will potentially have significant impact on the sustainable management of the basin's resources in the coming decades (McCartney et al., 2012).

7.3. Methods and Model Development Process

7.3.1. System dynamics simulation modelling

While in chapter 6, the focus was on the development of conceptual/dynamic hypothesis in the form of a CLD to capture the mental model of stakeholders, in this chapter, the attention is on converting parts of the CLD into a system dynamics simulation model (SDSM). SDSM is a computer-based method grounded in feedback control theory and the modern theory of non-linear dynamics (Sterman, 2000). It rests on the assumption that time delays, nonlinearities, system feedbacks, amplifications, and structural relationships between a system's elements can be more significant in determining aggregate system behaviour than the individual components themselves (Forrester, 1961; Sterman, 2000). In general, system dynamics states that a system's structure, and its concomitant feedbacks lead to its observed behaviour (Davies and Simonovic, 2011). Therefore,

observed actions are not external to the systems they affect, but rather, emanate from the unanticipated interrelationship between system elements (Sterman, 2000; Davies and Simonovic, 2011). Developing a computer model compels modellers to make their ideas explicitly clear (Forrester, 1971). A more detailed description of SDM approach can be found in Sterman (2000), Maani and Cavana (2007), and Ford (2010), while an extensive review of its applications in water resources context is provided by Winz et al. (2009).

As stated earlier, this chapter focused on developing a simulation model for the VRB. A SDSM is distinguished from CLD (i.e., qualitative mode/dynamic hypothesis) in several significant ways. CLDs, as depicted and described in chapter 6, are essentially problem structuring tools, and, as such, can yield qualitative models, indicating the causal relationships among the main system variables (Sterman, 2000). As influence diagrams, "they put a very complex problem, which may require complex pages of narrative explanation, onto one piece of paper" (Coyle, 2000, p. 240). However, they do not incorporate model parameters, functional forms, external inputs, and initial conditions required to completely to completely parametrised and test the model (Sterman, 2000). A simulation or a formal model on the other hand, captures these essential features. Also, insights drawn from CLDs are usually based on our mental models, and thus, have some major limitations: "they are vague, implicit, often biased, ambiguous, and non-testable" (Barlas, 2007, p.12) and generally ignores feedbacks, time delays, accumulations, flows, and nonlinearities (Sterman, 2000). A formal simulation model, on the other hand, is explicit, precise, less biased, unambiguous and testable (Barlas, 2007), making it possible to draw behavioural and policy inferences reliably, which is impossible using qualitative diagrammes or maps (Homer and Oliva, 2001). Further, CLDs do not allow modellers to infer the dynamic behaviour of complex systems; rather, the dynamic behaviour of systems can be observed via quantified simulation (Coyle, 2000; Barlas, 2007).

There are several benefits that can be gained by converting the CLD developed in chapter 6 into a computer-based system dynamics simulation model. For example, a simulation model essentially provides a laboratory in which one can experiment with complex dynamic systems to gain useful insight into how different elements of causal structure produce observed behaviour of system variables over a specified time (Forrester, 1961; Keating, 1999; Sterman, 2000; Simonovic, 2009; Ford, 2010; Barlas, 2007). Simulation allows modellers to experiment with the model of the real problem, rather than experimenting with the real system (Barlas, 2007). Simulation illuminates and strengthens the governing feedbacks in the dynamic hypothesis (Sterman, 2000). A simulation modelling is, therefore, the refinement, formalising, testing alternative assumptions, and putting finality on the dynamic hypothesis or the conceptual models using an explicit set of mathematical

relationships. A formal simulation model is usually developed to clarify our *mental model*, to make it rigorously possible to analyse and testable, as well as for making scientific improvement possible (Barlas, 2007). Formalising qualitative models and testing them via simulation often lead to radical changes in the way we understand complex dynamic systems from which insights could be generated into strategic policy scenarios to improve system behaviour (Coyle, 2000; Sterman, 2000). Fundamentally, a simulation model comprises the following key components: stock and flow diagrams, inputs, physical relationships (i.e., mathematical equations expressing the relationships among the physical variables of the system being modelled), non-physical relationships, operational rules, and simulation outputs (see Simonovic, 2009). A simulation model can be static or dynamic. Static models are independent of time, while dynamic models are time-dependent. The simulation model developed herein, is dynamic in nature. Modelling and simulation tend to function in combination: modelling determines structure and clarifies ideas, and simulation then reveals unexpected behaviours and clarifies their causes (Forrester, 1971).

SDSM was chosen to model the non-linear dynamics of the key feedback processes within VRB of Ghana, because it is considered as a hybrid method, which combines the advantages of continuous and discrete time concepts (Sterman,2000; Sahin et al., 2016). The discrete concept of time is based upon the distinction between time-points and finite time intervals, while the continuous concept deals with changes over time, based on infinitesimal mathematics (Sahin et al., 2016). Also, the approach helps provide a deeper understanding of how complex systems behave and evolve over time, giving a dynamic rather than a static view of such systems (Forrester, 1961; Sterman, 2000; Kelly et al., 2013). In addition, SDSM can be easily understood by different stakeholders and users since it is able to visibly show structure and relationships among different sub-systems (Stave, 2003). Further, SDSM is applied here due to its simple way of development and modification, SDSM environments promotes quick prototyping and significantly cut down programming effort (Ahmad and Simonovic, 2000). Finally, the fact that it is not limited to a particular system type means that biophysical and socio-economic sub-systems can be incorporated, simulated, and analysed within the same model (Sušnik et al., 2012). Generally, a system dynamics model starts with the development of a dynamic hypothesis (the conceptual model), generally referred to as a Causal Loop Diagram (CLD), which is then quantified and simulated using Stock and Flow Diagrams (SFDs) (Sterman, 2000), as demonstrated below.

As has been delineated in chapter 6, CLDs are useful qualitative analytical tools for representing relationships among system variables that produce a dynamic feedback structure (Sterman, 2000). An integrated qualitative conceptual system model (CLD) was developed for the VRB with the help of key stakeholders in the second stage of this study (see Figure 6.6, chapter 6). The current VRB-SD simulation model is based on this conceptual model – that is a quantification of the qualitative model or dynamic hypothesis. As shown in Figure 6.6 (chapter 6), overall, the conceptual system model (CLD) consists of 46 system variables, which are connected to each other by 83 links. The interactions generate 21 feedback loops comprising 14 reinforcing (positive) and seven balancing (negative) loops.

Ideally, the entire model could be quantified and simulated. However, one important criterion of a model is that it should be a generic and simplified representation of the real system (Forrester, 1995; Coyle, 2000; Ford, 2010; Fisher, 2011). This statement is akin to Albert Einstein's maxim that: "All models should be as simple as possible, but no simpler than necessary" (cited in Kenneth and David 2001, p. 112). Similarly, Casti (cited in Ruth and Hannon, 1997, p. 5), argues that "good models are the simplest ones that explain the data and yet do not explain it all, leaving some room for the model, or theory, to grow." Likewise, Argent et al. (2016) stressed that "the goal for the model should be for it to be simple enough to be usable, but complicated enough to be useful, whilst holding to the parsimonious principle of Ockham's razor." Moreover, developing models with many parameters and complex configurations to represent the reality of the social-environmental systems lead to models being too quantitatively uncertain to efficaciously inform the decision-making process (Voinov et al., 2014).

Given the above understanding, and coupled with time, cost, and logistical constraints, the Volta VRB-SD model has been constructed to be simple and useful, yet able to capture the major components or feedback loops as shown in the conceptual model depicted in chapter 6. Consequently, the VRB-SD model only captured eight feedback loops of the conceptual model/dynamic hypothesis (i.e., loops R1, R2, R11, R14, B1, B2, B3, and B4). Indeed, a discussion with the stakeholders revealed that these feedback loops capture the essential components of the system – that is the water resource sub-sector, the population sub-sector, and the production sub-sector (i.e., agriculture production). Taken together, the selection of these feedback is based on a combination of pragmatic reasons, stakeholder's preferences and suggestion, as well as previous scientific literature (See Gordon et al., 2013; Mul et al., 20015; Williams et al., 2016) describing the problems in the basin and its dynamics. In future, the simulation model could be expanded to

include the other feedback loops and relevant issues to ascertain how they might influence the system's behaviour.

7.3.1.2. Stock and Flow Diagrams

While CLDs present causal relationship between the key system variables, they are qualitative and cannot be used to simulate system behaviour. Stock and Flow Diagrams (SFDs) provide the mathematical and quantitative basis of a system dynamics model (Guo et al., 2001). The key assumption of SFDs is that systems can be represented as a collection of stocks and flows, so material or energy accumulates in stocks and moves between them through flows (Voinov and Bousquet, 2010). *Stocks* (*states*) are used to represent an entity that accumulates; an example of stock would be water stored in a reservoir or people in a country (Sterman, 2000; Forrester, 1961). Stocks, also known as *integrals* or *state variables,* characterise the state of the system at time *t,* and generate the information upon which decisions and actions are based (Sterman, 2000; Simonovic, 2009). *Flows* (*rates*) represent the rate at which material flows in and out of stocks (e.g. births and deaths represent inflows and outflows to a population stock), thus changing the levels within stocks. SFDs also contain *converters* (*auxiliaries)* and *connectors.* Converters are used to adjust flows (e.g. birth and death rates that control birth and death flows), define exogenous inputs to the model, calculate algebraic relationships and store graphical functions. Thus, converters are used to complete feedback loops within a system (Sušnik et al., 2012). Connectors are used to specify dependency with a model by connecting stocks, flows and converters together. The concept of the stocks and the flows in SD is deployed here because it is very appropriate to deal with the complex problems in water resources (Ahmad and Simonovic, 2000), such as the Volta River Basin.

7.3.2. Dynamic Simulation Model Settings and Description

SFDs provide the numerical basis of a system dynamics model (Sterman, 2000; Forester, 1961). The key assumption of SFDs is that systems can be represented as a collection of stocks (levels, accumulations) and flows (rates), so material or energy accumulates in stocks and moves between them through flows (Voinov and Bousquet, 2010). The CLD in this study was numerically structured in terms of SFDs consisting of three sub-sectors, all linked into a single system model simulating the interaction between the population dynamics, the water resources issues and agricultural production in the VRB over a 50-year period (2000-2050). The year 2050 is chosen for the model because it represented a long-term perspective to observe the long-term dynamic behaviour of the basin and the consequences of policies on long-term outcomes. Moreover, water

management problems in the basin are expected to exacerbate by 2020 and 2050 (Lemoalle, 2009; McCartney et al., 2012). The complete simulation model was implemented with STELLA®, an object-oriented, graphical simulation modelling environment marketed and distributed by *isee* systems (*isee* systems, www.isee systems.com). Stella was chosen because it has modular storytelling structures (Beall Thornton, 2016). Also, it facilitates the construction of complex water resources models effortlessly compared to using traditional programming languages (Ahmad and Simonovic, 2000). In addition, because of its dynamic modelling framework, Stella enables modellers to integrate feedback loops (i.e., cyclic processes) and portray complex system dynamics over time (Greiner et al., 2014). Further, Stella has user-friendly graphical interface that is easy to use by lay persons, because it has intuitive features that allow one to manipulate model parameters and perform simulation of different scenarios (Ahmad and Simonovic, 2000; Greiner et al., 2014).

Following a suggestion by Forrester (1961), the VRB-SD model has a time-step of 0.25 years, which means that the values of stocks, flows, and converters are calculated every ¼ year for the entire simulation run. Time Step, "also called Delta Time (DT), is the interval of time between model calculations; thus, DT represents the smallest time interval over which a change in the numerical values of any element in the model can occur" (Ahmad and Somonovic, 2000, p. 195). The standard values are 0.5, 0.25, 0.125 and so on. However, 0.25 it is smaller than strictly required, but produces smooth graphs (Coyle, 1996). Moreover, this value is selected because it is not too small to lead to delay during the model run or too large to result in an implicit delay in feedback (Kampmann 1991) or induced integration error in dynamic behaviours (Forrester 1961; Coyle, 1996; Barlas, 2007). It is important to note that DT is often selected by modellers to get the equations, which purport to represent the system to run on a computer platform. As Coyle (1996) pointed out, and reinforced by Barlas (2007), DT has nothing at all to do with the way real system works – it has no real life meaning – it is a figment of the calculation – so its value should not significantly affect the real system as simulated by the model. Although the VRB-SD model is an integrated model, for the sake of clarity, and owing to the modular nature of the simulation tool (Ahmad and Simonovic, 2000), the discussion below focuses on individual sub-sectors. More important, as done by Beall and Thornton (2016), modules were used to separate the structures for each sector to more easily display these structures to stakeholders. It is also important to note that the simulation did not begin at steady- state equilibrium. This is because the system is not always at equilibrium owing to rapidly changing environmental and socio-economic conditions.

7. 3.2.1. Population Sub-sector

Several demographic and environmental factors, including climate change drive changes in water resources systems. However, population dynamics has been noted as the main driving force of various water demands and uses (Davies and Simonovic, 2011; Wu et al., 2013). As such, population growth has been identified as the most important socio-economic factor that influences water resource use and availability within the VRB (Barry et al., 2005; Gordon et al., 2013; Mul et al., 2015; Williams et al., 2016). The population sub-sector of the VRB-SD model is shown in Figure 7.1. The model estimates population dynamics, which is considered to be strongly influenced by emigration and immigration rates, birth and death rates as well as the availability of food for human consumption. For this study, the population stock is divided into two categories: children and adults. Children flow into the adult population after a 16-year maturation delay. The death of children is assumed to the same as the adults. Consequently, the total population of the basin was calculated as the sum of the children and adult population. Population growth also affects labour force availability. Thus, labour force availability is incorporated in the model as a function of the adult population. The model is deliberately kept as simple as possible. As a result, not all factors that influence population dynamics were incorporated. Factors such as nutrition, access to health care, pollution and crowding all depend on the size and wealth of the population, creating several feedbacks. These are beyond the scope of the current model, but they are issues that can be included in future efforts.
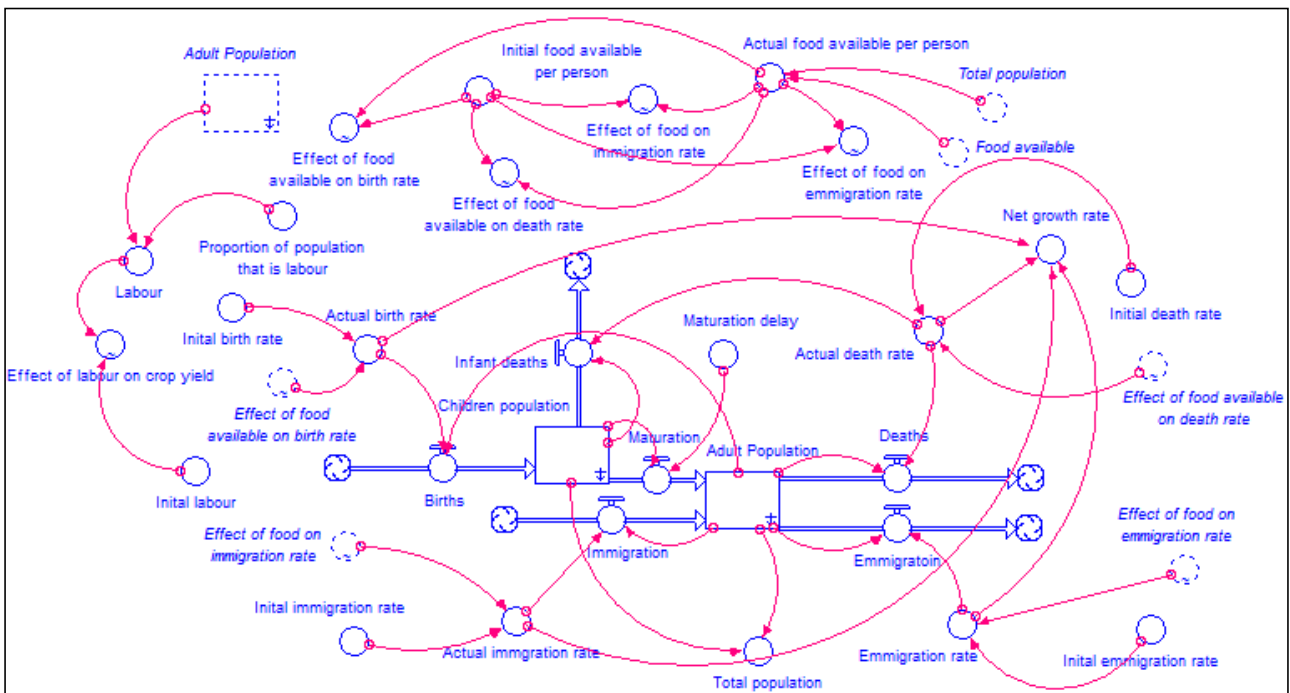
Figure 7.1. SFD of the population sub-sector

7. 3.2.2. Water Resources Sub-sector

The water resources sub-sector is depicted in Figure 7.2. This sub-sector represents water availability and demand within the VRB of Ghana. Water can come from surface water (i.e., from natural rainfall, rivers, streams, lakes) or groundwater resources (Barry et al., 2005; Mul et al., 2015). The water sub-sector of the simulation model focused on surface water resources, because the major water management issues in the basin focus on surface water resources (Barry et al., 2005; Jäger and Menge, 2012; UNEP-GEF Volta Project, 2013). In the past, Ghana's water policies were formulated under the premise of continued availability of sufficient surface water. Surface water is the first choice to meet all water demands in the basin, while groundwater is used when surface water supply is not available (Andah and Gichuki, 2003; Barry et al., 2005). The study also concentrated on surface water resources on the basis that it is controllable, unlike groundwater resources, which is uncontrollable (Safavi et al., 2015).
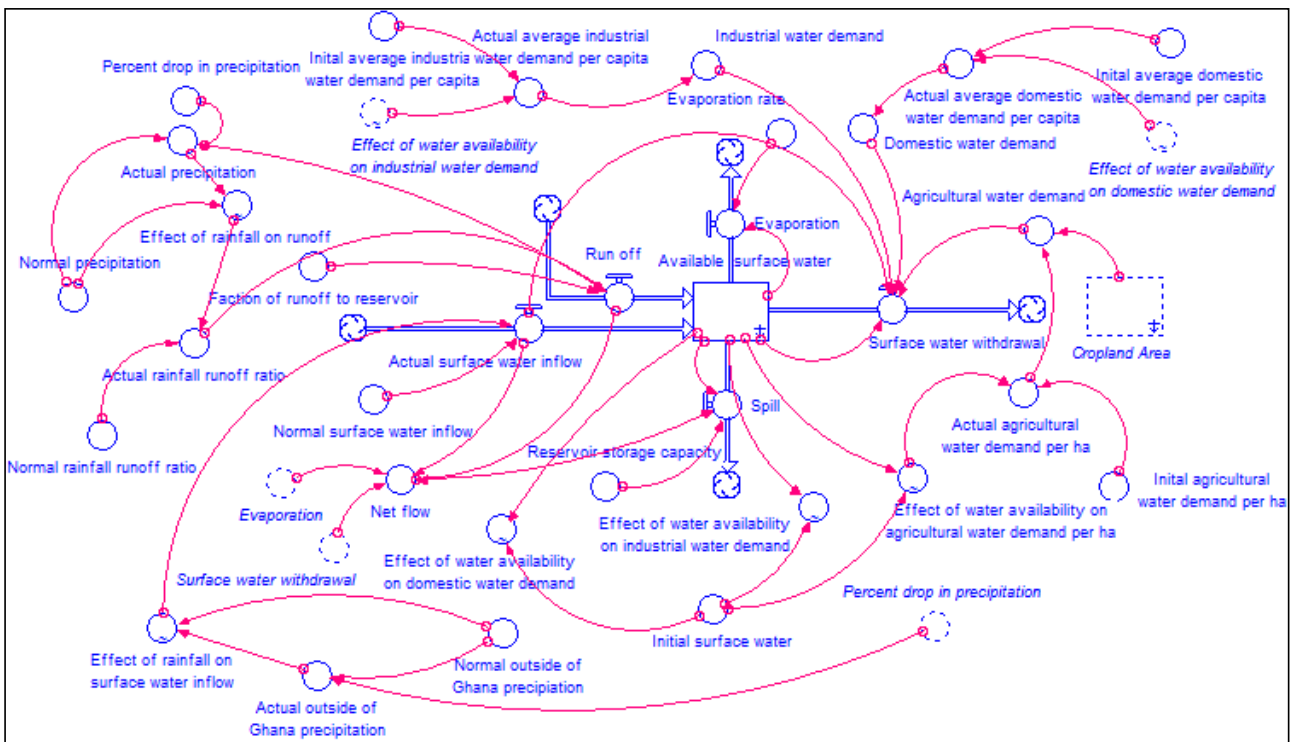
Figure 7.2. SFD of the water resources sub-sector

However, the omission of groundwater resources in the current model deserves an explanation. Groundwater flow to rivers in the basin is assumed to be insignificant, because mean monthly evapotranspiration exceeds mean monthly rainfall for most of the year for the entire basin (Jung et al., 2012). As a result, its current usage in the basin is very low, although this is likely to increase (Jäger and Menge, 2012; UNEP-GEF Volta Project, 2013). Indeed, it has been reported that groundwater production is still below 5 percent of the average annual groundwater recharge in most

of the basin, such that the current production should not be expected to have any significant effect on the regional water balance (Martin and van de Giesen, 2005; UNEP-GEF Volta Project, 2013). Moreover, surface water and groundwater are separate resources, with virtually no interaction between them (Jung et al., 2012). Water quality issues are also omitted from the current model because recent assessment reports suggest there are no widespread, or major severe quality problems in the basin (see UNEP-GEF Volta Project, 2013; Mul et al., 2015). Thus, the extend of the selected of the issues in the water resources sector was informed by consideration of where the greatest management problem is currently being observed. Again, despite the omission of these issues, they are important aspects in the basin that can be considered in future modelling efforts, given that groundwater and surface water resources in most river basins typically interact profoundly.

Further, as shown in Figure 7.2, surface water availability is governed by a number of factors, including the various demands, surface water inflows and outflows, groundwater discharge, run-off, and climate related factors (such as the amount of precipitation, temperature, and evaporation) (Chang et al., 2013). The total annual runoff for the VRB in Ghana is estimated to be 37.90 km^3 (Barry et al., 2005) and 70% of surface water inflows into the VRB of Ghana comes from outside the country (Gordon et al., 2013). Quantification of water demands was based on water demand for agriculture (irrigation), domestic, and industrial purposes. In the VRB-SD model domestic water demand was expressed as a function of population (Davies and Simonovic, 2011). Agricultural water demand generally accounts for more than 70% of the total demand, and would typically include irrigation, fisheries and livestock (Andah and Gichuki, 2003; Mul et al., 2015; Williams et al., 2016). Total water withdrawal from the basin was estimated as the sum of agricultural, domestic and industrial water demands. As the VRB is an open basin with an outlet to the sea, spillage represents that water that cannot be stored and flows into the sea. Notice that the main climatic variables captured in the model are precipitation change and evaporation. This is based on fact that precipitation is the key determinant of the hydrologic regime of most basins and based on the preferences of the stakeholders.

7. 3.2.3. Agricultural Production Sub-sector

The agricultural production sub-sector is depicted in Figure 7.3. Rain-fed agriculture is the economic bedrock of most of the VRB population. Indeed, agriculture constitutes more than 40% of the basin's economic activity (McCartney, et al. 2012). Rain-fed agriculture uses about 14% of the total rainfall of the total basin area (Lemoalle, 2009). Currently it is not clear how much is augmented by surface water withdrawal. However, due to high rainfall variability, there has been

increased calls to shift more food production away from rain-fed systems to irrigated agriculture (Lemoalle, 2009; McCartney et al., 2012). Thus, the agricultural sector focuses on the potential of irrigation agriculture through improved the use of the available rain water (Lemoalle, 2009). Generally, the agriculture sector consists of the crop production, livestock, and fishery sectors.
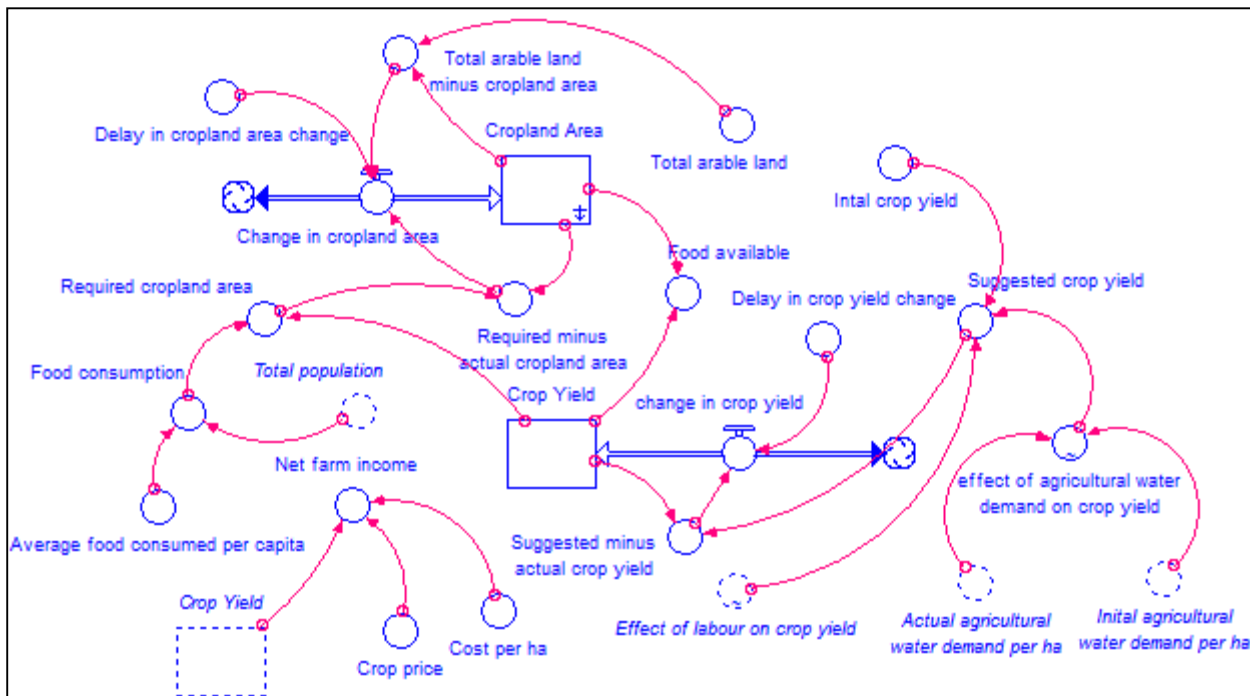
Figure 7.3. SFD of the agricultural production sub-sector

However, in this model, the livestock and fishery sectors have also been omitted, because they are mainly secondary economic activities in basin (Lemoalle, 2009; Gordon et al., 2013). Nevertheless, the model could be expanded in future to include these domains. Since cereal is the major crop produced throughout the basin (Barry et al., 2005; Mul et al., 2015; Williams et al., 2016), it provides a good indicator of the economic fortune of the basin. Accordingly, cereal yield, representing the combined production of the major cereals (millet, sorghum and maize, paddy rice, Groundnuts), was used as the stock for agricultural production. Crop yield depends on the cropland area, water, and labour availability. Cropland area is, in turn, influenced by many variables, including the demand for food, total arable land and the change in crop yield. As the focus is on cereal yield, the cropland area was estimated based on the area under cereal production.

7.3.4. Input Data and Model Parameterisation

Accurate and specific data for the VRB are not readily available as these data are embedded in national figures (Barry et al., 2005). Thus, most of the data used to parameterise the VRB-SD model

are national in scope, but should be representative of conditions within the basin in most cases, particularly in Ghana. Population and demographic figures were estimated based on census data available from the Ghana Statistical Service (GSS, 2010). Crop yield, cropland area and food production and consumption data were obtained from the Ministry of Food and Agriculture (MOFA, 2012) of Ghana. The initial values for available surface water and demands were obtained from the Volta River Authority and from published sources (e.g., Andah and Gichuki, 2003; Barry et al., 2005). The VRB-SD model was parameterised with data from the year 2000. The key parameters used in the model and their corresponding values are described in Table 7.1. Detailed Stella equations are provided in Appendix 3.

All assumptions are based on stakeholder suggestions during the participatory modelling workshop. As evinced in the model equations, most assumptions concerning the graphical relationships follow an 'extreme end effects' curve (Fisher, 2011). This is informed by the vulnerable nature of the VRB due to various environmental and socio-economic changes (Gordon et al., 2013; UNEP-GEF Volta Project, 2013). However, it was not possible to identify or obtain empirical data to compare these assumptions with. Despite this, it is believed they are reasonable assumptions given the stakeholders and our own understanding about the dynamics in the system. Finally, it is imperative to also note that in this model, the value of all excluded parameters is assumed to be zero (Sterman, 2000; Forrester, 1961; Ford and Beall, 2010). Nevertheless, their likely impacts on the model can be assessed in future studies.

Table 7.1: Details of some important parameter values used in the VRB-SD Model along with the data sources

Variable	Initial values used (unit)	Source
Water Resource sub-sector		
Precipitation in volume	500 (km^3)	Andreini et al. (2000)
Rainfall run-off ratio	0.08	Oguntunde et al. (2006)
Fraction of runoff to reservoir	1	Assumption
Surface water produced internally	29 (km^3)	Barry et al. (2005)
The total mean annual flow into the entire Volta River system (Ghana)	37.9 (km^3)	Barry et al. (2005)
Agricultural water demand	565 (Mm^3)	Andah and Gichuki (2003)
Domestic water demand	235 (Mm^3)	Andah and Gichuki (2003)
Industrial water demand	95 (Mm^3)	Andah and Gichuki (2003)
Reservoir storage capacity	150 (km^3)	UNEP-GEF Volta Project (2013).
Per capita water use	50 (m^3)	UNEP-GEF Volta Project (2013)
Population sub-sector		
Total population	6,900,368 (people)	Ghana Statistical Service (2010)
Population growth rate per year	2.5 (%)	Gordon et al. (2013)
Adult population	70 (% of total population)	
Total Fertility Rate	5.48 (per woman)	Ghana Statistical Service (2010)
Birth rate	30.87 (per 1,000 people)	Ghana Statistical Service (2010)
Death rate	9.10 (per 1,000 people)	Ghana Statistical Service (2010)
Immigration rate	3 (per 1000 people)	Assumption
Emigration rate	12 (per 1000 people)	Ghana Statiscal Service (2010)
Children population	30 (% of total population)	Ghana Statistical Service (2010)
Proportion of population that is in labour	60 (%)	Ghana Statistical Service (2010)
Food available per person	248 (kg/ha – yr)	MOFA (2012)
Per capita food consumption	423,00 (kg/capita)	MOFA (2012)
Total food consumption	83.98 (kcal/capita)	MOFA (2012)
Maturation delay	16 (years)	Assumption
Agricultural production sub-sector		
Cropland area	6,331 (per 1000 ha)	MOFA (2012)
Crop price	59.88 (USD)	This work
Cost per ha	225.18 (USD)	This work
Net-farm income	311.26 (USD)	This work
Delay in cropland area change	5 (yr)	Assumption
Crop yield	1,039 (kg/ha)	MOFA (2012)

7. 3.5. Model Testing

Model testing is an essential tool to learn about the flaws in a model and set the stage for a better understanding (Sterman, 2000). In principle, the more tests that are carried out, in which it cannot

be proven that the model is flawed, the more confidence is gained in the model (Bellocchi et al., 2015). The VRB-SD model was tested by performing several tests as suggested by Forrester and Senge (1980), Barlas (1996), and Sterman (2000), including a parameter-confirmation test, integration error test, and behaviour pattern test, and sensitivity analysis using extreme-conditions test. Parameter-confirmation testing involved checking to ensure that the equations contained in the model correspond to the relationships depicted in the conceptual model (the CLD). Integration error testing was performed by cutting the simulation time step into half as well as doubling it and checking for any possible erroneous changes in the model behaviour created by the underlying feedback structure (Sterman, 2000).

Behaviour pattern testing measured how accurately the model replicated the major behaviour patterns exhibited by the real system. To this end, the simulated model results were compared with the reference modes depicted in Figure 6.2 (refer to chapter 6). The following four important parameters in the model were selected for behavioural pattern testing based on the availability of historical data: total population, crop yields, cropland area, and agricultural water demand. Extreme conditions entail evaluating the validity of selected model equations, by assigning extreme values to their input variables, and comparing the value of the output variable to what would logically happen in the real system under the same extreme condition (Barlas, 1996; Sterman, 2000). In this case, the input value of food available was assumed to be zero after 2025. Similarly, precipitation was assumed to be zero (i.e., no rainfall), while the evaporation rate was presumed to increase by 50%. Results of the extreme conditions tests are shown in section 7.4.1. It should, however, be mentioned that like Greiner et al. (2014), the outputs VRB-SD model was not put to a formal output validation, which suggests a major limitation with regards to its scientific credibility, although its acceptability by the system stakeholders should not be in doubt.

7.3.6. Policy Scenarios Design

Following the model, different policy scenarios were designed and simulated over a period of 50 years (i.e., between 2000-2050) to assess the availability of land and water resources, their use and implications for agricultural development within the VRB of Ghana. Following Gohari et al. (2013), this stage of the analysis involved trial and error, as well as some assumptions about the effectiveness of different policies. First, the baseline run or Business-as-usual (BAU) scenario was run over the simulated period. The BAU assumed that current environmental and socioeconomic conditions within the basin would remain the same without any policy change. Besides the BAU, three additional policy scenarios were designed and simulated. These scenarios were designed

based on inputs received during the participatory stakeholder/modelling, as well as information drawn from the existing literature concerning the effective management of the basin.

Scenario 1 (water infrastructure development) represents a policy change, which assumes sustained development of water infrastructure in the form of small and medium scale reservoir expansion. As contained in the Ghana Poverty Reduction Strategy (GPRS I), the Water Vision for Ghana is to achieve an efficient and effective management system for the sustainable development of water resources to achieve full socio-economic benefits for present and future generations (Andah and Gichuki, 2003; Lemoalle, 2009). One important strategy for achieving this, according to stakeholders and available literature, is the expansion of small and medium scale reservoirs to ensure availability of water in sufficient quantity and quality, as well as the appropriate infrastructure for agriculture to sustain food production and food security, to increase incomes, and to promote rural development. Indeed, the importance of small reservoirs as a tool for poverty alleviation has been documented by the Small Multi-Purpose Reservoir Project of the Challenge Program on Water and Food (CPWF)[4] (Lemoalle, 2009).

Small reservoirs "are structures capturing and storing run-off at macro-catchment level, with sizes ranging from 3 to 30 ha" (Douxchamps et al., 2012). They are designed primarily for supplementary irrigation during dry spells, dry season irrigation, fishing, livestock and household watering, and groundwater recharge through decreasing run-off (Leemhuis et al., 2009; Venot et al., 2011; Douxchamps et al., 2012; Mul et al., 2015). According to a review by and Lemoalle (2009) and Douxchamps et al. (2012), small-scale dams and reservoirs made essential contribution to the sustainable use of water and poverty reduction in Ghana in the 1960s and 1970s. However, their development declined since the1980s in favour of medium and large public hydroelectric dams, and also due to limited investment and poor maintenance of existing ones (Venot et al. 2011). Meanwhile, there are several of them in Burkina Faso and the number is increasing (de Condappa et al., 2008; Leemhuis et al., 2009). Against this backdrop, stakeholders proposed doubling the capacity of existing reservoirs (i.e., a 100% increase). However, taking cognisance of potential funding, constraints, it was agreed among stakeholders that providing half of what is suggested would be realistic. Hence, we simulated a 50% increase in reservoir storage capacity, applied in the first year of the simulation.

Scenario 1 was also considered against the backdrop of climate change. This is because climate variability (especially changes in rainfall regime) has been noted as being the main cause for critical

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[4] The Challenge Program on Water and Food (CPWF) contributes to efforts of the international community to ensure global diversions of water to agriculture are maintained at the level of the year 2000.

water levels of the reservoirs in the basin (de Condappa et al., 2008; McCartney et al., 2012; Gordon et al., 2013). In this respect, scenario 1, also considered that there is enough water available for all uses, due to significant precipitation across the basin. Thus, it assumed a wetter climatic change scenario, consistent with other scenarios analysis (e.g., de Condappa et al. 2008; Amisigo et al., 2015). According to the Intergovernmental Panel on Climate Change (IPCC, 2013), although the projected precipitation is highly uncertain throughout the entire West Africa region, the range of possible precipitation changes will span both negative and positive values (mostly between −30 and +30 %). Thus, based on this analysis, a 30% increase in precipitation (i.e., the best-case scenario) was applied and simulated, assuming that infrastructure may be built incrementally (Amisago et al., 2015). Also under this scenario, it is assumed that enough money is earmarked for expanding agricultural facilities and funding water development infrastructure (after Simonovic, 2009).

Scenario 2 (cropland expansion) simulates the effect of cropland expansion within the VRB of Ghana. There is a consensus that approximately 50% of a typical country in West Africa is arable; however, only a small proportion is cultivated in the countries of the VRB (Lemoalle, 2009). Because of rapid population growth and the need to improve agricultural production under Ghana's poverty reduction strategy, more arable lands are envisaged to be put under cultivation or irrigation. Hence, scenario 2 simulates the effect of cropland expansion of water resource availability, water demands, and agricultural production. The underlying assumption for this scenario was that current cropland area would increase, and abandoned croplands are brought into sustainable production.

Scenario 3 (dry years scenario/conditions). As have been document by some analyst (Leemhuis et al., 2009), the Volta River basin has witnessed an extremely wet year in 1968, as well as extremely dry years (i.e., in 1986 and1997). Cognisance of this, this scenario envisaged water scarcity and persistent dry spells characterised by decreasing precipitation due to climate change since it is the ultimate determinant of water availability in the region. Thus, given the future changes in precipitation trends for West Africa as projected by the IPPC (2013), and described in scenario 1, scenario 3 considered a 30% increase in precipitation in the basin (i.e., the worst-case scenario) and an assumed 50% reduction of available water in the main basin storages. Descriptions of the simulation scenarios and the parameters that were varied in the model are summarised in Table 7.2. It is recognised that these scenarios may be inherently unrealistic, but as stated earlier, this study is more interested in understanding the behaviour than the numerical outcomes. The results of these scenarios were compared to the BAU scenario to examine the overall policy implications.

Table 7.2: Description of selected policy scenarios

Policy scenario	Description of parameters
Business as Usual	Business as usual (BAU)
Scenario 1 (water infrastructure development and reservoir expansion)	Reservoir storage capacity is increased by 50%; precipitation is increased by 30%; agricultural water demand per ha is increased by 30%. Effects of agricultural water demand is offset by 20%. All other parameter values and graphical relationships are held at their base case values.
Scenario 2 (cropland expansion)	Cropland area, delay in cropland change, and total arable are increased by 30%. Effects of agricultural water demand is offset by 20%. All other parameters and graphical relationships are held at their base case values.
Scenario 3 ("Dry conditions")	Precipitation is decreased by 30%; available surface water is decreased by 50%; Effects of agricultural water demand is offset by 20%. Agricultural water demand per ha is decreased by 30%. Effects of agricultural water demand is offset by 20%. All other parameters and graphical relationships are held at their base case values.

7.4. Results

7.4.1. Model Testing

The results of the model testing are shown in Figure 7.4. The simulated results followed the same trend as the observed data, indicating that the model is well calibrated. These plots show that the model is not over-predicting or under-predicting the patterns and behaviours inherent in the VRB. These behaviour patterns indicate that the model satisfactorily fits the available data. However, there some slide variations in the patterns, which could be attributed to uncertainties associated with the model structure, parameter uncertainty, or input uncertainty (Refsgaard et al., 2007).
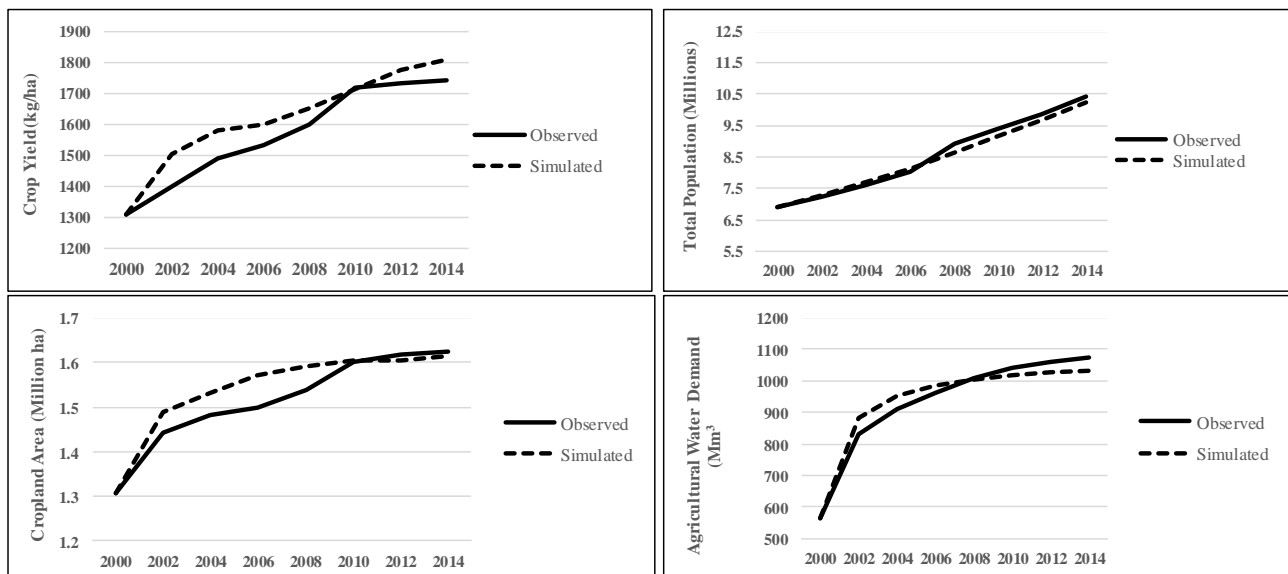
Figure 7.4: Comparison between observed and simulated data

Further, the errors could be due to the assumptions made for the model parameters and graphical relationships. Nevertheless, the aim of the model is to understand the dynamic behaviour patterns of key system variables, and not to make precise numerical prediction of levels and volumes regarding those variables. Indeed, many system dynamicists have concluded that, by their nature, system dynamics models are not designed to make accurate predictions of system variables (point predictions), rather they are formulated to predict significant time patterns of interests (pattern prediction) (Forrester, 1961; Barlas, 1996; Sterman, 2000; Kelly et al., 2013).

With regards to the extreme conditions test using sensitivity analysis, when available food is assumed to be zero, total population and domestic water demand decline sharply to zero in five years, then remain the same for the rest of the simulation period (see Figure 7.5).
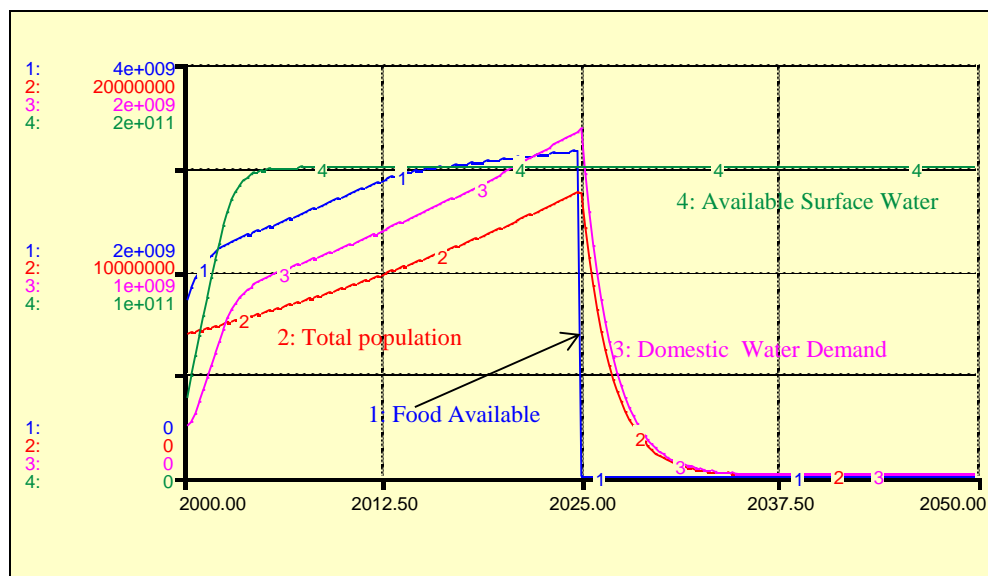
Figure 7.5: Behaviour of selected model variables in the simulation period under extreme conditions (i.e., when food available is assumed to be zero after 2025).

However, available water stays as results of population collapse. Further, if precipitation is assumed to have dropped by 100% (i.e., no rain), and the evaporation rate is increased by 50% after 2025, total population, available surface water, agricultural and domestic water demands all collapsed within five years (Figure 7.6). Overall, the model performed satisfactorily well under these test conditions, which suggest again that the model is strong enough to simulate the period 2010-2050.
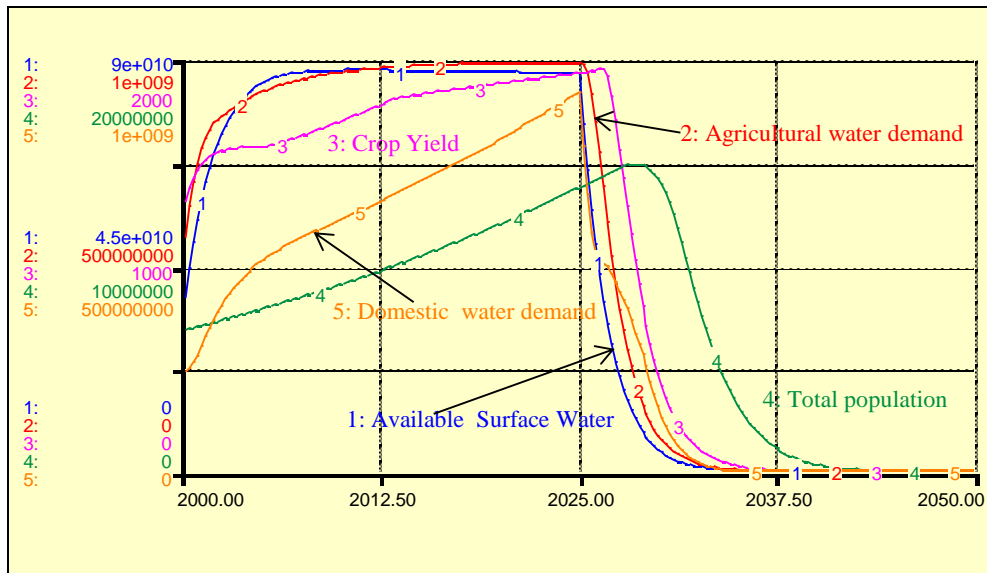
Figure 7.6: Behaviour of selected model variables in the simulation period under extreme conditions (i.e., when precipitation is assumed to be zero and evaporation rate is assumed to increase by 50% after 2025).

7.4.2. Policy scenario analysis

7. 4.1. Baseline Model Run (Business as Usual Scenario)

For BAU, available surface water (line 1) plateaus around 2006 (Figure 7.7). Similarly, agricultural water demand plateaus around 2010. Total population and domestic water demand grow exponentially. These upward trends in total population and domestic water demand, coupled with the plateauing of available surface water, could lead to future water deficit within the basin, with negative implications for agricultural production, which is the mainstay of the basin's economy. Further, crop yield plateaus at 2030 because of water limitations.
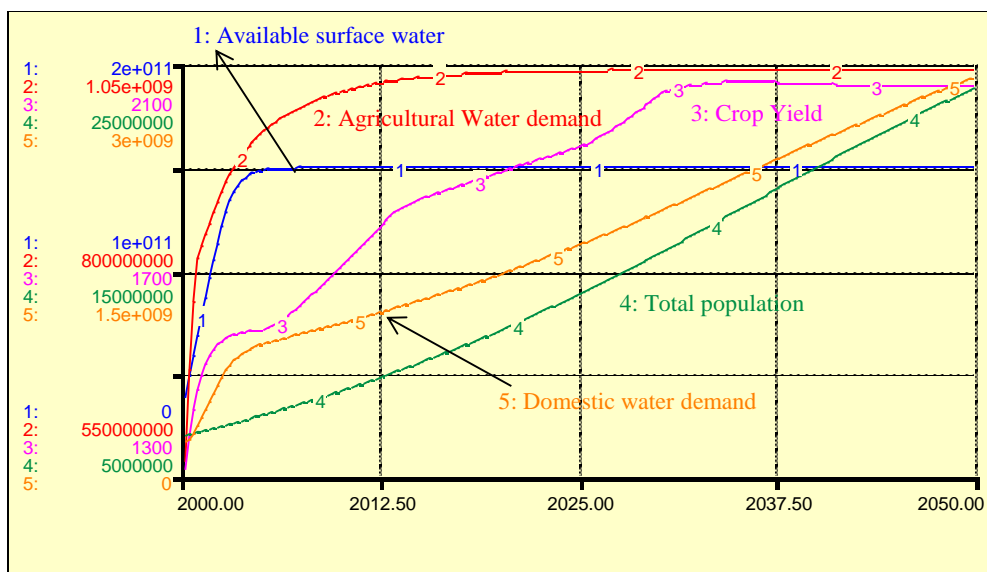
Figure 7.7: Behaviour of selected variables under the baseline model run (BAU).

7.4.3. Analysis of Designed Policy Scenarios

By 2050, maximum growth is expected to occur under scenario 1 (water infrastructure development) and the least growth is expected to occur under scenario 3 (dry conditions) (Figure. 7.8).
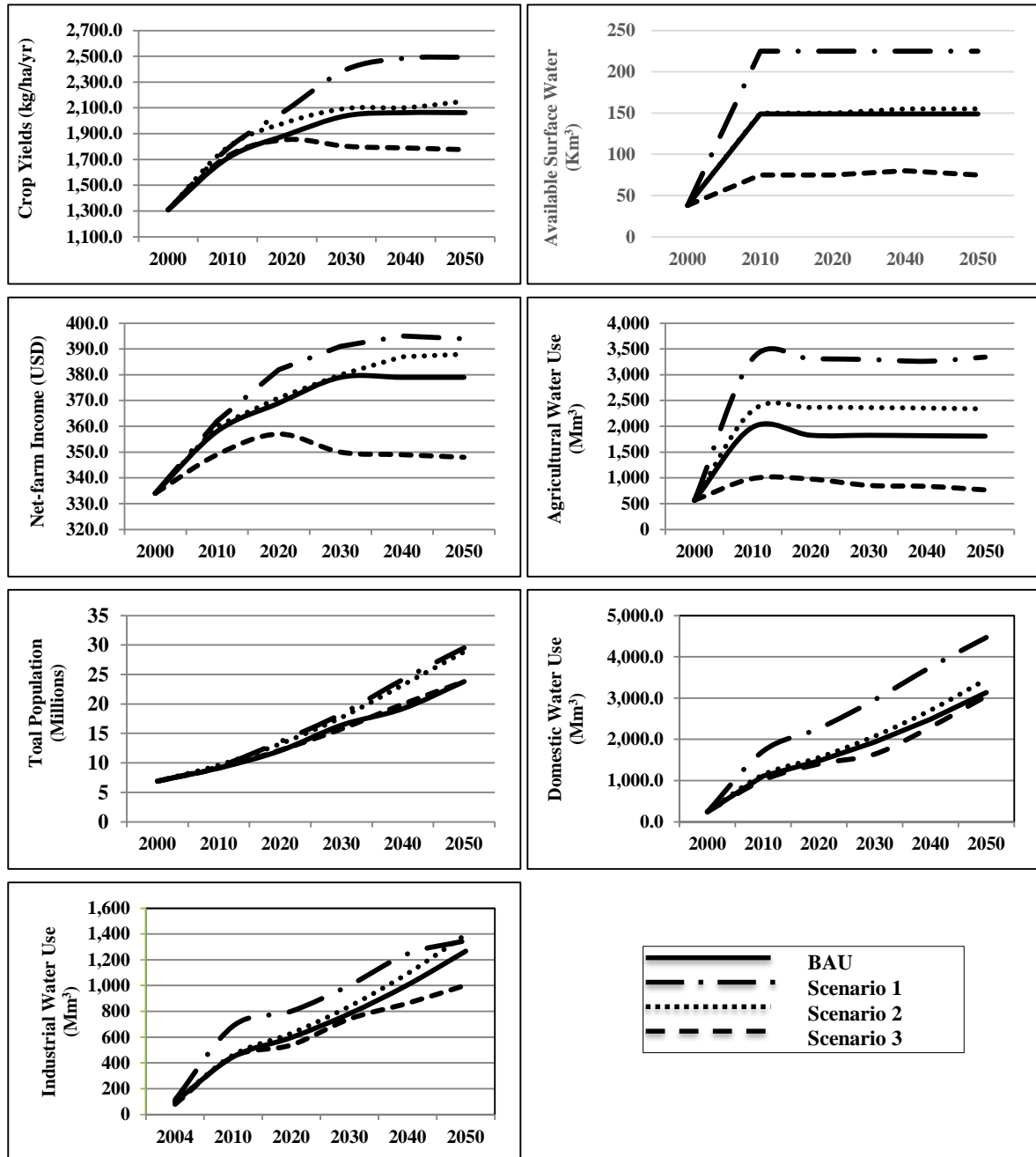
Figure 7.8: Behaviour of selected variables in the simulated period (2000-2050) under different policy scenarios.

All scenarios display limits to growth behaviour, except for population, which is expected to continue to grow under all scenarios. Limits to growth in crop yield and net farm income are expected to occur around 2040 under scenario 1, while these limits are reached a decade earlier (around 2030) under the BAU scenario and 20 years earlier (around 2020) under scenario 3. The

trends in agricultural water demand reflect those of crop yield, however the peak in water demand occurs earlier than the peak in yield because yield is not only limited by water, it is also limited by the availability of labour, which continues to grow with population beyond the peak in the water supply. Domestic and industrial water demands increase with population; however, growth in water demand begins to plateau towards 2050 due to the limits of water supply or available water.

7.5. Discussion

The results suggest that in the case of VRB of Ghana, cropland expansion is likely to lead to an outcome similarly to BUA and will not maximise the benefits to people living within the basin. This finding is contrary to popular assumption that future agricultural development in Africa would have to come from the expansion of cropland (Deininger and Byerlee, 2011; Hertel, 2011; Chamberlin et al., 2014). Moreover, pursuing such a strategy is unsustainable because cropland expansion in the tropical environments is associated with deforestation and significant environmental costs (Byerlee et al., 2014; Chamberlin et al., 2014). If scenario 3 (dry conditions) were to occur, the results suggest that all water demands (agriculture, domestic, and industrial) may not be met in the future, which will have a profound impact on crop yield and consequently food security within the basin. This finding confirms the results of recent model-based studies and assessments that analysed the impact of climate change on water resource availability within the VRB (e.g., Bhaduri et al., 2011; McCartney et al., 2012; Sood et al., 2013; Amisigo et al., 2015). This suggests that a system-wide demand management programme must part of Ghana'swater resources management and agricultural development strategies for the VRB of Ghana.

Water infrastructure development (scenario 1) appears to provide the maximum benefits to local people through improved crop yields and net-farm income. Increased incomes would also have a positive impact on education, nutrition and health, and social equity. Improved water security would also be a pathway to improved food security, socio-economic development and poverty reduction. If this scenario is complemented with other policy mechanisms such as soil fertility management and the provision of micro-credit, agricultural production within the VRB of Ghana could be greatly enhanced. An important consideration is that the development of water infrastructure would come at a cost as it would compete with other spending priorities. Water infrastructure would also require associated water allocation management and good governance (Agyenim, 2011), which would need to be supported by institutional development in Ghana. The results of all policy scenarios analysed

in this study, including BAU, show that total population growth will continue to increase, driving increases in agricultural, domestic and industrial water demands.

These upward trends are consistent with previous estimation of water use and demands within the basin (e.g., Andah and Gichuki, 2003; Jung et al., 2012). Given this situation, it is also imperative for policy-makers to understand that simply supplying more water without effective demand management will not prevent future water shortages. It will only delay them. Hence, a combination of population growth control, water conservation and strategic water demand management would assist the VRB of Ghana to meet its current and future water needs in a sustainable manner. It is also important to reiterate that the scenarios tested in this study should not be seen as rigid prescriptions. Their purpose is to build our understanding of the long-term dynamics of the system and inspire decision-makers to look beyond existing policies and management strategies.

Overall, the model results presented in this study are likely to play an important role in water resources management and agricultural development. It should be noted, however, that the model as collaboratively constructed is, like any other model, imperfect and incomplete (Meadows et al., 1972). Thus, the findings presented in this paper should be interpreted in light of the assumptions and limitations inherent in the modelling process. For example, the model considered by stakeholders and in the literature to be important in shaping the dynamics of the basin. Thus, as noted in the preceding sections, issues such as land use/cover change, the diverse ecosystem services, water quality, groundwater, and market-related factors were omitted. However, given that we live in rapidly changing environment, the magnitude these variables could change within a year or even a month or a day, which may render them significant. It is, therefore, important to continuously assess their likely impact in the model. It is for this reason that they have been marked for future consideration.

It is also important to emphasise that the model is developed for biophysical and socio-economic conditions prevalent in Ghana. This suggests that some degree of caution should be exercised when using the results associated with the model assumptions and scenarios or extrapolating the findings to all riparian countries of the VRB. Nevertheless, it does present significant insights into the potential and current directions of water resources management within Ghana, which is likely to have an influence across political and geographic boundaries. A future endeavour would be to expand the scope of the study to include issues from these other countries with the view of developing a basin-wide water resources management decision support tool, and to also incorporate other components such as water quality and groundwater resources. However, as already stated,

given the sensitive nature of most SD models, the inclusion of these issues and consideration of basin-wide conditions may have a significant impact on the model behaviour and the results that underpin the insights from the study.

7.6. Conclusions

This paper describes the development of a system dynamic model (SDM) that captures that the interactions and feedbacks between the key components of the VRB of Ghana (i.e., the population sub-sector, water resource sub-sector and agricultural production sub-sector). The model was developed in a participatory process with stakeholders. The specific objectives of the study were to use the model as a learning tool to improve our understanding of the long-term dynamics of the VRB of Ghana and as a basis for exploring alternative policy scenarios for sustainable water resources management and agricultural development. The model was tested using both structural and behavioural pattern tests, and extreme conditions tests. The SDM was used to simulate the outcomes of three different policy scenarios: *scenario 1* (development of water infrastructure), *scenario 2* (cropland expansion), and *scenario 3* (dry conditions) over 50 years (i.e., between 2000-2050). The results show that all scenarios reach limits to growth, however, crop yield and net farm income was maximised under scenario 1. This will benefit food security, poverty reduction, and socio-economic development within the VRB of Ghana.

Although SDMs have been built for river basins in other parts of the world, the study is one of the few applications in Sub-Saharan Africa and the first application in the VRB. Other model-based studies within the basin have used mechanistic models that are not conducive to improving stakeholder shared understanding of how the system works. Using the SDM approach, and engaging stakeholders in model development, this study has implemented a process compatible with improving stakeholder understanding of the dynamic behaviour of the VRB over time, and more importantly, the interactions between the river basins sub-systems that determine this behaviour over time.

CHAPTER 8: CONCLUSIONS, CONTRIBUTION AND RESEARCH LIMITATIONS

8.1. Introduction

This final chapter summarises and synthesises the key findings of this thesis as they relate to the aim and objectives as outlined in chapter 1. In doing so, a reflective narrative about the study is provided. The theoretical and practical implications and the fundamental contribution of the research are also presented and discussed. Finally, I highlight the key limitations of the work and potential areas for further research.

8.2. Reflection and Insights

Up until this stage, the study documented the modelling process and its results. This section reflects on, and documents the stakeholders and researcher/modellers' experiences and insight gained regarding the application and development of the system dynamics model in the Volta River Basin. Reflection is generally understood as engaging in one's feelings (e.g., assumptions, attitudes, biases, resentments etc.) (Maani and Cavana, 2007). Reflecting and documenting the participatory process of developing integrated models have become vitally important, due to the growing need to allow researchers/modellers to learn and improve upon their own modelling practice. As Rodela et al. (2012, p. 17) underlined, "a journey through methodological choices gains specific relevance when it is accompanied by a reflection on practices of knowledge production and validation." Also, Simonovic (2009) stressed that, the process of reflection differentiates theory from practice, unearths important insights derived from experience, and provides a frame for uncovering many unseen facets of employing a theoretical approach in pursue of a strategy to a solve real-world problems. In a more recent assessment Seidl (2015) concludes that the level of reflection about participatory processes is rarely explored in participatory modelling projects.

Against this backdrop, the discussion presented here is what Schön (1983, cited in Bots et al., 2011) describes as "reflection on action." In doing so, I have attempted to show how the insights and experiences gained differed or converged with what is reported elsewhere in the literature. I hope that these insights and experiences would inform future modelling efforts, particularly in a developing country context. An effective reflection may entail an evaluation of the modelling process geared towards capturing the participants' experiences. The reflection and insights are based on my observation during the fieldwork, the collaborative modelling workshop, and feedback received from the modelling participants. Thus, the insights, as discussed below, are taken from the

perspective of the stakeholder who co-constructed the model and from the perspective of the researcher/modeller.

8.2.1. Process Evaluation and Insights: Stakeholder's Perspective

According to Jones et al. (2009), the success of participatory effort is seldom evaluated. Consequently, Hewitt et al. (2014) stressed that evaluation of a PM effort is an important step of the work, not only because it would assist in evaluating the degree to which the modelling process has contributed or is likely to contribute to the broader aims (e.g., more sustainable resource management), but also because, it is crucial for gauging the effectiveness of the approach deployed. Importantly, the generalisation of the outcome and results of a shared learning and co-constructed model beyond its applied context is difficult, if not impossible ((Voinov and Bousquet, 2010; Bennett et al., 2013). In this situation, evaluating the learning process and the role the model-building process played in the learning become vitally essential (Voinov and Bousquet, 2010).

In this respect, some valid and important questions that follow a participatory modelling effort could be (see Videira et al., 2010, p. 455): "Did the process foster learning and insight? Did the process improve communication and exchange of viewpoints? Did it promote a shared view of the problem or actions?" Currently, there are no widely accepted protocols for evaluating the success of a participatory modelling exercise. However, surveys, questionnaire and protocols have been suggested as the most appropriate evaluation tools (Voinov and Bousquet, 2010). Also, qualitative measures may be employed (Beall et al., 2011). In this study, a questionnaire consisting of both open and closed-format questions (see Appendix 3) was used to evaluate both the modelling process and the model outputs/outcomes. The closed format questions were coded on a 3-point scale and scored from: *I agree*; *I Disagree*; and *No Answer.* Many of the questions were modified from previous studies (e.g., Videira et al., 2003, 2009; Carmona et al., 2013). All 27 stakeholder participants responded to the questions.

Regarding the process (see Figure 8.1), a majority of participants (96%) thought the modelling process was a good method for planning and management; and that the process has helped improve their understanding of the complex problems within the VRB (93%); open and transparent (85%), and that it was useful to them (93%) as their views were represented in the final model (94%). All participants indicated that they have learned from the co-modelling process. The most cited learning outcome, which is consistent with Vieira et al. (2003) was an increase in the ability to integrate the complex management problems of the Volta River Basin into one consistent framework. Several

participants felt that the modelling process and accompanying discussions added greater value and insight to their knowledge and expertise because they knew better where it fit into their decision-making process. For example, one stakeholder commented that: "collaborating with other people in this process has helped me to familiarise myself more with the problems in the basin." Some participants stated that, seeing the model outputs helped them to understand the complexity of the problem in the basin. For instance, one remarked that: "I have heard a lot about feedback-loops and feedback-effects, but I never knew how they play out in reality. This modelling process has taught me a lot." Some were thankful that they had learned a new skill (e.g., use of the software tools), which they could apply in their various workplaces. Quoting a statement from one participant: "with this new modelling skill, (like Vensim and Stella), I am one step ahead of my colleagues in the office."
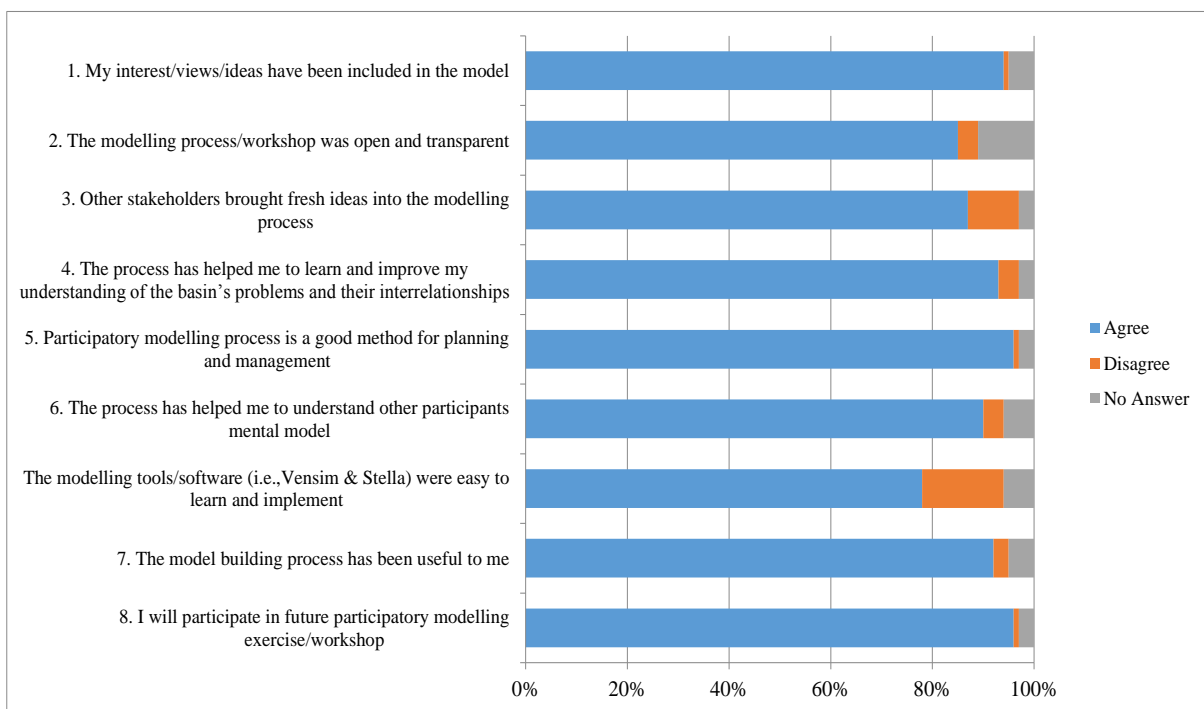
Figure 8.1. Evaluation of the modelling process

With respect to the model outputs (Figure 8.2), most participants (96%) thought that the use of the conceptual model (i.e., the CLD) and the simulation model (even in its preliminary form) were important system tools to represent and simplify complex environmental issues in the basin. Participants also felt that the developed models represent the reality on the ground (93%). Overall, there were strong feelings among the stakeholders that the developed models were credible, relevant, and consistent, and may potentially be used to enhance learning and facilitate decision-making within the basin (93%). As one stakeholder indicated that: "I like the fact that I can simply manipulate one or two policy variables and instantly visualise their implication on the overall

system. It's a useful policy-making tool. I like it." Overall, the participants experience and perception of the modelling process and the resultant outputs were largely very positive. This insight is consistent with experience from recent participatory modelling experiments (Videira et al., 2003, 2009; Metcalf et al., 2010; Carmona et al., 2013; Inam et al., 2015). Consequently, all participants expressed appreciation for the opportunity to discuss the river basin problems in such a structured manner, reflecting on their knowledge, opinions, views, values, perspectives, and interests. Many expressed their willingness to participate in future participatory modelling efforts.
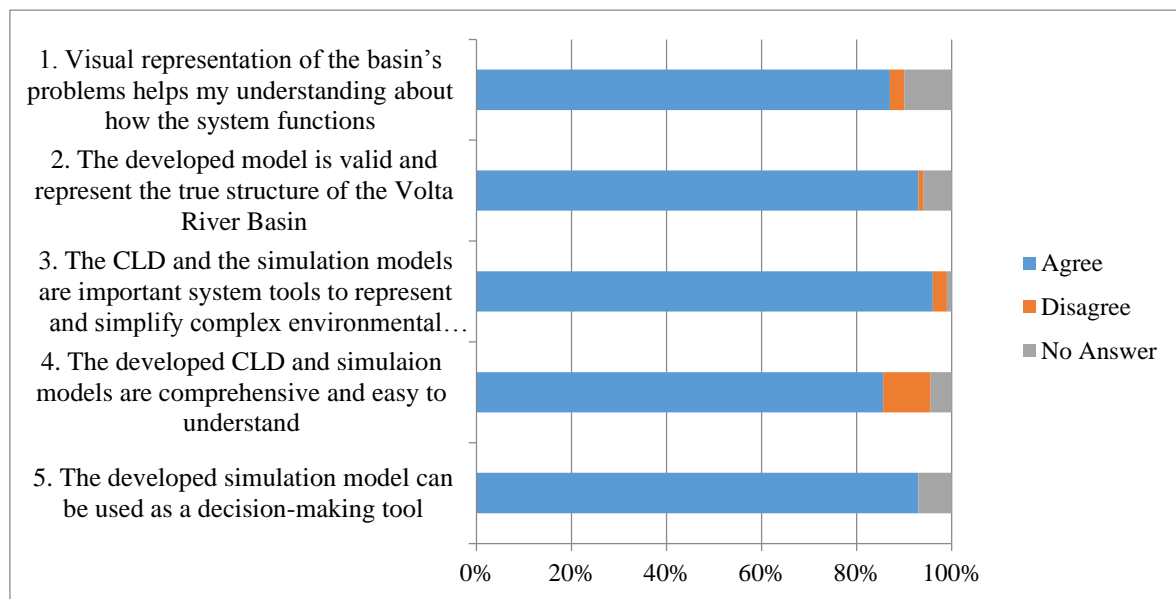
Figure 8.2. Evaluation of the model outputs/outcomes

In addition, some stakeholders indicated that the modelling process was successful in empowering them, in that, they learned to stand up and express their views in the presence of more powerful stakeholders. This corroborates the empirical work of Bot et al. (2011) carried in the Philippines. However, many of the stakeholders reckoned that the time allocated for the entire process was inadequate. For some of them, it was the first time they participated in a model building exercise, so it was difficult for them to grasp the entire process and follow through in such a limited time. This was particularly the case during the parameterisation and formulation of the simulation model. As one participant intimated: "the modelling process is interesting, but developing the stock-and-flow structure requires enough time to complete." In general, most participants acknowledged that the process had been difficult, tiring, and time-consuming, while others conceded that at some stage, they were doubtful the task could be successfully carried out. However, they noted that patient and impartial facilitation was instrumental in keeping them motivated, and that their perception changed after seeing the completed CLD and the simulation model, which was in its preliminary form and had to be completed by the researcher/modeller.

The evaluation results and feedback from stakeholders, as illustrated above, suggest that PM process and its outputs (i.e., the models) are important vehicles for enhancing social learning, participation, and facilitating a shared and better understanding of complex problems within water resources systems, such as the Volta River Basin. Social leaning is generally understood as a process in which participants are involved in a dialectic exchange of information and ideas in a structured group situation, leading them to learn from each other and develop a deeper and collective understanding of a complex issue and its possible solutions (Muro and Jeffrey, 2008; Barreteau et al., 2010; Stave, 2010; Reed et al., 2010). Also, having stakeholders stating that they now perceive the problems differently indicates that PM can be a powerful tool for changing current paradigms and mental model of how complex environmental systems functions.

What is also apparent from the evaluation results is that the process has succeeded in building stakeholders' knowledge, capacity and skills regarding the use of the technical tools, such as the use of the Vensim and Stella modelling tools (or software). This is indicated by stakeholders expressing that the modelling tools were easy to learn and implement, with some participants becoming excited about the possibility to use them in their own modelling experiments. This finding supports the notion that in certain situations, a model is considered valuable not for the accuracy of its predictive power, but for other outcomes, such as community and capacity-building, as well as the ontological and educational functionality that it conveys to stakeholder groups or users who benefitted by taking part in the modelling process (see Voinov and Bousquet, 2010; Krueger et al., 2012; Bennett et al., 2013).

In addition, as indicated by participants' perception that their values, opinions or positions have been represented, the decisions made herein, can be viewed as legitimate (Carr et al., 2015). This means that the results have the potential of being implemented. Further, the declaration that the process was inclusive, open and transparent, as well as the desire to be involved in future efforts are also important insights worth noting, as they have implication for model use and uptake. As Seidl (2015, p. 757) underlined, "…the degree of success of a participatory process can be read from stakeholders' trust in modelers' expertise and the amount and quality of information they give, as well as whether they intend to use the model and/or its results and will actually continue in future collaborations."

8.2.2. Reflection, Insights, and Lessons Learned: Researcher/modeller Perspective

Although the modelling process and the results have resulted in a shared or collective understanding of the Volta River Basin problems and its dynamics, it has also led to a few insights, experiences, challenges, and lessons worth documenting from my perspective as the researcher/modeller.

First, many modellers/researchers emphasised that adequate preparation at the initial stage determines the success or failure of any modelling project (Forrester, 1961; Sterman, 2000; Stave, 2003; Voinov et al., 2016). In this case, the preliminary individual interviews held with potential stakeholders prior to the group model building workshop proved to be useful. While these interviews enabled me to obtain background information about the system and the stakeholders, appreciate the magnitude of the problems, and accordingly, defined the scope and boundary of the model, it was also an important vehicle for building trust and strong relationships with the stakeholders. An example of this trust and relationship came up when one of the participants after learning about the nature of the project, freely offered his office space and conference facilities for the modelling workshop. This helped saving valuable financial resources that otherwise would have been required.

More importantly, through these interviews, I learned about the gender, political, and cultural sensitivity issues to beware of, such as attributing corruption to a particular department or making statements that may be perceived to be a direct attack on the main political parties in the country. This information was helpful when facilitating the modelling workshop. Thus, an important take home lesson is that holding a preliminary interview prior to a group model building can result in saving significant financial resource, anticipating problems and building trust between participant stakeholders and scientific modellers. This experience further indicates that preliminary individual interviews can avoid costly mistakes, wasted time and efforts, and more importantly, and help moderate political and cultural sensitivities during the co-construction of a shared system model. From this perspective, this study reinforces the value of preliminary interviews as highlighted by the participatory modelling community (e.g., Weil,1980; Videira et al., 2009, 2010).

Second, PM project may be initiated by local decision makers, governmental bodies, citizen activists, or scientific researchers (Voinov and Gaddis, 2008; Carr, 2015). This study was initiated by the researcher/modeller, with the original intent of modelling ecosystem health in the basin. However, during the preliminary interviews and the workshop, this objective had to be changed, as stakeholders highlighted water management and agricultural production as key concerns. While embracing their concerns, considerable care was taken to ensure that the process followed standard

scientific principles and objectivity (Argent et al., 2016; Voinov and Bousquet, 2010), by triangulating the elicited stakeholder's knowledge with published scientific literature. One benefit from this, however, was that by allowing stakeholders' priorities and questions to dictate the modelling process, enthusiasm was high throughout the modelling process. So was the sense of ownership. Nonetheless, the key learning here is that nothing is set in stone in PM process. This insight suggests that to fully benefit from a PM process, it important to be flexible to accommodate stakeholders' concerns (Voinov and Bousquet, 2010).

A third experience and challenge to note, relates to the number of participants engaged. On the one hand, there is a general understanding that involving several committed stakeholders can considerably improve the participatory modelling process (Voinov and Gaddis, 2008). But on the other hand, it has also been noted that involving too many stakeholders can add more complexity to the problem (Rockmann et al., 2012), especially in a co-construction process (Voinov and Bousquet, 2010). In this study, it was difficult to manage 27 participants. Specifically, although participants got on well, they had difficulty integrating the different problems and issues. This situation was ameliorated by breaking the participants into smaller sub-groups, where they developed different sub-models, which were integrated in a plenary session. The downside of this was that it took time for participants to learn about each other 's perspectives and build trust. Thus, while the large number of stakeholders enabled me to capture a diversity of views and interests (Ferreyra, and Beard, 2007), we have to be well aware that the larger the stakeholder group, the more unwieldy the results and the most problematic to integrate the diversity of interests and perspectives (also see Chan et al., 2010; Laniak et al., 2013).

Fourth, it is widely acknowledged that a participatory modelling exercise can be a slow, time-consuming, and a resource intensive process, overlaid with the practical difficulties (Sterman, 2000; Sterman, and Sweeney, 2007; Laniak et al., 2013; Voinov et al., 2016). In developing countries, attempting to do it alone can even be more frustrating, costly, and unproductive. In this study, two "gatekeepers" (who also acted as co-facilitators during model building) were essential to its success. In a research context, "gatekeepers" are considered as "people who can assist researchers gain access to remote places, institutions, departments, businesses and other people of relevance to a project" (Collins et al., 2016, p.136). It is also important to remember that the payment of royalties to local elders, chiefs, customary landowners, and local people may be required to have unrestricted access to some research sites. Indeed, Chan et al. (2010) experienced this situation in their work in the Solomon Islands. However, this may not be the case for modellers in more advanced countries. All the same, these insights go to support the notion that the socio-cultural context in which

stakeholders are embedded is crucial to the success (or not) of participatory modelling exercise (Hedelin, 2007; Voinov and Bousquet, 2010; Carr et al., 2015).

Finally, while other studies (e.g., Stave, 2010) found the problem definition and the conceptualisation stage of the modelling process to be more time-consuming, in this case, the model quantification (i.e., simulation model formulation) proved challenging for stakeholders. Specifically, it was difficult for several participants to grasp the logic behind the stock and flow relationships. Some of them were discouraged by the model parameterisation, quantification, and the equation formulations. In fact, it must be noted that, the conversion of the dynamic hypothesis/conceptual model to the simulation model was a slow and time-consuming process, as every equation and assumption had to be clearly explained for the understanding of all stakeholders. Indeed, enthusiasm dropped at this stage of the process. However, things change quickly when the first simulation was run, with one participant stating: "I think it is now making sense." Another said: "changing the parameter values and seeing the impacts on the whole system in real-time is what I like most about this modelling approach." Unfortunately, while considerable efforts were made, there was no time to fully parameterised and simulate the model with the stakeholders. Thus, it was subsequently finalised by the researcher and the outputs evaluated by few experts. In this light, it may be argued that the modelling process accomplished more success at the problem framing and the model conceptualisation phase than at the simulation stage. Indeed, in a participatory modelling effort for river basin planning in Southern Europe, Kallis et al. (2006) came to the similar conclusion, thus, highlighting the difficulty involved in participatory system dynamics simulation modelling.

In relation to the above problem, a reasonable approach would have been to develop a preliminary model, which could have then been modified by stakeholders (Voinov and Bousquet, 2010) as done by Mai (2013). However, the drawback of this approach is that the stakeholders would be denied of the opportunity of genuine "co-construction process and co-learning", which, in turn, could affect the credibility, and hence, hamper the acceptability of the model results. Also, this is likely to reduce the feeling of ownership and legitimacy of the results among the stakeholders (Videira et al., 2003; Rockmann et al., 2012). As Voinov and Bousquet (2010) and Laniak et al., 2013) argue, if the modelling process is deemed to be exclusive, results may not be trusted and accepted by the stakeholders and the decision-making community. However, given this encountered problem, a recommendation suggested by Beall and Ford (2010, p.10) may be an appropriate take away lesson: "simulate early and often." More insights might also be gained if enough time is devoted to the simulation model development stage. Nevertheless, this experience highlights that in certain

situations, it may be impossible to go through the whole model-building process (Vennix, 1999). It is, however, important to point out that, the difficulty encountered with the stock and flow construction is not limited to this study context. Indeed, previous studies in Western context have shown that even "highly educated people," with strong training in science and mathematics (including calculus) find it difficult to understand basic stock-flow problems (see Sweeney and Sterman, 2000; Kainz and Ossimitz, 2002; Sterman and Sweeney, 2007; Cronin et al., 2009; Sterman, 2010; Sterman, 2012) – a problem, Cronin et al. (2009, p.117), described as "stock-flow (SF) failure."

Taken together, the above discussion demonstrates that, implementing a PM process is not trivial. It can be time-consuming, mentally, and physically strenuous on the part of the researchers-modellers and, more crucially, the stakeholders involved. It, therefore, requires a high level of commitment from stakeholders and the modellers involved in the process (Voinov and Bousquet, 2010; Voinov et al., 2016).

8.3. Summary of Key Findings

As stated in the introduction, a major challenge in the Volta River Basin is to increase understanding of rapidly changing socio-economic and biophysical conditions on the water resources of a semi-arid region. To help address this challenge, this study set out to promote shared understanding about the problems by developing a computer-based system dynamics simulation model that integrates both socio-economic and biophysical processes to support decision-making concerning sustainable water resources planning and management and agricultural development in the basin. In doing so, one overarching research question was framed: How can socio-economic issues be better integrated with biophysical issues to inform river basin planning and management? Based on this question, three distinct research objectives were formulated and, subsequently, addressed:

1. To explore and identify the key biophysical and socio-economic drivers and factors that influence sustainable water resource management and agricultural development in the Volta River Basin.

2. To develop an integrated qualitative/conceptual system model that captures the systemic feedback loops, processes and structures governing the system behaviour and their implications for current and future water resource management agricultural development.

3. To develop a formal integrated system dynamics simulation model that allows for different policy scenarios and strategies to be designed and tested over time.

The key findings of the study addressing the research aim and objectives as outlined in chapter one are as follows. With respect to the analysis on the drivers of change and processes using interviews and structured expert judgments approach, precipitation variability, water availability, land use change, drought events, and population growth were perceived as most important, while biodiversity loss, social conflicts, pest and disease occurrence, urbanization, and pollution were viewed as less critical. A majority of these drivers, such as land use change were characterised as "slow" acting processes as compared to rapidly changing drivers (e.g., population growth). Intra- and inter-expert groups agreement were found to be significant and convergent, indicating the reliability of the results.

Using the results of the drivers of change as a guide, dynamic hypothesis (or a conceptual model) was first developed, facilitating a better understanding of the feedback structure and function of the basin. The conceptual model indicated that the VRB system is governed by several feedback processes, including seven balancing (negative) feedback loops and 14 reinforcing (positive) loops, concluding that positive feedback loops dominant the Volta River Basin water resources system. These feedback loops revolve around the issues of available surface water resources, total population growth, crop yield/agricultural productivity, soil fertility, and poverty level. Consequently, the main parts of the conceptual model were translated into a system dynamics simulation model to gain an insight into the dynamic behaviour of the basin in a 50-year time horizon. The simulation model consisted of three interacting constituent sub-models: population sub-model, water resources sub-model, and crop/agricultural production sub-model. Structural and behavioural pattern tests, and extreme conditions test were used to evaluate and validate the performance of the model. The results showed that the simulated outputs agreed well with the observed reality of the system.

Besides business as usual scenario, which suggests an unsustainable trajectory, three additional policy scenarios were simulated to assess their impact on water demands, total population, crop yield, water availability, and net-farm income. These were the reservoir expansion and development (scenario 1), cropland expansion (scenario 2), and dry conditions (scenario 3). The results showed that scenario 1 would provide maximum benefit concerning sustainable water resources management and agricultural development in the basin. The evaluation results and feedback from stakeholders suggest that PM process and its outputs (i.e., the models) are important instruments for enhancing social learning, participation, and promoting a shared and better understanding of complex problems within water resources systems, such as the Volta River Basin. Overall, the

model results could help inform planning and policy decisions within the basin to enhance food security, livelihoods development, socio-economic growth, and sustainable management of natural resources.

However, it was noted that implementing a participatory system dynamics process is not trivial. Consequently, several challenges and lessons, which can guide future work were highlighted based on my experience. These include: the importance of preliminary interviews, being cognisance that the modelling objective could be changed and dictated by stakeholders, involving a manageable number of participants, maximising the value of "gatekeepers" in the process, and devoting enough time for model quantification and simulation.

8.4. General Research Contribution and Implications

Given what is now known about the complex problems and dynamics of the Volta River Basin of Ghana, what are the implications for theory and practice? This is discussed in the sections below.

8.4.1. Theoretical Contribution and Implications

As discussed in the theory chapters (i.e., chapters 2 and 3), this research questions traditional approaches to researching natural resource and environmental systems, particularly water resources and agricultural systems. Consequently, the thesis adopted a systems-based/systems thinking approach that directs attention towards key system variables, non-linear dynamics behaviour over time, feedback processes underlying those dynamic behaviours, and unanticipated consequences. Compared with more conventional approaches, this research has contributed to systems thinking by adding important empirical insights to advance a systems-based approach, including understanding inter-connectivity and complexity. Within the Volta River Basin, where this study was implemented, this research represents a change in thinking about the design of sustainable management strategies to address current and future challenges. It could significantly change the paradigm set that local and national managers use for future water resources management.

Second, rather than modelling social systems and biophysical systems separately, this study considered the socio-economic and environmental/biophysical drivers and processes simultaneously using a linked social-ecological (SESF) or human-environmental system framework (HESF). These frameworks served as guides to identifying the key system variables and a lens to a systematic and transparent process of model development under conditions of rapid environmental and socio-economic change. The thesis, thus, helps advance the coupled social-ecological system framework,

which is essential for understanding complex social-ecological systems (Schlüter et al., 2014), such as the Volta River Basin. This is even more important, given the shift toward integrated natural resource management and sustainability science. Finally, this study not only explored and identified the various drivers of change, but it also demonstrated how these drivers can be assessed and characterised. Specifically, the drivers identified were characterised as "slow" changing drivers that tend to act slowly over time in a somewhat predictable manner with long-term impacts, and "fast" changing drivers that change rapidly in the short term (Chapin et al., 2009; Gunderson and Holling, 2002; Walker et al., 2012). The study provided an indicative assessment of the rate of change (i.e., trend) in each driver, and assessed the relative importance of such drivers as they influence sustainable agricultural development and water availability. In the current context of uncertain and rapid environmental and socio–economic change, the research has helped provide clarity in our understanding of the drivers of change, while extending the empirical work of Msangi and Rosegrant (2011) and Huber-Sannwald et al. (2012).

Third, like other participatory methods, this study built a more equity and confidence in a heterogeneous group of people by providing a framework to share knowledge, cultural and traditional principles, access to power and status, ability to communicate and interact (Voinov and Bousquet, 2010, p. 1273). Within this context, Hedelin (2007, p. 158) argues that a planning process for sustainable river basin management must promote structuring of the planning process as a "rational discourse" and engage itself in the "handling of power asymmetries." Although, the participants composed of laypersons (e.g., farmers), scientist and government officials who are generally considered to be of high social standing it was interesting to observe all participants discuss their ideas with confidence and assurance. As is apparent in the post workshop evaluation, many of the stakeholders indicated that the modelling process was successful in empowering them, in that, they learned to stand up and express their views in the presence of more powerful stakeholders. In this respect, we see a convergence between participatory practice (or modelling) and *Habermas' theory* of rational discourse, which posits that reaching a consensus is part of a utopian ideal speech situation in which all persons are at liberty to articulate their views and question one another's assumptions and power differences do not exist, resulting in a new, shared, and more robust knowledge (Hebermas, 1979, cited in Carr et al., 2015*)*.

Fourth, by combining a variety of knowledge and data (i.e., empirical, scientific and non-scientific/ indigenous knowledge), biophysical and socio-economic data, to provide a holistic understanding of the Volta River Basin, the PM process as implemented here has helped to illuminate on the theory of post-normal science as it relates to complex environmental problem solving at the river basin

scale. A post-normal science theory is a type of scientific parading, which tries to solve complex problems with a consideration that expert knowledge is insufficient (Funtowicz and Ravetz, 1993; Ravetz, 2006).

Finally, an important outcome of this study was the development of computer-based conceptual and simulation models that consider the main and important the relationships between the key variables and their dynamic behaviour at a river basin scale. This research approach breaks down research silos and brings scientists from various disciplines together with decision makers and local stakeholders to solve an environmental management problem for which the social, economic, and environmental issues are highly interdependent. The research, therefore, contributes to the advancement of integrated environmental modelling (IEM) agenda that is motivated by the need to solve increasingly complex real-world problems involving the environment and its relationship to human systems and activities (social and economic) (Laniak et al., 2013). Further, as stated in the introduction, system dynamics modelling and its application has grown in the past 60 years. However, it has rarely been applied to study water resource systems in sub-Saharan Africa. It is, therefore, anticipated that the study will encourage research in this direction.

8.5.2. Practical Contribution and Implications

From a practical standpoint, the set of drivers identified and analysed in this study can provide decision-makers with useful information about the system state and dynamics. More crucially, with the results of this study, decision-makers are better placed to track changes in those critical drivers affecting the sustainability of the basin and, consequently, target policy and investment interventions for sustainable water resources management and agricultural development. Further, system dynamics is generally regarded as a practical tool policy-makers can use to solve important, complex socio-economic and sustainability problems – that is so-called wicket problems (Forrester1961; Sterman, 2000; Sterman, 2012). Thus, this research provides stakeholders and managers, including local farmers, NGOs, and policy makers, with decision support and planning tools in the form of conceptual and simulation models to help achieve sustainable water management and agricultural development. The models also show current knowledge, which can be of profound significance for communication with stakeholders and for facilitating a better understanding of whole system processes and impacts.

Indeed, and as evinced in the process evaluation and reflective narrative, the modelling exercise generated considerable interest among the stakeholders who were engaged in the process. Many of

the stakeholders who attended the workshops and contributed to the development of the models are now familiar with participatory modelling based on systems thinking. They thought that the use of conceptual models (in this case, the CLDs), was an important system and visualisation tool to represent and simplify complex environmental issues. They also felt that the developed model represents reality on the ground; and that it could be used as a simple decision support tool in the basin and have requested to use the models in their workplace, since it incorporated the main problematic issues and the feedback between them.

Further, in many parts of Africa, political decisions are crucial to put policy into in practice. From this perspective, thus, this study and the associated model results have been delivered in the right political environment and conditions. In fact, it has been completed at the time the government of the day has declared keen interest and commitment to the development of the water resources sector to boost agriculture through the expansion of irrigation infrastructure. In his recent State of Nation (SoN) address, the President of the Republic states: "We have decided to embark upon a programme to provide water to enable all-year farming. We are calling it the *one-village-one-dam policy*. It is a programme that I expect will rapidly get the support of the population, and should help to transform food insecurity in our country" (Government of Ghana, 2017). This means that the political conditions are favourable for the potential implementation of the model results. On this basis, it is envisaged that the study results may provide a vital piece of information to assist the planning and implementation of the policy.

Finally, it is generally accepted that system dynamics has the potential to make revolutionary contributions to education and learning in general (Sterman, 2000; Barlas, 2007; Ford, 2010). In model-based case studies, students can experiment with simulation models of the case, which gives them a chance to rigorously test their own theories of how the problems in the case could be avoided. Similarly, it is hoped that the simulation model can serve as a learning and educational tool for people studying dynamics in Sub-Saharan African social-ecological systems.

8.4.3. Methodological Contribution

The research was grounded in a pragmatic relativist/holistic methodological paradigm/epistemology, a paradigm which until recently, has been suppressed by the traditional reductionist/logical positivist paradigm. After sixty years of its development, the system dynamics approach has rarely been applied to study water resources management systems in Sub-Saharan Africa. To the best of the researcher's knowledge, this research represents one of the relatively few

studies to use an integrated system dynamics and simulation modelling approach to explore a complex environmental problem at the river basin scale in sub-Saharan Africa. Thus, given the paucity of system dynamics application in Africa, this is a distinctive and significant methodological contribution. The novel context also has the potential to provide a useful base for future studies.

Another important aspect of the research is that the modelling process focused on individual and social learning, and provided a valuable methodological and conceptual insight into the participatory modelling approach based on the principle of system thinking and system dynamics in a developing country context, where data have often been limited or unavailable, yet, the stakes are usually high. A more direct benefit of the approach applied here is that it has also provided a deeper understanding of the problem issues in our case study context; issues which can now be compared with findings from other similar situations using similar approaches. Further, the thesis has demonstrated how qualitative data/information from interviews, workshops, and intrinsic mental models of diverse stakeholders from local farmers, NGOs, research scientists and academics, to policy makers can be combined with existing survey and historical quantitative information to developed integrated conceptual and simulation models that can be used to support decision making in a complex environmental system. Thus, the blending of different knowledge and information sources to address a complex environmental problem is a significant methodological contribution.

Finally, the study has added to the broader literature on the system dynamics and participatory modelling process. A fundamental principle of research is to establish or confirm facts, reaffirm the results of previous work (Robson, 2011; Bryman, 2012). The findings as presented in this study affirm some of the existing principles and modelling practices documented in previous studies and in situations where the participatory system dynamics approach was taken. Collectively, it is hoped that the study will help raise/establish the level of confidence and the validity and robustness of the participatory modelling approach based system dynamics, as it is replicated and tested in different geographical contexts across the world. It will also affirm the place of the PM methodology as a tool of choice in developing countries, where there is a strong need for integrating highly technical expert knowledge with indigenous and non-expert, non-technical knowledge and values. This is particularly important in view of a recent review of the participatory modelling approach, in which Voinov et al. (2016, p.198) expressed concern about the reward academics and researchers receive for the development of new tools and methods, while the "extension, adaptation, application, or even testing of existing tools and methods" in new case studies have received relatively the least attention and support. In this respect, whilst the application of the existing approach relied on its

pre-existence as a sound methodology, it has contributed in determining how system dynamics and PM approach stood up under the dynamic operational setting of the case study area. As Voinov et al. (2016) emphasised, this type of validation is essential in modelling and science in general.

8.5. Research Limitations and Direction for Future Research

According to Beall and Thornton (2016, p.18), "we must realise that we never solve all our problems and challenges, we move from solution to the next challenge." Also, Hannon and Ruth (2001, p.4) argued that "modelling is a never-ending process – we build, revise, compare and change models." Accordingly, some limitations that present opportunities for further research can be identified because of this research study. First, the Volta River basin is a trans-national basin that runs across six riparian areas in West African countries: Burkina Faso, Ghana, Togo, Benin, Cote D'Ivoire, and Mali. However, due to time, financial, and logistical constraints, this study only focused on the Ghana part of the basin. Thus, the scope or geographical boundary of the model could be expanded to include key problematic issues from the other riparian countries of the basin, with concentration on developing a basin-wide system dynamics model for integrated water resources planning and management. Indeed, the model equations, graphical functions, and data sources may act as a template for such efforts. Second, the development of conceptual system model (CLD)/dynamic hypothesis produced 21 feedback loops, 14 reinforcing (positive) feedback loops and seven balancing (negative) feedback loops encompassing the biophysical and socio-economic components of the basin. However, these have also not been considered in the formal simulated model for pragmatic reasons, and should therefore be avenues for extension. Other limitations in relation to the above, that present opportunities for extensions include the integration of fishery and livestock, sub-models, groundwater and water quality issues as deemed necessary by future modellers/researchers.

Third, the system dynamic modelling approach as applied in this study has contributed to an improved understanding of the feedback structure and dynamics behaviour of the Volta River basin. However, some authors allude, one of its drawbacks is that it cannot handle spatial data very well (Voinov and Bousquet, 2010; Sušnik et al., 2012; Kelly et al., 2013). Consequently, the spatial issues within the basin were not captured in the current study, but their inclusion could offer another dimension and insight to the results. To this end, the combination of the system dynamics with geographic information system (GIS) analytical tools to model the feedback-based dynamic processes and spatial relationship in time and space may be a worthwhile venture. In fact, the work of Ruth and Pieper (1994) and Ahmad and Simonovic (2004) are exemplary of such an approach.

Fourth, a noteworthy point to mention when discussing modelling relates to uncertainties. This is because, uncertainty is generally accepted to be an integral aspect part of any effort to manage and understand environmental problems, including modelling (Jung et al., 2012; Voinov and Bousquet, 2010; Guilaume et al., 2012; Hamilton et al., 2015). Walker et al. (2003) characterised uncertainty uncertainties in model development by its level along the spectrum from determinism to total ignorance; and its nature (epistemic, stochastic or ambiguity uncertainty). Refsgaard et al. (2007) categorised as: input uncertainty, model structure uncertainty, parameter uncertainty, model technical uncertainty. Indeed, this research does not rule out the presence of all these forms of uncertainties in the model. However, the drawback to draw attention here, relates to parameter uncertainty (i.e., the uncertainties concerning parameter values) (Refsgaard et al., 2007). For example, in developing and parameterising the simulation model, some assumptions and inferences were made based on the researcher's and stakeholder's best judgment and their understanding of the basins' problems and challenges. Also, some variables and issues, which may be relevant, have been omitted to keep the models simple and comprehensible.

Further, some parameter values were obtained from the literature, or calibrated within the bounds found in literature, and not from on-site measurements (Jung et al., 2012). Thus, the current data used may be incomplete, unreliable, or even invalid for what it claims to represent, which could bias the results of the integrated models toward the conclusion (Sterman, 2002; Olsson and Anderson, 2007). Moreover, certain parameters may change due to future rapid change in environmental, socio-economic and technological conditions (Qin et al., 2011). Some of these changes may be exogenous to the focal system (e.g., climate change, new policies), while others could be endogenous (e.g., new data or new priorities) (Voinov and Bousquet, 2010). This means that some of the parameter estimates and other plausible assumptions, particularly the graphical functions used in the simulation model, are open to question, and should be confirmed, and accordingly, adjusted using empirical data when it becomes available. After all, "science based values are not set in stone, they change when new knowledge becomes available" (Voinov et al., 2014, p. 2011). Having said this, in this study, great efforts were made to obtain the best data available, but it was not possible to fully assess quality and exactness.

Finally, it is vital to acknowledge that there are no models that can represent the 'true' or complete reality of a system, as they are only approximations of real systems (Mai, 2013). Thus, although the models developed in this study were verified and validated through standard best practice, it is imperative to note that, ideally, no model can ever be fully verified or validated (Barlas, 1996;

Sterman, 2000, 2002). This is because "all models are wrong; all models, mental or formal, are limited, simplified representations of the real world" (Sterman, 2000, p.846). Moreover, open systems and model results are always "non-unique" (Oreskes et al., 1994). Indeed, many system dynamicists recognize the "impossibility" of perfect model validation (e.g., Oreskes et al., 1994; Barlas, 1996; Sterman, 2000; Olsson and Andersson, 2007). For instance, Olsson and Andersson (2007) argue that models will never provide an answer by themselves to the "best solution" for an environmental problem; models only provide input to a decision in the form of indications of which sources that are important or the plausible scale of the effects of a suggested measure. As such, the model developed in this study may not be the best, despite the multiple tests to establish their robustness and reliability. Hence, the results should be interpreted with caution. Nevertheless, the acceptability and the trustworthiness of the results by the system stakeholders may not be in doubt, since they took part in the model development and are, therefore, aware of the model assumptions, aware of the degree of model reliability and recognize that the model included the best available knowledge and data, and understand that there will always be inherent uncertainty in the model results (Voinov and Bousquet, 2010).

Despite the above limitations, the results of this study have contributed significantly to improve the current knowledge and shared understanding of the systems' function by giving importance to the relationships among the main variables and drivers. This model integrates what the researcher and the system stakeholders view as the important issues, processes, and complex dynamics that operate in basin over time. The participatory model-building exercise allowed the stakeholders to holistically view the complex challenges in the Volta River Basin and the potential solutions to the problems. The overall goal of the research was to develop an integrated system dynamics model that provides an understanding of the feedback structure and dynamic behaviour concerning water resources management and agricultural development within the Volta River Basin, West Africa. This has been achieved through the application of a contemporary approach – systems-based/systems thinking approach and its concomitant tools: *participatory modelling, causal loop diagrams, and system dynamics simulation modelling approach*. This research was conducted with the understanding that a flawless research design or model rarely exists. However, if a research project is carefully designed and executed, while acknowledging weaknesses and limitations, the research can achieve its intended purpose.

References

Adger, W. N. (2003). Building resilience to promote sustainability. *IHDP Update* 2, 1-3.

Agarwal, C., Green, G. M., Grove, J. M., Evans, T. P., and Schweik, C. M. (2002). A review and assessment of land-use change models: dynamics of space, time, and human choice. General Technical Report (GTR), NE-297. U.S. Department of Agriculture, Forest Service. Newton Square, PA.

Agyenim, J. B. (2011). Investigating Institutional Arrangements for Integrated Water Resource Management in Developing Countries: The Case of White Volta Basin, Ghana, Vrije Universiteit.

Ahmad, A., Khan, S., and Rana, T. (2009). System Dynamics Approach for Modelling Seasonality of River Flows. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.564.5018&rep=rep1&type=pdf (Accessed Febuary 23, 2014).

Ahmad, S., and Simonovic, S. P. (2000). System dynamics modelling of reservoir operations for flood management. *Journal of Computing in Civil Engineering* 14, 190-198.

Ahmad, S., and Simonovic, S. P. (2004). Spatial system dynamics: new approach for simulation of water resources systems. *Journal of Computing in Civil Engineering* 18, 331-340.

Alberti, M., Asbjornsen, H., Baker, L. A., Brozovic, N., Drinkwater, L. E., Drzyzga, S. A., Jantz, C. A., Fragoso, J., Holland, D. S., and Kohler, T. A. (2011). Research on coupled human and natural systems (CHANS): approach, challenges, and strategies. *Bulletin of the Ecological Society of America* 92, 218-228.

Allison, H. E. (2003). Linked Social-Ecological Systems: A Case Study of the Resilience of Western Australian Agricultural Region, School of Environmental Science, Murdoch University, Unpublished PhD thesis, Unpublished PhD Thesis.

Allison, H., and Hobbs, R. J. (2006). "Science and policy in natural resource management: understanding system complexity," Cambridge: Cambridge University Press.

Amisigo, B. A., McCluskey, A., and Swanson, R. (2015). Modeling impact of climate change on water resources and agriculture demand in the Volta Basin and other basin systems in Ghana. *Sustainability* 7, 6957-6975.

An, L. (2012). Modeling human decisions in coupled human and natural systems: review of agent-based models. *Ecological Modelling* 229, 25-36.

Anastasopoulou, S., Chobotova, V., Dawson, T. P., Kluvankova-Oravska, T., and Rounsevell, M. (2009). Identufying and Assessing socio-economic and environmental drivers that affect ecosystems and their services, Report Project RUBICODE.

Andah, W. and Gichuki, F. (2003). Volta basin profile: strategic research for enhancing agricultural water productivity (Draft). Accra: International Water Management Institute, *Challenge Program on Water and Food*.

Andah, W. E., van de Giesen, N., and Biney, C. A. (2003). Water, climate, food, and environment in the Volta Basin. *Contribution to the project ADAPT, Adaptation strategies to changing environments. ADAPT, Accra*.

Andreini, M., van Giesen, N., van Edig, A., Focu, M., Andah, W. (2000). Volta Basin water balance. ZEF Discussion Papers on development Policy, No. 21. Bonn, Germany: Zentrum fur Entwicklungsofrschung.

Antunes, P., Kallis, G., Videira, N., and Santos, R. (2009). Participation and evaluation for sustainable river basin governance. *Ecological Economics* 68, 931-939.

Antunes, P., Santos, R., and Videira, N. (2006). Participatory decision making for sustainable development—the use of mediated modelling techniques. *Land use policy* 23, 44-52.

Antwi-Agyei, P., Stringer, L.C. and Dougill, A.J. (2014). Livelihood adaptations to climate variability: insights from farming households in Ghana. *Regional environmental change* 14 (4):1615-1626.

Argent, R. M., Sojda, R. S., Guipponi, C., McIntosh, B., Voinov, A. A., and Maier, H. R. (2016). Best practices for conceptual modelling in environmental planning and management. *Environmental Modelling & Software* 80, 113-121.

Awotwi, A., Kumi, M., Jansson, P., Yeboah, F., and Nti, I. (2015). Predicting Hydrological Response to Climate Change in the White Volta Catchment, West Africa. *Journal of Earth Science & Climatic Change* 6, 249. http://dx.doi.org/10.4172/2157-7617.1000249.

Bai, X., van der Leeuw, S., O'Brien, K., Berkhout, F., Biermann, F., Brondizio, E. S., Cudennec, C., Dearing, J., Duraiappah, A., and Glaser, M. (2015). Plausible and desirable futures in the Anthropocene: A new research agenda. *Global Environmental Change* 39, 351–362.

Balée, W. L., and Erickson, C. L. (2006). "Time and complexity in historical ecology: studies in the neotropical lowlands," Columbia University Press, New York, USA.

Balint, P. J., Stewart, R. E., and Desai, A. (2011). "Wicked environmental problems: managing uncertainty and conflict," Island Press. Washington D.C, USA.

Barlas, Y. (1996). Formal aspects of model validity and validation in system dynamics. *System dynamics review* 12, 183-210.

Barlas, Y. (2007). System dynamics: systemic feedback modeling for policy analysis. *SYSTEM* 1-29. http://gu.friends

partners.org/Global_University/Global%20University%20System/List%20Distributions/201

2/MTI2350_20121123/SYSTEM%20DYNAMICS_%20SYSTEMIC%20FEEDBACK%20
MODELING%20FOR%20POLICY%20ANALYSIS%20copy.pdf

Barlas, Y., and Carpenter, S. (1990). Philosophical roof of model validation: two paradigms. *System Dynamics Review* 6 (2): 148-166.

Barnes, C. (1995). The art of catchment modeling: What is a good model? *Environment International* 21, 747-751.

Barreteau, O., Bots, P., and Daniell, K. (2010). A framework for clarifying "participation" in participatory research to prevent its rejection for the wrong reasons. *Ecology and Society* 15(2):1. http://www.ecologyandsociety.org/vol15/iss2/art1/.

Barry, B., Obuobie, E., Andreini, M., Andah, W., and Pluquet, M. (2005). The Volta River Basin. *In* "Comprehensive Assessment of Water Management in Agriculture Comparative study of river basin development and management". International Water Management Institute, Sri Lanka.

Barton, J., and Haslett, T. (2007). Analysis, synthesis, systems thinking and the scientific method: rediscovering the importance of open systems. *Systems Research and Behavioral Science* 24, 143-155.

Batterbury, S. and Warren, A. (2001). Te African Sahel 25 years after the great drought: assessing progress and moving towards new agendas and approaches. *Global Environmental Change-Human and Policy Dimensions* 11 (1), 1-8.

Bawden, R. J. (1991). Systems thinking and practice in agriculture. *Journal of Dairy Science* 74, 2362-2373.

Beall King, A., and Thornton, M. (2016). Staying the Course: Collaborative Modelling to Support Adaptive and Resilient Water Resource Governance in the Inland Northwest. *Water* 8, 232.

Beall, A. M., and Ford, A. (2010). Reports from the field: assessing the art and science of participatory environmental modelling. *International Journal of Information Systems and Social Change (IJISSC)* 1, 72-89.

Beall, A., Fieldler, E., Boll, J., and Cosens, B. (2011). Sustainable water resource management and participatory system dynamics. Case Study: Developing the Palouse Basin Participatory Mode. *Sustainability* **3**, 720-742.

Beisner, B. E., and Cuddington, K. (2005). Why a History of Ecology? an Introduction. *In* "Ecological Paradigms Lost: Routes of Theory Change" (K. Cuddington and B. Beisner, eds.). Elsevier Academic Press, Burlington, USA.

Bell, S., and Morse, S. (2008). "Sustainability indicators: measuring the immeasurable?," Earthscan/James & James, London, UK.

Bellamy, J. A., Walker, D. H., McDonald, G. T., and Syme, G. J. (2001). A systems approach to the evaluation of natural resource management initiatives. *Journal of Environmental Management* 63, 407-423.

Bellamy, J. A., Walker, D. H., McDonald, G. T., and Syme, G. J. (2012). Tracking Progress in Natural Resource Management: A systems approach to evaluation. *Evaluation of Integrated Catchment Management in a Wet Tropical Environment: Collected Papers of LWRRDC R&D Project CTC7, Canberra: Land & Water Australia.< htt p://irum. sl. csiro. au/icm/publications. htm> (accessed* June 16, 2015).

Bellocchi, G., Rivington, M., Matthews, K., and Acutis, M. (2015). Deliberative processes for comprehensive evaluation of agroecological models. A review. *Agronomy for Sustainable Development* 35, 589-605.

Bennett, J.N., J. Blythe., S. Tyler and C.N. Ban. (2016). Communities and change in the anthropocene: understanding social-ecological vulnerability and planning adaptations to multiple interacting exposures. *Regional Environmental Change* 16: 907–926.

Bennett, N. D., Croke, B. F., Guariso, G., Guillaume, J. H., Hamilton, S. H., Jakeman, A. J., Marsili-Libelli, S., Newham, L. T., Norton, J. P., and Perrin, C. (2013). Characterising performance of environmental models. *Environmental Modelling & Software* 40, 1-20.

Berkes, F. (2003). Alternatives to conventional management: Lessons from small-scale fisheries. *Environments* 31, 5-20.

Berkes, F. (2008). Exploring some conceptual issues in coping with global change in marine systems. Paper presented at the *In* "Coping with global change in marine social-ecological systems". FAO, Rome, Italy.

Berkes, F. (2010). Shifting perspectives on resource management: resilience and the reconceptualization of'natural resources' and'management'. *MAST Maritime Studies* 9, 11-38.

Berkes, F., and Folke, C., eds. (1998). "Linking Social and Ecological Systems: Management Practices and Social and ocial mechanisms for building resilience." Cambridge University Press, Cambridge, UK.

Berkes, F., Colding, J., and Folke, C. (2003). "Navigating social-ecological systems: building resilience for complexity and change," Cambridge University Press, Cambridge, UK.

Beven, K. (2002). Towards a coherent philosophy for modelling the environment. *In* "Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences", Vol. 458, pp. 2465-2484. The Royal Society.

Bhaduri, A., Manna, U., Barbier, E., and Liebe, J. (2011). Climate change and cooperation in transboundary water sharing: an application of stochastic Stackelberg differential games in Volta river basin. *Natural Resource Modeling* 24, 409-444.

Bharati, L., Rodgers, C., Erdenberger, T., Plotnikova, M., Shumilov, S., Vlek, P., and Martin, N. (2008). Integration of economic and hydrologic models: Exploring conjunctive irrigation water use strategies in the Volta Basin. *Agricultural water management* 95, 925-936.

Biancalani, R., Nachtergaele, F., Petri, M., and Bunning, S. (2011). "Land Degradation Assessment in Drylands: Methodology and Results." Food and Agriculture Organisation of the United Nations, Rome, Italy.

Biggs, R., Westley, F. R., and Carpenter, S. R. (2010). Navigating the back loop: fostering social innovation and transformation in ecosystem management. *Ecology and Society* 15, 9.

Binder, C. R., Hinkel, J., Bots, P. W., and Pahl-Wostl, C. (2013). Comparison of Frameworks for Analyzing Social-ecological Systems. *Ecology and Society* 18, 26.

Biswas, A. K. (2008). Integrated water resources management: is it working? *Water Resources Development* 24, 5-22.

Bohensky, E. L., Evans, S. L., Anderies, J., Biggs, D., and Fabricius, C. (2015). Principle 4-Foster Complex Adaptive System Thinking *In* "Principles for Building Resilience: Sustaining Ecosystem Services in Social-Ecological Systems" (R. Biggs, M. Schluter and L. M. Schoon, eds.). Cambridge University Press, Cambridge, UK.

Born, S. M., and Sonzogni, W. C. (1995). Integrated environmental management: strengthening the conceptualization. *Environmental Management* 19, 167-181.

Bosch, O. J. H., King, C. A., Herbohn, J. L., Russell, I. W., and Smith, C. S. (2007). Getting the big picture in natural resource management—systems thinking as 'method' for scientists, policy makers and other stakeholders. *Systems Research and Behavioral Science* 24, 217-232.

Botkin, D. B. (1990). "Discontinous harmonies: a new ecology for the twenty-first century," Oxford University Press, Oxford, UK.

Bots, P. W., Bijlsma, R., Von Korff, Y., Van der Fluit, N., and Wolters, H. (2011). Supporting the constructive use of existing hydrological models in participatory settings: a set of "rules of the game". *Ecology and Society* 16, 19 p.

Boven, K. (2009). "Environmental Modelling: An Uncertain Future? An introduction to techniques for uncertainty estimattion in environmental prediction" Routledge, London.

Boyd, A., Brown, M., and Midgley, G. (2004). Systemic Intervention for Community OR: Developing Services with Young People (Under 16) Living on the Streets. *In* "Community Operationsl Research: Or and Systems Thinking for Community Development" (G. Midgley and A. Ochoa-Arias, eds.). Kluwer Academic Press/Plenum Publishers, New York, USA.

Brown, O., and Crawford, A. (2009). Climate change and security in Africa. *Manitoba: IISD*, 8.

Brown, V. A., Harris, A. J., and Russell, J. (2010). Towards a Just and Sustainable furture. *In* "Tackling Wicked Problems: Through the Transdisciplinary Imagination" (V. A. Brown, John A. Harris and J. Russell, eds.). Earthscan, UK.

Bryman, A. (2012). "Social research methods (4th. Ed.)," Open University Press, Oxford, UK.

Bryman, A., and Bell, E. (2007). "Business research methods (2nd. edition)," Oxford University Press, USA.

Bunge, M. (1979). "Ontology II: A World of Systems," Dordrecht, Reidel.

Butler, C., Adamowski, J. (2015). Empowering marginalized communities in water resources management: Addressing inequitable practices in Participatory Model Building. *Journal Environmental Management* 153, 153-162. doi:10.1016/j.jenvman.2015.02.010

Butler, C., and Adamowski, J. (2015). Empowering marginalized communities in water resources management: Addressing inequitable practices in Participatory Model Building. *Journal of environmental management* 153, 153-162.

Byerlee, D., Stevenson, J., and Villoria, N. (2014). Does intensification slow crop land expansion or encourage deforestation? *Global food security* 3, 92-98.

Cai, X., Molden, D., Mainuddin, M., Sharma, B., Ahmad, M.-u.-D., and Karimi, P. (2011). Producing more food with less water in a changing world: assessment of water productivity in 10 major river basins. *Water International* 36, 42-62.

Campbell, B., Hagmann, J., Sayer, J., Stroud, A., Thomas, R., and Wollenberg, E. (2006a). What kind of research and development is needed for natural resource management? *Water International* 31, 343-360.

Campbell, B., Hagmann, J., Stroud, A., Thomas, R., and Wollenberg, E. (2006b). Navigating amidst complexity: Guide to manage R&D interventions for improving livelihoods and the environment. *Center for International Forestry Research, Bogor, Indonesia*, 82.

Capra, F. (1982). The turning point: Science, society, and the rising culture. London: Flamingo.

Capra, F. (1996). "The web of life: A new scientific understanding of living systems," New York, Random House Inc.

Cardwell, H., Langsdale, S. and Stephenson, K. (2009). A Shared Vision Planning Primer. IWR Report 08- R-02. Available at: http://www.sharedvisionplanning.us/docs/2008-R-02.pdf (Accessed on October 12, 2016).

Carmona, G., Varela-Ortega, C., and Bromley, J. (2013). Participatory modelling to support decision making in water management under uncertainty: Two comparative case studies in the Guadiana river basin, Spain. *Journal of environmental management* 128, 400-412.

Carpenter, S. R., H. A. Mooney, J. Agard, D. Capistrano, R. S. DeFries, S. Diaz, T. Dietz, A. K. Duraiappah, A. Oteng-Yeboah and H. M. Pereira (2009). Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment. *Proceedings of the National Academy of Sciences* 106(5): 1305-1312.

Carpenter, S., Walker, B., Anderies, J. M., and Abel, N. (2001). From Metaphor to Measurement: Resilience of What to What? *Ecosystems* 4, 765-781.

Carpini, M. X. D., Cook, F. L., and Jacobs, L. R. (2004). Public deliberation, discursive participation, and citizen engagement: A review of the empirical literature. *Annual Review Political. Science* **7**, 315-344.

Carr, G. (2015). Stakeholder and public participation in river basin management—an introduction. *Wiley Interdisciplinary Reviews: Water* 2, 393-405.

CGIAR (2013). Summary of CPWF Research in the Volta River Basin. CGIAR Challenge Program on Water and Food. Vol. 2014. Available at: https://cgspace.cgiar.org/bitstream/handle/10568/34065/CPWF%20Volta%20basin%20summary%20A4%20final%2020%20Feb%202014%20small.pdf?sequence=5 (Accessed 18 March 2014).

Chaffin, B. C., and Gunderson, L. H. (2016). Emergence, institutionalization and renewal: Rhythms of adaptive governance in complex social-ecological systems. *Journal of environmental management* 165, 81-87.

Chamberlin, J., Jayne, T., Headey, D. (2014). Scarcity amidst abundance? Reassessing the potential for cropland expansion in Africa. *Food Policy* 48, 51-65.

Chambers, R. (1997). Shortcut and participatory methods for gaining social information for projects. *Sustainable development: social organization, institutional arrangements and rural development* 6, 177-208.

Chan, T., Ross, H., Hoverman, S., and Powell, B. (2010). Participatory development of a Bayesian network model for catchment-based water resource management. *Water Resources Research* 46(7): W07544, doi:10.1029/2009WR008848, 2.

Chang, H., Jung, I.-W., Strecker, A., Wise, D., Lafrenz, M., Shandas, V., Moradkhani, H., Yeakley, A., Pan, Y., and Bean, R. (2013). Water supply, demand, and quality indicators for assessing the spatial distribution of water resource vulnerability in the Columbia River basin. *Atmosphere-Ocean* 51, 339-356.

Chapin, F. S., Folke, C., and Kofinas, G. P. (2009). A Framework for Understanding Change. *In* "Principles of Ecosystem Stewardship Resilience-Based Natural Resource Management in a Changing World" (F. S. Chapin, P. G. Kofinas and C. Folke, eds.), pp. 3-28. Springer Science+Business Media, LLC, New York.

Chapin, F. S., Lovecraft, A. L., Zavaleta, E. S., Nelson, J., Robards, M. D., Kofinas, G. P., Trainor, S. F., Peterson, G. D., Huntington, H. P., and Naylor, R. L. (2006). Policy strategies to address sustainability of Alaskan boreal forests in response to a directionally changing climate. *Proceedings of the National Academy of Sciences* 103, 16637-16643.

Chapman, A., and Darby, S. (2016). Evaluating sustainable adaptation strategies for vulnerable mega-deltas using system dynamics modelling: Rice agriculture in the Mekong Delta's An Giang Province, Vietnam. *Science of The Total Environment* 559, 326-338.

Chen, D., and Stroup, W. (1993). General system theory: Toward a conceptual framework for science and technology education for all. *Journal of Science Education and Technology* 2, 447-459.

Cheung, M. (2008). The reductionist-holistic worldview dilemma. *MAI Review, Research Note 5* 3.

Chow, T.E, and Sadler, R. (2010). The consensus of local stakeholders and outside experts in suitability modeling for future camp development. *Landscape and Urban Planning* 94 (1):9-19.

Cinner, J. E., Folke, C., Daw, T., and Hicks, C. C. (2011). Responding to change: using scenarios to understand how socioeconomic factors may influence amplifying or dampening exploitation feedbacks among Tanzanian fishers. *Global environmental change* 21, 7-12.

Clark, R. N., and Stankey, G. H. (2006). Integrated research in natural resources: The key role of problem framing. *USDA Forest Service - General Technical Report PNW*, 1-63.

Collins, K. B., and Ison, R. L. (2010). Trusting emergence: Some experiences of learning about integrated catchment science with the Environment Agency of England and Wales. *Water resources management* 24, 669-688.

Collins, R., Dent, B., and Bonney, L. (2015). A Guide to Value-Chain Analysis and Development for Overseas Development Assistance Projects. Australian Centre for International Agricultural Research (ACIAR). Available at: http://aciar.gov.au/files/15500_aciar_chain_analysis_web.pdf. (Accessed on October 12, 2016).

Connell, J. H., and Sousa, W. P. (1983). On the evidence needed to judge ecological stability or persistence. *The American Naturalist* 121, 789-824.

Cook, C., and Bakker, K. (2012). Water security: Debating an emerging paradigm. *Global Environmental Change* 22, 94-102.

Cooke, R., and Goossens, L. (2004). Expert judgement elicitation for risk assessments of critical infrastructures. *Journal of Risk Research* 7, 643-656.

Cornell, S. E., Prentice, I. C., House, J. I., and Downy, C. J. (2012). "Understanding the earth system: global change science for application," Cambridge University Press, UK.

Costanza, R. (1996). Ecological economics: reintegrating the study of humans and nature. *Ecological Applications*, 978-990.

Costanza, R., and Ruth, M. (1998). Using dynamic modeling to scope environmental problems and build consensus. *Environmental Management* 22, 183-195.

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S. J., Kubiszewski, I., Farber, S., and Turner, R. K. (2014). Changes in the global value of ecosystem services. *Global Environmental Change* 26, 152-158.

Coyle, G. (2000). Qualitative and quantitative modelling in system dynamics: some research questions. *System Dynamics Review* 16, 225-244.

Coyle, R. G. (1996). "System Dynamics Modeling. APractical Approach " Chapman and Hall, London.

Creighton, L.J. (2010). How to Conduct a Shared Vision Planning Process. IWR Report 10-R-6. A Report Submitted to: U.S. Army Corps of Engineers Institute for Water Resources Casey Building 7701 Telegraph Road Alexandria, VA 22315. Available online at: http://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/10-R-6.pdf (accessed on October 30, 2016).

Creswell, J. W. (2003). "Research Design: Qualitative, Quantitative, and Mixed Methods Approaches (second edition)," Sage., California, USA.

Creswell, J. W. (2009). "Research Design: Qualitative, Quantitative, and Mixed Methods Approaches (third edition)," Third/Ed. Sage, California, USA.

Creswell, J. W., and Clark, V. L. P. (2007). "Designing and conducting mixed methods research," Wiley Online Library, London, UK.

Cronin, M. A., Gonzalez, C., and Sterman, J. D. (2009). Why don't well-educated adults understand accumulation? A challenge to researchers, educators, and citizens. *Organizational Behaviour and Human Decision Processes* 108, 116-130.

Crook, C., and Garratt, D. (2005). Positicist paradigm in Contemporary Social Science Research. *In* "Research Methods in the Social Sciences" (B. Somekh and C. Lewin, eds.). Sage, London, UK.

Crutzen, P. J., and Steffen, W. (2003). How long have we been in the Anthropocene era? *Climatic Change* 61, 251-257.

Cumming, G. S. (2011). The resilience of big river basins. *Water International* 36, 63-95.

d'aquino, P. & Bah, A. (2014). The multi-level participatory modelling of land use policies in African drylands: a method to embed adaptability skills of drylands societies in a policy framework. *Journal of Environmental Management* 132**,** 207-219.

d'Aquino, P., and Bah, A. (2013). Land Policies for Climate Change Adaptation in West Africa A Multilevel Companion Modeling Approach. *Simulation & Gaming* 44, 391-408.

Daly, H. E., and Cobb, J. B. (1994). "For the Common good: Redirecting the economy toward community, the environment, and a sustaibale future," Beacon Press, Boston, USA.

Darnhofer, I., Gibbon, D., and Dedieu, B. (2012). Farming Systems Research: an approach to inquiry. *In* "Farming Systems Research 3 into the 21st Century: The New Dynamic: DOI 10.1007/978-94-007-4503-2_1" (I. Darnhofer, D. Gibbon and B. Dedieu, eds.). Springer Science+Business Media Dordrecht 2012.

Davies, E. G., and Simonovic, S. P. (2011). Global water resources modeling with an integrated model of the social–economic–environmental system. *Advances in Water Resources* 34, 684-700.

Davis, A, and J.R. Wagner. 2003. Who knows? On the importance of identifying "experts" when researching local ecological knowledge. *Human Ecology* 31 (3):463-489.

Dawadi, S., and Ahmad, S. (2012). Changing climatic conditions in the Colorado River Basin: implications for water resources management. *Journal of Hydrology* 430, 127-141.

Dawadi, S., and Ahmad, S. (2013). Evaluating the impact of demand-side management on water resources under changing climatic conditions and increasing population. *Journal of Environmental Management* 114, 261-275.

de Condappa, D., Chaponnière, A. and Lemoalle, J., 2008.- Decision tool for water allocation in the Volta basin. Communication to World Water Congress, Montpellier 2008. Available at :http://www.iwra.org/congress/resource/abs238_article.pdf. (Accessed on December 24, 2016).

de Condappa, D., Chaponnière, A., and Lemoalle, J. (2009). A decision-support tool for water allocation in the Volta Basin. *Water International* 34, 71-87.

De Leo, G. A., and Levin, S. (1997). The multifaceted aspects of ecosystem integrity. *Conservation Ecology* 1, 3.

Dearing, J. A., Braimoh, A. K., Reenberg, A., Turner, B. L., and van der Leeuw, S. (2010). Complex Land Systems: the Need for Long Time Perspectives to Assess their Future. *Ecology and Society* 15.

Deaton, M., and Winebrake, J. J. (2012). "Dynamic modeling of environmental systems," Springer Science & Business Media, New York.

Deininger, K. W., and Byerlee, D. (2011). "Rising global interest in farmland: can it yield sustainable and equitable benefits?," World Bank Publications. Available at: https://siteresources.worldbank.org/DEC/Resources/Rising-Global-Interest-in-Farmland.pdf (Accessed May 23, 2014).

Delden, H. v., Luja, H., and Engelen, G. (2007). Integration of multi-scale dynamic spatial models of socioeconomic and physical processes for river basin management. *Environmental Modelling and Software* 22, 223-238.

Dent, E. B. (2003). The interactional model: An alternative to the direct cause and effect construct for mutually causal organizational phenomena. *Foundations of science* 8, 295-314.

Denzin, N. K., and Lincoln, S. Y. (2003). Introduction: The discipline and Practice of Qualitative Research. *In* "The Landscape of Qualitative Research: Theories and Issues (2nd. Ed)" (N. K. Denzin and S. Y. Lincoln, eds.), pp. 1-46. Sage Publications, London.

Denzin, N. K., and Lincoln, Y. S. (2011). "The SAGE handbook of qualitative research (4th. ed)," Thousand Oaks : Sage Publications, Incorporated, London, UK, USA.

Denzin, N., and Lincoln , Y. (2005). Paradigmatic controversies, contradictions, and emerging confluences. *In* "Handbook of qualitative research (3rd ed)" (N. Denzin and Y. Lincoln eds.), pp. 191-215. Sage., Thousand Oaks, CA.

Denzin, N., and Lincoln, Y., eds. (2000). "Handbook of Qualitative Research." Sage Publication Inc. , London.

Douthwaite, B., de Haan, N., Manyong, M. V., and Keatinge, J. (2003). Blending "Hard" and "Soft" Science: the "Follow-the-Technology" Approach to Catalyzing and Evaluating Technology Chnage. *In* "Integrated Natural Resource Management" (B. M. Campbell and J. A. Sayer, eds.). CAB International Oxfordshaire, UK.

Douxchamps, S., Ayantunde, A., and Barron, J. (2012). Evolution of Agricultural Water Management in Rainfed Crop-Livestock Systems of the Volta Basin. Colombo, Sri Lanka: CGIAR Challenge Program for Water and Food (CPWF). 74p. (CPWF R4D Working Paper Series 04).

Dow, S. C. (1997). Methodological pluralism and pluralism of method. *Salanti, A. and E. Screpanti, Pluralism in Economic-New Perspectives in History and Methodology. E. Elgar*, 89-99.

Drescher, M., A. Perera, C. Johnson, L. Buse, C. Drew, and M. Burgman. 2013. Toward rigorous use of expert knowledge in ecological research. *Ecosphere* 4(7): 83.

Du-Toit, R. D., Pollard, S. R., Dlamini, V., and Chuma, E. (2003). Learning from change: transforming practices through collaborative action in a communal wetland of Mpumalanga, South Africa. Association for Water and Rural Development (AWARD), South Africa.

Epstein, G., Vogt, J. M., Mincey, S. K., Cox, M., and Fischer, B. (2013). Missing ecology: integrating ecological perspectives with the social-ecological system framework. *International Journal of the Commons* 7, 432-453.

Ewert, F., van Ittersum, M. K., Bezlepkina, I., Therond, O., Andersen, E., Belhouchette, H., Bockstaller, C., Brouwer, F., Heckelei, T., and Janssen, S. (2009). A methodology for

enhanced flexibility of integrated assessment in agriculture. *Environmental Science & Policy* 12, 546-561.

Fahmy, H. (1999). A new modeling approach for water resources policy analysis. *Water resources research* 35, 295-304.

Falloon, P., and Betts, R. (2010). Climate impacts on European agriculture and water management in the context of adaptation and mitigation. The importance of an integrated approach. Science of the Total Environment, 408, 5667–5687.

FAO (2003). "Agriculture, Food and Water " FAO, Rome, Italy

Farley, C., and Farmer, A. (2013). Climate Chnage and Water Resources in West Africa: Transboundary River Basins, African and Latin American Resilience to Climate Change (ARCC). United States Agency for International Development (USAID), Washington DC, USA.

Farolfi, S., Müller, J.-P., and Bonté, B. (2010). An iterative construction of multi-agent models to represent water supply and demand dynamics at the catchment level. *Environmental modelling & software* **25**, 1130-1148.

Fazey, I., J.A. Fazey, J. Fischer, K. Sherren, J. Warren, R.F. Noss, and S.R. Dovers. 2007. Adaptive capacity and learning to learn as leverage for social-ecological resilience. *Frontiers in Ecology and the Environment* 5 (7):375-380.

Feilzer, M. Y. (2010). Doing mixed methods research pragmatically: Implications for the rediscovery of pragmatism as a research paradigm. *Journal of mixed methods research* 4, 6-16.

Fernandez, R. J., Archer, E. R. M., Ash, A. J., Dowlatabadi, H., Hiernaux, P. H. Y., Reynolds, J. F., Vogel, C. H., Walker, B. H., and Wiegand, T. (2002). Degradation and recovery in socio-ecological systems: a view from the household/farm level. *In* "In Do Humans Create Deserts? The Ecological, Meteorological, and Human Dimensions of Global Desertification" (J. F. Reynolds and M. Stafford-Smith, eds.), pp. 297-323. Dahlem University Press, Berlin.

Ferreyra, C., and Beard, P. (2007). Participatory evaluation of collaborative and integrated water management: Insights from the field. *Journal of Environmental Planning and Management* 50, 271-296.

Fischer, C.T. and Wertz, F.J. (2002). Empirirical phenomenological analysis of being criminally victimised. In Huberman, A.M. and Miles, M.B (eds.). The Qualitative researchers's companion. Sage, London pp. 275-305

Fish, R, Winter. M., Oliver. D.M., Chadwick. D., Selfa. T., Heathwaite, A. and Hodgson, C. (2009). Unruly pathogens: eliciting values for environmental risk in the context of heterogeneous expert knowledge. *Environmental Science & Policy* 12 (3): 281-296.

Fisher, D.M. (2011). *Modeling Dynamic Systems* (3 edn), isee systems, Inc.

Flick, U. (2007). "Designing qualitative research," London: Sage Publications Limited, London, UK.

Foley, J. (2014). GMOs, silver bullets and the trap of reductionist thinking. Available at: *http://ensia. com/voices/gmos-silver-bullets-and-the-trap-of-reductionist-thinking (Accessed March 13, 2012).*

Folke, C. (2003). Social-ecological resilience and behavioural responses. *Individual and Structural Determinants of Environmental Practice. Ashgate Publishers, London, UK*, 226-242.

Folke, C. (2006). Resilience: The emergence of a perspective for social-ecological systems analyses. *Global environmental change* 16, 253-267.

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T., and Rockstrom, J. (2010). Resilience Thinking: Integrating Resilience, Adaptability and Transformability. *Ecology and Society* 15.

Folke, C., Hahn, T., Olsson, P., and Norberg, J. (2005). Adaptive governance of social-ecological systems. *Annual Review. Environmental Resources* 30, 441-473.

Foran, T., Butler, J. R., Williams, L. J., Wanjura, W. J., Hall, A., Carter, L., and Carberry, P. S. (2014). Taking Complexity in Food Systems Seriously: An Interdisciplinary Analysis. *World Development* 61, 85-101.

Ford, A. (2010). "Modeling the environment: an introduction to system dynamics modeling of environmental systems (2nd. edn.)," Washington, DC :Island press.

Ford, D. N., and Sterman, J. D. (1998). Expert knowledge elicitation to improve formal and mental models. *System Dynamics Review* 14, 309-340.

Forrester, J. W. (1958). Industrial dynamics: a major breakthrough for decision makers. *Harvard Business Review* 36, 37-66.

Forrester, J. W. (1961). "Industrial dynamics," MIT press Cambridge, MA.

Forrester, J. W. (1968). A response to Ansoff and Slevin. *Management Science* 14, 601-618.

Forrester, J. W. (1969). "Urban Dynamics," Pegasus Communications, Inc. .

Forrester, J. W. (1973). "World Dynamics, 1st edn, 1971, 2nd edn. pp. 380. ," Wright- Allen Press, Cambridge, Massachusetts.

Forrester, J. W. (1991). System Dynamics and the Lessons of 35 Years. *In* "The Systemic Basis of Policy Making in the 1990s" (K. B. D. Greene, ed.). Cambridge University Press, Cambridge.

Forrester, J. W. (1994). Policies, decisions and information sources for modeling, . *In* "Modeling for Learning Organizations. " (J. D. W. Morecroft and D. J. Sterman, eds.). Productivity Press, Portland.

Forrester, J. W. (1995). Counterintuitive behavior of social systems. *Collected papers of jay W. Forrester*. Available from: http://computationalmodelingblogs.stanford.edu/winter2012/files/2012/01/Forrester-1995-Counterintuitive-Behavior.pdf (Accessed November 30, 2014).

Forrester, J. W., and P. M. Senge. (1980). Tests for Building Confidence in System Dynamics Models. In System Dynamics. ed. A. A. Legasto, J. W. Forrester and J. M. Lyneis. Amsterdam: North-Holland.

Forrester, J.W. (1971). Counterintuitive behavior of social systems. *Technology Review*, 73 (3):52–68.

Frame, B., and Brown, J. (2008). Developing post-normal technologies for sustainability. *Ecological Economics* 65, 225-241.

Fuller, S. (2000). Thomas Kuhn: A philosophical history for our times. University of Chicago Press Chicago, USA.

Fulton, E. A., Smith, A. D. M., Smith, D. C., and van Putten, I. E. (2011). Human behaviour: the key source of uncertainty in fisheries management. *Fish and Fisheries* 12, 2-17.

Funtowicz, S. O., and Ravetz, J. R. (1993). Science for the post-normal age. *Futures* 25, 739-755.

Gain, A. K., and Giupponi, C. (2015). A dynamic assessment of water scarcity risk in the Lower Brahmaputra River Basin: An integrated approach. *Ecological Indicators* 48, 120-131.

Gain, A. K., and Giupponi, C. (2015). A dynamic assessment of water scarcity risk in the Lower Brahmaputra River Basin: An integrated approach. *Ecological Indicators* 48, 120-131.

Gallopín, G. C., Funtowicz, S., O'Connor, M., and Ravetz, J. (2001). Science for the Twenty-First Century: From Social Contract to the Scientific Core. *International Social Science Journal* 53, 219-229.

Gao, Y. & Margolies, A. (2009). Transboundary Water Governance in the Volta River Basin. Available:https://wikis.uit.tufts.edu/confluence/display/aquapedia/Transboundary+Water+Governance+in+the+Volta+River+Basin [Accessed July 2, 2014].

Garbarino, S., and Holland, J. (2009). Quantitative and Qualitative Methods in Impact Evaluation and Measuring Results. Social Development Direct, issues paper. Discussion Paper. University of Birmingham, Birmingham, UK.

Gasparatos, A., El-Haram, M., and Horner, M. (2009). The argument against a reductionist approach for measuring sustainable development performance and the need for methodological pluralism. *In* "Accounting Forum", Vol. 33, pp. 245-256. Elsevier.

Geist, H. J., and Lambin, E. F. (2001). What drives tropical deforestation. *LUCC Report series* 4, 116.

Geist, H. J., and Lambin, E. F. (2002). Proximate causes and underlying driving forces of tropical deforestation. *BioScience* 52, 143-150.

Gell, P., Fluin, J., Tibby, J., Hancock, G., Harrison, J., Zawadzki, A., Haynes, D., Khanum, S., Little, F., and Walsh, B. (2009). Anthropogenic acceleration of sediment accretion in lowland floodplain wetlands, Murray–Darling Basin, Australia. *Geomorphology* 108, 122-126.

Geyer, R. (2003). Europeanisation, Complexity and the British Welfare State. Available at: http://aei.pitt.edu/1719/1/Geyer.pdf (Accessed Febuary 21, 2012).

Ghana statistical Service (2010). Ghana Population and Housing Census. Ghana Statistical Service, Accra, Ghana.

Gill, J., and Johnson, P. (2010). "Research methods for managers (4th Edition)," Sage Publications Limited.

Giordano, M. and Shah, T. (2014). From IWRM back to integrated water resources management. International Journal of Water Resources Development 30, 364-376. http://dx.doi.org/10.1080/07900627.2013.851521

Girard, C., Rinaudo, J.-D., Pulido-Velazquez, M., and Caballero, Y. (2015). An interdisciplinary modelling framework for selecting adaptation measures at the river basin scale in a global change scenario. *Environmental Modelling & Software* 69, 42-54.

Gladwin, T. N., Kennelly, J. J., and Krause, T. S. (1995). Shifting paradigms for sustainable development: Implications for management theory and research. *Academy of Management Review*, 874-907.

Gohari, A., Eslamian, S., Mirchi, A., Abedi-Koupaei, J., Bavani, A. M., and Madani, K. (2013). Water transfer as a solution to water shortage: a fix that can backfire. *Journal of Hydrology* 491, 23-39.

Gordon, C., and Amatekpor, J. K. (1999). "The sustainable integrated development of the Volta Basin in Ghana," Volta Basin Research Project, University of Ghana.

Gordon, C., Nukpezah, D., Tweneboah-Lawson, E., Ofori, B., Yirenya-Tawiah, D., Pabi, O., Ayivor, J., Koranteng, S., and Darko, D. (2013). West Africa–Water Resources Vulnerability Using a Multidimensional Approach: Case Study of Volta Basin. *In* "Climate Vulnerability: Understanding and Addressing Threats to Essential Resources (Volume 1): Vulnerability of Human Health to Climate" (R. A. Pielke, J. Adegoke and Y. C. Wright, eds.), pp. 283–309 Elsevier Inc. Academic Press, USA.

Government of Ghana (2017). Full Text: President Akufo-Addo's maiden State of Nation Address. Available from: http://www.myjoyonline.com/politics/2017/February-21st/full-text-president-akufo-addos-maiden-state-of-nation-address.php (accessed on February 21, 2017).

Government of Ghana (GoG) (2003). Ghana Poverty Reduction Strategy, 2003–2005. An Agenda for Growth and Prosperity. Accra: National Development Policy Commission.

Graham, M. H., and Dayton, P. K. (2002). On the evolution of ecological ideas: paradigms and scientific progress. *Ecology* 83, 1481-1489.

Green, T. R., Taniguchi, M., Kooi, H., Gurdak, J. J., Allen, D. M., Hiscock, K. M., Treidel, H., and Aureli, A. (2011). Beneath the surface of global change: Impacts of climate change on groundwater. *Journal of Hydrology* 405, 532-560.

Greene, J. C. (2006). Toward a methodology of mixed methods social inquiry. *Research in the Schools* 13, 93-98.

Greene, J. C. (2008). Is mixed methods social inquiry a distinctive methodology? *Journal of mixed methods research* 2, 7-22.

Greiner, R., Puig, J., Huchery, C., Collier, N., and Garnett, S. T. (2014). Scenario modelling to support industry strategic planning and decision making. *Environmental Modelling & Software* 55, 120-131.

Guba, E., and Lincoln , Y. (1994). Competing paradigms in qualitative research. *In* "Handbook of qualitative research " (N. Denzin and Y. Lincoln eds.), pp. 105-177. Sage, Thousand Oaks, CA.

Guillaume, J.H.A., Qureshi, M.E., Jakeman, A.J., 2012. A structured analysis of uncertainty surrounding modelled impacts of groundwater-extraction rules. *Hydrogeological Journal* 20, 915-932.

Gunderson, L. H. (2003). Adaptive dancing: interactions between social resilience and ecological crises. *Navigating social-ecological systems: Building resilience for complexity and change*, 33-52.

Gunderson, L. H., and Holling, C. S. (2002). "Panarchy: understanding transformations in human and natural systems," Island Press, New York, USA.

Gunderson, L. H., and Pritchard, L. (2002). "Resilience and the behaviour of large-scale systems," Washington D.C: Island Press, New York, USA.

Gunderson, L. H., Holling, C. S., Prictchard, L. J., and Perterson, G. D. (2002). Resilience of Large Scale Resource Systems. *In* "Resilience and Behaviour of Large scale Systems" (L. H. Gunderson and L. J. Pritchard, eds.). Island Press, Washington, D.C, USA.

Guo, H., Liu, L., Huang, G., Fuller, G., Zou, R., and Yin, Y. (2001). A system dynamics approach for regional environmental planning and management: A study for the Lake Erhai Basin. *Journal of Environmental Management* 61, 93-111.

Gupta, H. V., Clark, M. P., Vrugt, J. A., Abramowitz, G., and Ye, M. (2012). Towards a comprehensive assessment of model structural adequacy. *Water Resources Research* 48. W08301, doi:10.1029/2011WR011044.

Haag, D., and Kaupenjohann, M. (2001). Parameters, prediction, post-normal science and the precautionary principle—a roadmap for modelling for decision-making. *Ecological Modelling* 144, 45-60.

Haase, D. (2011). Participatory modelling of vulnerability and adaptive capacity in flood risk management. *Natural Hazards* 1-21.

Hall, S.J. (2011). Climate Change and Other External Drivers in Small-Scale Fisheries: Practical Steps for Responding. In: *Small-scale Fisheries Management: Frameworks and Approaches for the Developing World, (*Eds). R.S. Pomeroy, N. Andrew. CABI, Cambridge, pp.132–159.

Hämäläinen, R. P. (2015). Behavioural issues in environmental modelling: The missing perspective. *Environmental Modelling & Software* 73, 244-253.

Hamilton, S. H., ElSawah, S., Guillaume, J. H., Jakeman, A. J., and Pierce, S. A. (2015). Integrated assessment and modelling: overview and synthesis of salient dimensions. *Environmental Modelling & Software* 64, 215-229.

Hammer, M. (2015). "The ecosystem management approach: implications for marine governance," Ashgate, Farnham.

Hannon, B., and Ruth, M. (2001). "Dynamic Modeling (2nd. edn.)," Springer, New York, USA.

Hare, M. (2011). Forms of participatory modelling and its potential for widespread adoption in the water sector. *Environmental Policy and Governance* 21, 386-402.

Hassan, I., and Ghauri, P. N. (2014). Research Design. *International Business and Management* 30, 75-81.

Hassanzadeh, E., Elshorbagy, A., Wheater, H., and Gober, P. (2014). Managing water in complex systems: An integrated water resources model for Saskatchewan, Canada. *Environmental Modelling & Software* 58, 12-26.

Hassanzadeh, E., Zarghami, M., and Hassanzadeh, Y. (2012). Determining the main factors in declining the Urmia Lake level by using system dynamics modeling. *Water Resources Management* 26, 129-145.

Hazell, P., and Wood, S. (2008). Drivers of change in global agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences* 363, 495-515.

Hedelin, B. (2007). Criteria for the assessment of sustainable water management. *Environmental Management* 39, 151-163.

Heise, U. (2008). "Sense of place and sense of planet: The environmental imagination of the global," Oxford University Press, Oxford, England.

Herr, A., Dambacher, J. M., Pinkard, E., Glen, M., Mohammed, C., and Wardlaw, T. (2015). The uncertain impact of climate change on forest ecosystems–How qualitative modelling can guide future research for quantitative model development. *Environmental Modelling & Software*.

Hertel, T. W. (2011). The global supply and demand for agricultural land in 2050: A perfect storm in the making? *American Journal of Agricultural Economics* 93, 259-275.

Hewitt, R., Van Delden, H., and Escobar, F. (2014). Participatory land use modelling, pathways to an integrated approach. *Environmental Modelling & Software* 52, 149-165.

Hinkel, J., Bots, P. W., and Schlüter, M. (2014). Enhancing the Ostrom social-ecological system framework through formalization. *Ecology and Society* 19, 51.

Hjorth, P., and Bagheri, A. (2006). Navigating towards sustainable development: A system dynamics approach. *Futures* 38, 74-92.

Holling, C. S. (1987). Simplifying the complex: the paradigms of ecological function and structure. *European Journal of Operational Research* 30, 139-146.

Holling, C. S. (1994). Simplifying the Complex: the paradigms of ecological function and structure. *Futures* 26, 598-609.

Holling, C. S. (1995). What Barriers? What Bridges? . *In* "Barriers and Bridges to the Renewal of Ecosystems and Institutions" (L. H. Gunderson, C. S. Holling and S. S. Light, eds.). Columbia University Press, New York.

Holling, C. S., and Meffe, G. K. (1996). Command and control and the pathology of natural resource management. *Conservation Biology* 10, 328-337.

Homer, J. B., and Hirsch, G. B. (2006). System dynamics modeling for public health: background and opportunities. *Journal Information* 96(3):452-458.

Homer, J., and Oliva, R. (2001). Maps and models in system dynamics: a response to Coyle. *System dynamics review* 17, 347-355.

Huber-Sannwald, E., Palacios, M. R., Moreno, J. T. A., Braasch, M., Peña, R. M. M., de Alba Verduzco, J. G., and Santos, K. M. (2012). Navigating challenges and opportunities of land degradation and sustainable livelihood development in dryland social–ecological systems: a case study from Mexico. *Philosophical Transactions of the Royal Society B: Biological Sciences* 367, 3158-3177.

Inam, A., Adamowski, J., Halbe, J., and Prasher, S. (2015). Using causal loop diagrams for the initialization of stakeholder engagement in soil salinity management in agricultural watersheds in developing countries: A case study in the Rechna Doab watershed, Pakistan. *Journal of environmental management* 152, 251-26.

IPCC (2013). Climate Change 2013: The Physical Science Basis. In T. F. Stocker, D. Qin, G. -K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex & P. M. Midgley (Eds.), Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (p. 1535). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. doi:10.1017/CBO9781107415324

Israel, M., and Hay, I. (2006). "Research Ethics for Social Scientists," Sage, London.

Jäger, M., and Menge, S. (2012). The Volta River Basin: An assessment of groundwater need. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR [Available from www.splash-era.net/downloads/groundwater/8_VBA_final_report.pdf. (Accessed April 17, 2014).

Jakeman, A. J., Letcher, R. A., and Norton, J. P. (2006). Ten iterative steps in development and evaluation of environmental models. *Environmental Modelling & Software* 21, 602-614.

Jakeman, A.J., Letcher, R.A., (2003). Integrated assessment and modelling: features, principles and examples for catchment management. *Environmental Modelling and Software* 18, 491-501.

Jeffrey, S., and Hawkins, R. D. (2008). "Creativity Revealed: Discovering the Source of Inspiratio," Creative Crayon Publishers, New York.

Johnson, A. (1982). Reductionism in Cultural Ecology: The Amazon Case. *Current Anthropology* 23, 413-418.

Johnson, R. B., and Onwuegbuzie, A. J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational Researcher* 33, 14-26.

Johnson, R. B., Onwuegbuzie, A. J., and Turner, L. A. (2007). Toward a definition of mixed methods research. *Journal of mixed methods research* 1, 112-133.

Johnston, R., and Kummu, M. (2012). Water resource models in the Mekong Basin: a review. *Water Resources Management* 26, 429-455.

Johnston, R., and Smakhtin, V. (2014). Hydrological modeling of large river basins: how much is enough? *Water resources management* 28, 2695-2730.

Johnston, R., and Smakhtin, V. (2014). Hydrological modeling of large river basins: how much is enough? *Water resources management* 28, 2695-2730.

Jones, N.A., Perez, P., Measham, T.G., Kelly, G.J., d'Aquino, P., Daniell, K.A., Dray, A., Ferrand, N. (2009). Evaluating participatory modeling: developing a framework for cross-case analysis. *Environmental management* 44 (6), 1180-1195.

Jung, G., Wagner, S., and Kunstmann, H. (2012). Joint climate–hydrology modeling: an impact study for the data-sparse environment of the Volta Basin in West Africa. *Hydrology Research* 43, 231-248.

Kainz, D., and Ossimitz, G. (2002). Can students learn stock-flow-thinking? An empirical investigation. *In* "Proceedings of the 20th international conference of the system dynamics society", Palermo, Italy

Kallis, G., Videira, N., Antunes, P., Pereira, Â. G., Spash, C. L., Coccossis, H., Quintana, S. C., del Moral, L., Hatzilacou, D., and Lobo, G. (2006). Participatory methods for water resources planning. *Environment and Planning C: Government and Policy* 24, 215-234.

Kampmann, C. (1991). Replication and Revision of a Classic System Dynamics Model: Critique of Population Control Mechanisms in a Primitive Agricultural Society. System Dynamics Review. 7(2): 159-198.

Kappel, C. V., Halpern, B. S., Selkoe, K. A., and Cooke, R. M. (2012). Eliciting Expert Knowledge of Ecosystem Vulnerability to Human Stressors to Support Comprehensive Ocean Management. *In* "Expert Knowledge and Its Application in Landscape Ecology" (H. A. Perera, A. Drew and J. C. Johnson, eds.), pp. 253-277. Springer Science+Business Media, LLC, New York, USA.

Kay, J. J., Regier, H. A., Boyle, M., and Francis, G. (1999). An ecosystem approach for sustainability: addressing the challenge of complexity. *Futures* 31, 721-742.

Keating, E. K. (1999). Issues to Consider While Developing a System Dynamics Model. *online] http://blog. metasd. com/wp-content/uploads/2010/03/SDModelCritique. pdf (accessed 19 June 2015).*

Kelleher, C., Wagener, T. (2011). Ten guidelines for effective data visualization in scientific publications. *Environmental Modelling and Software* 26 (6), 822-827.

Kelly, K. L. (1998). A systems approach to identifying decisive information for sustainable development. *European Journal of Operational Research* 109, 452-464.

Kelly, R. A., Jakeman, A. J., Barreteau, O., Borsuk, M. E., ElSawah, S., Hamilton, S. H., Henriksen, H. J., Kuikka, S., Maier, H. R., and Rizzoli, A. E. (2013). Selecting among five common modelling approaches for integrated environmental assessment and management. *Environmental Modelling & Software* 47, 159-1.

Kendall, M.G, and B.B. Smith. 1939. The problem of m rankings. *The annals of mathematical statistics* 10 (3): 275-287.

Kenneth, P.B, and David, R.A. (2001). Kullback–Leibler information as a basis for strong inference in ecological studies', *Wildlife Research* 28, 111–9.

Kerr, T.J., Kulkarni, M, andAlgar, A. (2011) Integrating Theory and Predictive Modeling for Conservation Research. *In* "Predictive Species and Habitat Modeling in Landscape Ecology: Concepts and Applications" (C. A. Drew, F. Y. Wiersma and F. Huettmann, eds.), pp. 9-280. Springer Science+Business Media, LLC, New York.

Kittinger, J. N., Finkbeiner, E. M., Glazier, E. W., Crowder, L. B., and Feedbacks, C. (2012). Human Dimensions of Coral Reef Social-Ecological Systems. *Ecology and Society* 17, 17.

Klayman, J., J. B. Soll., Juslin,P. and Winman, A. (2006). Subjective confidence and the sampling of knowledge. Information sampling and adaptive cognition, eds. K. Fiedler., and P. Juslin, pp.153-182. Cambridge: University of Cambridge Press, Cambridge.

Kleindorfer, G. B., O'Neill, L., and Ganeshan, R. (1998). Validation in simulation: various positions in the philosophy of science. *Management Science* 44, 1087-1099.

Knight, R. L., and Meffe, G. K. (1997). Ecosystem management: agency liberation from command and control. *Wildlife Society Bulletin* 25, 676-678.

Kolavalli, S., and Williams, T.O. (2016). Socioeconomic trends and drivers of change. In The Volta River Basin: Water for Food, Economic Growth and Environment, eds. Williams, T., O., V. Smakhtin., A.C. Biney., and L.M. Mul, pp. New York, NY: Routledge.

Kolb, M., Mas, J.-F., and Galicia, L. (2013). Evaluating drivers of land-use change and transition potential models in a complex landscape in Southern Mexico. *International Journal of Geographical Information Science* 27, 1804-1827.

Kragt, M. E., Robson, B. J., and Macleod, C. J. (2013). Modellers' roles in structuring integrative research projects. *Environmental Modelling & Software* 39, 322-330.

Kricher, J. C. (2009). "The balance of nature: ecology's enduring myth," Princeton University Press, USA.

Krueger, T., Page, T., Hubacek, K., Smith, L., Hiscock, K. (2012). The role of expert opinion in environmental modelling. *Environmental Modelling and Software* 36, 4-18.

Kuhn, T. (1970). "The Structure of Scientifc Revolution," 2/Ed. Harper and Row, New York.

Kuhn, T. S. (1962). " The structure of scientific revolutions," Chicago University Press, Chicago, Illinois, USA.

Kuhn, T. S. (2012). "The structure of scientific revolutions," University of Chicago press, Chicago.

Kuhnert, P. M., Martin, T. G., and Griffiths, S. P. (2010). A guide to eliciting and using expert knowledge in Bayesian ecological models. *Ecology letters* 13, 900-914.

Kumar, M. D., and van Dam, J. C. (2013). Drivers of change in agricultural water productivity and its improvement at basin scale in developing economies. *Water International* 38, 312-325.

Lakatos, I., and Musgrave, A. (1970). Criticism and the growth of knowledge. (I. Lakatos and A. Musgrave, eds.), pp. 91-196. Cambridge University Press, Cambridge, UK.

Langsdale, S., Beall, A., Bourget, E., Hagen, E., Kudlas, S., Palmer, R., Tate, D., and Werick, W. (2013). Collaborative modeling for decision support in water resources: Principles and best practices. *JAWRA Journal of the American Water Resources Association* 49, 629-638.

Langsdale, S., Beall, A., Carmichael, J., Cohen, S., and Forster, C. (2007). An exploration of water resources futures under climate change using system dynamics modeling. *Integrated Assessment* 7. 1–79.

Laniak, G. F., Olchin, G., Goodall, J., Voinov, A., Hill, M., Glynn, P., Whelan, G., Geller, G., Quinn, N., and Blind, M. (2013). Integrated environmental modeling: a vision and roadmap for the future. *Environmental Modelling & Software* 39, 3-23.

Laszlo, A., and Krippner, S. (1998). Systems Theories: Their Origins, Foundations and Development. *In* "Systems Theories and a Priori Aspects of Perception" (J. S. Jordan, ed.), pp. 47–74. Elsevier, Amsterdam.

Laszlo, E. (1972). " Introduction to Systems Philosophy: Toward a New Paradigm of Contemporary Thought," Gordon & Breach, New York.

Laube, W., and van de Giesen, N. (2006). Ghanaian water lawand policy: institutional and hydrological perspectives. *In* "hydrological information in water law and policy: current practices and future potential" (J. S. Wallace, P. Wouters and S. Pazvakavambwa, eds.). Water policy series, Kluwar, Dordrecht, Nethelands.

Layder, D. (1993). "New strategies in social research: An introduction and guide," Polity Press Cambridge.

Le, Q. B., Seidl, R., and Scholz, R. W. (2012). Feedback loops and types of adaptation in the modelling of land-use decisions in an agent-based simulation. *Environmental Modelling & Software* 27, 83-96.

Leach, M., and Fairhead, J. (2000). Challenging Neo-Malthusian Deforestation Analyses in West Africa's Dynamic Forest Landscapes. *Population and Development Review* 26(1): 17-43.

Lecompte, M.D., and Schensul, J.J. (1999). Designing and Conducting ethnographic research. AltaMira Press, Walnut Creek, California, USA

Leemhuis, C., Jung, G., Kasei, R., and Liebe, J. (2009). The Volta Basin water allocation system: Assessing the impact of small-scale reservoir development on the water resources of the Volta Basin, West Africa. *Advances in Geosciences* 21, 57-62.

Lemoalle, J. (2007). "Global trends in the Volta basin. Volta Basin Focal Project Report No 3. IRD," Montpellier, France, and CPWF, Colombo, Sri Lanka, 26 p.

Lemoalle, J. (2009). "Basin Focal Project Volta. CPWF Project Report series, Challenge Program on Water and Food," Colombo, Sri Lanka, 81p.

Levin, S. A. (1998). Ecosystems and the biosphere as complex adaptive systems. *Ecosystems* 1, 431-436.

Levin, S., Xepapadeas, T., Crépin, A.-S., Norberg, J., De Zeeuw, A., Folke, C., Hughes, T., Arrow, K., Barrett, S., and Daily, G. (2013). Social-ecological systems as complex adaptive systems: modeling and policy implications. *Environment and Development Economics* 18, 111-132.

Lewis-Beck, M. S., Bryman, A., and Lia, T.F. (eds.). (2004). The SAG Eencyclopedia of social science research methods. Sage, Thousand Oaks, California, USA.

Lincoln, Y. S., Lynham, A. S., and Guba, G. E. (2011). Paradigmatic Controversies, Contradictions, and Emerging Confluences, Revisited. *In* " Handbook of qualitative research (4th.Ed)." (N. K. Denzin and S. Y. Lincoln, eds.). Sage, Thousand Oaks, CA:

Liniger, H.P. and Critchley, W. (2007). Where the land is greener: Case studies and analysis of soil and water conservation initiatives worldwide. World Overview of Conservation Approaches and Technologies. CTA, FAO, UNEP, CDE.

Lippe, M., Minh, T. T., Neef, A., Hilger, T., Hoffmann, V., Lam, N., and Cadisch, G. (2011). Building on qualitative datasets and participatory processes to simulate land use change in a mountain watershed of Northwest Vietnam. *Environmental Modelling & Software* 26, 1454-1466.

Lister, N. M. E. (1998). A systems approach to biodiversity conservation planning. *Environmental Monitoring and Assessment* 49, 123-155.

Liu, C., Frazier, P., and Kumar, L. (2007a). Comparative assessment of the measures of thematic classification accuracy. *Remote sensing of environment* 107, 606-616.

Liu, H., Benoit, G., Liu, T., Liu, Y., and Guo, H. (2015a). An integrated system dynamics model developed for managing lake water quality at the watershed scale. *Journal of environmental management* 155, 11-23.

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., Pell, A. N., Deadman, P., Kratz, T., and Lubchenco, J. (2007b). Complexity of coupled human and natural systems. *science* 317, 1513-1516.

Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K. C., Gleick, P., and Kremen, C. (2015b). Systems integration for global sustainability. *Science* 347, 1258832.

Liu, Y., Gupta, H., Springer, E., and Wagener, T. (2008). Linking science with environmental decision making: Experiences from an integrated modeling approach to supporting sustainable water resources management. *Environmental Modelling & Software* 23, 846-858.

Ludwig, D. (1996). Barriers and Bridges to the Renewal of Ecosystems and Institutions. *Ecological Economics* 19 185-192.

Ludwig, D. (2001). The era of management is over. *Ecosystems* 4, 758-764.

Ludwig, D., Hilborn, R., and Walters, C. (1993). Uncertainty, resource exploitation, and conservation: lessons from history. *Science(Washington)* 260, 17.

Luke, T. W. (1997). "Ecocritique: Contesting the Politics of nature, economy and culture," University of Minisota Press, Minneapolis.

Luke, T. W. (2002). The practices of adaptive and collaborative environmental management: A critique. *Capitalism, Nature, Socialism* 13, 1-27.

Luzadis, V. A., Goslee, K. M., Greenfield, E. J., and Schaeffer, T. D. (2002). Toward a more integrated ecosystem model. *Society &Natural Resources* 15, 89-94.

MA (2003). "Ecosystems and Human Well-Being: A Framework for Assessment," Island Press, Washington, DC.

MA (2005). "Ecosystem and Human Well-being. Vol 2," Island Press, Washington DC.

Maani, K. E., and Cavana, R. Y. (2007). "Systems Thinking, System Dynamic: Managing Change and Complexity (2nd. edition)," Prentice Hall, Auckland, New Zealand.

Mackenzie, N., and Knipe, S. (2006). Research dilemmas: Paradigms, methods and methodology. *Issues in educational research* 16, 193-205.

Madani, K., and Mariño, M. A. (2009). System dynamics analysis for managing Iran's Zayandeh-Rud river basin. *Water resources management* 23, 2163-2187.

Mai, V.T. (2013). Sustainable Tourism - Systems Thinking and System Dynamics Approaches: A Case Study in Cat Ba Biosphere Reserve of Vietnam. An Unpublished PhD these submitted to School of Agriculture and Food Sciences, University of Queensland, Brisbane, Australia.

Mainuddin, M., Kirby, M., and Qureshi, M. E. (2007). Integrated hydrologic–economic modelling for analyzing water acquisition strategies in the Murray River Basin. *Agricultural Water Management* 93, 123-135.

Manson, S. M. (2001). Simplifying complexity: a review of complexity theory. *Geoforum* 32, 405-414.

Martin, E., Gascoin, S., Grusson, Y., Murgue, C., Bardeau, M., Anctil, F., Ferrant, S., Lardy, R., Le Moigne, P., and Leenhardt, D. (2016). On the use of hydrological models and satellite data to study the water budget of river basins affected by human activities: Examples from the Garonne Basin of France. *Surveys in Geophysics* 37, 223-247.

Martin, N., and Van De Giesen, N. (2005). Spatial distribution of groundwater production and development potential in the Volta River basin of Ghana and Burkina Faso. *Water International* 30, 239-249.

Martin, T.G, M.A Burgman, F. Fidler, P.M Kuhnert, S. Low-Choy, M. McBride, and K. Mengersen. (2012). Eliciting expert knowledge in conservation science. *Conservation Biology* 26 (1):29-38.

Martins, J. H., Camanho, A. S., and Gaspar, M. B. (2012). A review of the application of driving forces–Pressure–State–Impact–Response framework to fisheries management. *Ocean & Coastal Management* 69: 273–281.

Mathevet, R., Antona, M., Barnaud, C., Fourage, C., Trébuil, G., and Aubert, S. (2014). Contexts and Dependencies in the ComMod Processes. *In* "Companion Modelling: A Participatory Approach to Support Sustainable Development" (M. ÉTIENNE, ed.). Springer, France: Springer.

Maurel, P., Craps, M., Cernesson, F., Raymond, R., Valkering, P., and Ferrand, N. (2007). Concepts and methods for analysing the role of Information and Communication tools (IC-tools) in Social Learning processes for River Basin Management. *Environmental Modelling & Software* 22, 630-639.

Maxim, L., Spangenberg, J. H., and O'Connor, M. (2009). An analysis of risks for biodiversity under the DPSIR framework. *Ecological Economics* 69, 12-23.

Mayumi, K., and Giampietro, M. (2006). The epistemological challenge of self-modifying systems: Governance and sustainability in the post-normal science era. *Ecological Economics* 57, 382-399.

Mbatu, R. S. (2010). The Balance of Nature: Ecology's Enduring Myth,. *International Journal of Environmental Studies* 67, 94-95.

McAllister, R. R. J., Abel, N., Stokes, C. J., and Gordon, I. J. (2006). Australian pastoralists in time and space: the evolution of a complex adaptive system. *Ecology and Society* 11, 41.

McCartney, M., Forkuor, G., Sood, A., Amisigo, B., Hattermann, F., Muthuwatta, L., 2012. The water resource implications of changing climate in the Volta River Basin. Colombo, Sri Lanka: International Water Management Institute (IWMI). 40p. (IWMI Research Report 146). http://dx.doi:10.5337/2012.219

McDonagh, J., Bunning, S., Nachtergaele, F., and Biancalani, R. (2008). "Land Degradation Assessment in Drylands local assessment (LADA-L) manual." Food and Agricultural Organisation of the United Nations, Rome, Italy.

McGinnis, M. D., and Ostrom, E. (2014). Social-ecological system framework: initial changes and continuing challenges. *Ecology and Society* 19, 30.

McLafferty, J. C. L., Slate, J. R., and Onwuegbuzie, A. J. (2010). Transcending the Quantitative-Qualitative Divide With Mixed Methods Research: A Multidimensional

Framework for Understanding Congruence and Completeness in the Study of Values. *Counseling and Values* 55, 46-62.

Meadows, D. H. (1999). "Leverage points: Places to intervene in a system," Sustainability Institute Hartland, VT. Available at: http://leadership-for-change.southernafricatrust.org/downloads/session_2_module_2/Leverage-Points-Places-to-Intervene-in-a-System.pdf (Accessed on June 17, 2014).

Meadows, D. H., Meadows, D. L., Randers, J., and Behrens III, W. W. (1972). The limits to growth. *New York: Universe Books Publishers.*

Mebratu, D. (2001). The Knowledge Dimension of the Sustainability Challenge. *International Journal of Economic Development* 3(1). Available at: http://www.spaef.com/IJED_PUB/v3n1_mebratu.html (Accessed 2 April 2012).

Medema, W., McIntosh, B.S., Jeffrey, P.J. (2008). From premise to practice: a critical assessment of integrated water resources management and adaptive management approaches in the water sector. Ecology & Society. 13(2): 29. http://www.ecologyandsociety.org/vol13/iss2/art29/.

Meppem, T., and Bourke, S. (1999). Different ways of knowing: a communicative turn toward sustainability. *Ecological Economics* 30, 389-404.

Mertens, D. M. (2005). " Research methods in education and psychology: Integrating diversity with quantitative and qualitative approaches (2nd. ed.)," Sage. , Thousand Oaks: Sage. .

Metcalf, S. S., Wheeler, E., BenDor, T. K., Lubinski, K. S., and Hannon, B. M. (2010). Sharing the floodplain: Mediated modeling for environmental management. *Environmental Modelling & Software* 25, 1282-1290.

Meyer, M. A., and Booker, J. M. (2001). "Eliciting and analyzing expert judgment: a practical guide," ASA-SIAM Series on Statistics and Applied Probability, London.

Miller, T. R., Baird, T. D., Littlefield, C. M., Kofinas, G., Chapin III, F. S., and Redman, C. L. (2008). Epistemological pluralism: reorganizing interdisciplinary research. *Ecology and Society* 13, 46.

Mingers, J. (1997). Multi-paradigm multimethodology. *In* "Multimethodology: Theory and Practice of Combining Management Science Methodologies" (J. Mingers and A. Gill, eds.), pp. 1-20. Wiley, Chichester.

Mingers, J., and Brocklesby, J. (1997). Multimethodology: towards a framework for mixing methodologies. *Omega* 25, 489-509.

Ministry of Food and Agriculture (MOFA) (2012). Facts and Figures 2012. Statistics, Research and Information Directorate (SRID), Ministry of food and Agriculture, Accra, Ghana.

Ministry of Water Resources Works and Housing (2007). National Water Policy (W. a. H. Ministry of Water Resources, ed.). Ghana, Government of Ghana.

Mirchi, A., and Watkins Jr, D. (2013). A systems approach to holistic total maximum daily load policy: case of Lake Allegan, Michigan. *Journal of Water Resources Planning and Management* 139, 544-553.

Mirchi, A., Madani, K., Watkins, D., and Ahmad, S. (2012). Synthesis of System Dynamics Tools for Holistic Conceptualization of Water Resources Problems. *Water resources management*, 1-22.

Molina, J., Bromley, J., García-Aróstegui, J., Sullivan, C., and Benavente, J. (2010). Integrated water resources management of overexploited hydrogeological systems using Object-Oriented Bayesian Networks. *Environmental Modelling & Software* 25, 383-397.

Molle, F. (2007). Scales and power in river basin management: the Chao Phraya River in Thailand1. *The Geographical Journal* 173, 358-373.

Morgan, D. L. (2007). Paradigms Lost and Pragmatism Regained Methodological Implications of Combining Qualitative and Quantitative Methods. *Journal of mixed methods research* 1, 48-76.

Morse, J. M., and Chung, S. E. (2008). Toward holism: The significance of methodological pluralism. *International Journal of Qualitative Methods* 2, 13-20.

Moss, S., Pahl-Wostl, C., and Downing, T. (2001). Agent-based integrated assessment modelling: the example of climate change. *Integrated Assessment* 2, 17-30.

Msangi, S., and Rosegrant, M. (2011). World agriculture in a dynamically changing environment: IFPRI's long-term outlook for food and agriculture. *In* "Looking Ahead in World Food and Agriculture: Perspectives to 2050" (P. Conforti, ed.), pp. 57-93. FAO, Rome.

Mul, M., Obuobie, E., Appoh, R., Kankam-Yeboah, K., Bekoe-Obeng, E., Amisigo, B., Logah, F.Y. Ghansah, B. and McCartney, M. (2015). Water Resources Assessment of the Volta River Basin. Vol. IWMI Working Paper 166. Colombo, Sri Lanka: International Water Management Institute (IWMI)

Muro, M., and Jeffrey, P. (2008). A critical review of the theory and application of social learning in participatory natural resource management processes. *Journal of environmental planning and management* 51, 325-344.

Nelson, G. C., Bennett, E., Berhe, A. A., Cassman, K., DeFries, R. S., Dietz, T., Dobermann, A., Dobson, A., Janetos, A., and Levy, M. A. (2006). Anthropogenic drivers of ecosystem change: an overview. *Ecology and Society* 11.

Neuman, L. W. (2011). "Social Research Methods: Qualitative and Quantitative Approaches (7th edition)," Pearson Education Inc., Boston, USA.

Niang, I., Ruppel, O. C., Abdrabo, M. A., Essel, A., Lennard, C., Padgham, J., and Urquhart, P. (2014). Africa. *In* "Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change" (V. R. Barros, C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White, eds.), pp. 1199-1265. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Niazi, A., Prasher, S. O., Adamowski, J., and Gleeson, T. P. (2014). A system dynamics model to conserve arid region water resources through aquifer storage and recovery in conjunction with a dam. *Water* 6, 2300-2321.

Norberg, J., and Cumming, G. S. (2008). "Complexity theory for a sustainable future," Columbia University Press.

Norgaard, R. (1994). "Development betrayed: The end of progress and a coevolutionary revisioning of the future," Routledge, London, UK.

Norgaard, R. B. (1989). The case for methodological pluralism. *Ecological Economics* 1, 37-57.

Norton, B. G. (2005). "Toward Unity among Environmentalists," Yale University Press., New Haven.

Nyankyi-Frimpong, H, and R. Bezner-Kerr. 2015. The relative importance of climate change in the context of multiple stressors in semi-arid Ghana. *Global Environmental Change* 32: 40-56.

Ochola, W. O., Sanginga, P. C., and Bekalo, I. (2011). "Managing Natural Resources for Development in Africa: A Resource Book," University of Nairobi Press, Nairobi, Kenya.

Oguntunde, P. G., Friesen, J., van de Giesen, N., and Savenije, H. H. G. (2006). Hydroclimatology of the Volta River Basin in West Africa: trends and variability from 1901 to 2002. *Physics and Chemistry of the Earth, Parts A/B/C* 31, 1180-1188.

Oldfield, F., Barnosky, A. D., Dearing, J., Fischer-Kowalski, M., McNeill, J., Steffen, W., and Zalasiewicz, J. (2014). The Anthropocene Review: Its significance, implications and the rationale for a new transdisciplinary journal. *The Anthropocene Review* 1, 3-7.

O'Leary, R. A., Choy, S. L., Murray, J. V., Kynn, M., Denham, R., Martin, T. G., and Mengersen, K. (2009). Comparison of three expert elicitation methods for logistic regression on predicting the presence of the threatened brush tailed rock wallaby Petrogale penicillata. *Environmetrics* 20, 379-398.

O'Leary, Z. (2004). "The essential guide to doing research," Sage, London.

Olson, J. M., Alagarswamy, G., Andresen, J. A., Campbell, D. J., Davis, A. Y., Ge, J., Huebner, M., Lofgren, B. M., Lusch, D. P., and Moore, N. J. (2008). Integrating diverse methods to understand climate–land interactions in East Africa. *Geoforum* 39, 898-911.

Olsson, J. A., and Andersson, L. (2007). Possibilities and problems with the use of models as a communication tool in water resource management. *In* "Integrated Assessment ofWater Resources and Global Change. A North-South Analysis" (E. CRASWELL, M. BONNELL, D. BOSSIO, S. DEMUTH and N. V. D. GIESEN, eds.). Springer, The Netherlands.

Onwuegbuzie, A. J., and Leech, N. L. (2005). On becoming a pragmatic researcher: The importance of combining quantitative and qualitative research methodologies. *International Journal of Social Research Methodology* 8, 375-387.

Oreskes, N., Shrader-Frechette, K., and Belitz, K. (1994). Verification, validation, and confirmation of numerical models in the earth sciences. *Science* 263, 641-646.

Ostrom, E. (2007). Sustainable Social-Ecological Systems: An Impossibility? *In* "Workshop in Political Theory and Policy Analysis", Indiana University.

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science* 325, 419-422.

Page, T., Heathwaite, A., Thompson, L., Pope, L., and Willows, R. (2012). Eliciting fuzzy distributions from experts for ranking conceptual risk model components. *Environmental Modelling & Software* 36, 19-34.

Pahl-Wostl, C. (1995). "The dynamic nature of ecosystems: chaos and order entwined," England: John Wiley & Sons Ltd.

Pahl-Wostl, C. (2007). The implications of complexity for integrated resources management. *Environmental Modelling & Software* 22, 561-569.

Pahl-Wostl, C., Arthington, A., Bogardi, J., Bunn, S. E., Hoff, H., Lebel, L., Nikitina, E., Palmer, M., Poff, L. N., and Richards, K. (2013). Environmental flows and water governance: managing sustainable water uses. *Current Opinion in Environmental Sustainability* 5, 341-351.

Pahl-Wostl, C., Giupponi, C., Richards, K., Binder, C., de Sherbinin, A., Sprinz, D., Toonen, T., and van Bers, C. (2013). Transition towards a new global change science: Requirements for methodologies, methods, data and knowledge. *Environmental Science & Policy* 28, 36-47.

Pahl-Wostl, C., Jeffrey, P., Isendahl, N., and Brugnach, M. (2011). Maturing the new water management paradigm: progressing from aspiration to practice. *Water resources management* 25, 837-856.

Pahl-Wostl, C., Lebel, L., Knieper, C., and Nikitina, E. (2012). From applying panaceas to mastering complexity: toward adaptive water governance in river basins. *Environmental Science & Policy* 23, 24-34.

Paine, R. (2005). Foward. *In* "Ecological Paradigms Lost: Routes of Theory Change" (K. Cuddington and B. Beisner, eds.). Elsevier Academic Press, Burlington, USA.

Paine, R. T. (2002). Advances in ecological understanding: by Kuhnian revolution or conceptual evolution? *Ecology* 83, 1553-1559.

Passell, H. D., and Assembly, M. R. G. W. (2003). "Cooperative water resources modeling in the Middle Rio Grande Basin," Sandia National Laboratories. Available at: http://www.waterassembly.org/archives/Water-related%20Publications/Modeling%20SAND%20Report%20FINAL.pdf (Accessed July 17, 2015).

Patton, M. (2002). "Qualitative methods and evaluation (3rd ed.)," Thousand Oaks, CA: Sage.

Pendall, R., Foster, K. A., and Cowell, M. (2010). Resilience and regions: building understanding of the metaphor. *Cambridge Journal of Regions, Economy and Society* 3, 71-84.

Perera, A. H., C. A. Drew, and C. J. Johnson. (2012). Experts, expert knowledge, and their roles in landscape ecological applications. In Expert knowledge and its application in landscape, eds. A. H. Perera., C. A. Drew, and C. J. Johnson, pp.1-10. New York, NY: Springer.

Petschel-Held, G., Lasco, R., Bohensky, E., Domingos, T., Guhl, A. s., Lundberg, J., and Zurek, M. (2005). Drivers of Ecosystem Change. *In* "cosystems and human well-being : current state and trends : findings of the Condition and Trends Working Group of the Millennium Ecosystem Assessment" (R. Hassan, Robert, R. Scholes and A. Ash, eds.), Vol. 1. Island Press, Washington D.C.

Philips, D. (2003). "The truth of ecology: Nature, culture, and literature in America," Oxford University Press, Oxford, England.

Phillips, D. C. (1976). "Holistic thought in social science," Stanford University Press.

Phillips, J. D. (2004). Divergence, sensitivity, and nonequilibrium in ecosystems. *Geographical Analysis* 36, 369-383.

Pickett, S. T., Kolasa, J., and Jones, C. G. (2007). "Ecological understanding: the nature of theory and the theory of nature," Amsterdam: Elsevier Inc.

Polhill, J. G., Filatova, T., Schlüter, M., and Voinov, A. (2016). Modelling systemic change in coupled socio-environmental systems. *Environmental Modelling & Software* 75, 318-332.

Pollard, S., and Du Toit, D. (2008). Integrated water resource management in complex systems: How the catchment management strategies seek to achieve sustainability and equity in water resources in South Africa. *Water SA* 34, 671-679.

Pollard, S., and du Toit, D. (2011). Towards Adaptive Integrated Water Resources Management in Southern Africa: The Role of Self-organisation and Multi-scale Feedbacks for Learning and Responsiveness in the Letaba and Crocodile Catchments. *Water resources management*, 1-17.

Pollard, S., du Toit, D., Cousins, T., Kotze, D., Riddell, E., Davis, C., Addy, S., Chuma, E., and Mkhabela, B. (2009). SUSTAINABILITY INDICATORS IN COMMUNAL WETLANDS AND THEIR CATCHMENTS. WRC Report 2010 No.1709/1/10 pp.xvi + 129. Available at: https://www.cabdirect.org/cabdirect/abstract/20113259946 (Accessed 15 June 2012).

Popper, K. (1972). "Conjections and Refutations: the growth of scientific knowledge," Routledge and Keegan Paul, London.

Proust, K., and Newell, B. (2006). Catchment and community: Towards a management-focused dynamical study of the ACT water system. Vol. Actew Project WF-30038 Final Report. Australian National University/Actew Corporation, Camberra, Australia.

Qin, H.-P., Su, Q., and Khu, S.-T. (2011). An integrated model for water management in a rapidly urbanizing catchment. *Environmental Modelling & Software* 26, 1502-1514.

Rahmandad, H., and Sterman, J. D. (2012). Reporting guidelines for simulation-based research in social sciences. *System Dynamics Review* 28, 396-411.

Rammel, C., and Van Den Bergh, J. C. J. M. (2003). Evolutionary policies for sustainable development: adaptive flexibility and risk minimising. *Ecological Economics* 47, 121-133.

Rammel, C., Stagl, S., and Wilfing, H. (2007). Managing complex adaptive systems - A co-evolutionary perspective on natural resource management. *Ecological Economics* 63, 9-21.

Randers, J. (1980). Guidelines for Model Conceptualization. In Elements of the System Dynamics Method, ed. by J. Randers. Portland, OR: Productivity Press.

Randers, J. (2013). 2052–A Global Forecast for the Next Forty Years using a mix of models. *In* "Contribution to ISDC", Boston, Massachusetts.

Rapport, D. J., and Hildén, M. (2013). An evolving role for ecological indicators: From documenting, ecological conditions to monitoring drivers and policy responses. *Ecological Indicators* 28, 10-15.

Rapport, D., and Friend, A. (1979). "Towards a Comprehensive Framework for Environmental Statistics: A Stress-response Approach, 1979," Statistics Canada.

Ravetz, J. R. (2006). Post-normal science and the complexity of transitions towards sustainability. *Ecological Complexity* 3, 275-284.

Redman, C. L., Grove, J. M., and Kuby, L. H. (2004). Integrating social science into the long-term ecological research (LTER) network: social dimensions of ecological change and ecological dimensions of social change. *Ecosystems* 7, 161-171.

Reed, M. S., Dougill, A. J., and Baker, T. R. (2008). Participatory indicator development: what can ecologists and local communities learn from each other. *Ecological Applications* 18, 1253-1269.

Reed, M. S., Evely, A. C., Cundill, G., Fazey, I., Glass, J., Laing, A., Newig, J., Parrish, B., Prell, C., Raymond, C., and Stringer, L. C. (2010). What is Social Learning? *Ecology and Society* 15(4), pp. r1.

Reed, M. S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., Prell, C., Quinn, C. H., and Stringer, L. C. (2009). Who's in and why? A typology of stakeholder analysis methods for natural resource management. *Journal of Environmental Management* 90, 1933-1949.

Refsgaard, J. C., Van Der Sluijs, J. P., Højberg, A. L., and Vanrolleghem, P. A. (2007). Uncertainty in the environmental modelling process–a framework and guidance. *Environmental Modelling & Software* 22, 1543-1556.

Reice, S. R. (1994). Nonequilibrium determinants of biological community structure. *American Scientist* 82, 424-435.

Resilience Alliance (2010). Assessing Resilience in Social-Ecological Systems: Workbook for Practitioners (Revised Version 2.0). Available at: http://www.resalliance.org/3871.php (Accessed March 28, 2012)

Richardson, G. P. (1999). Reflections for the future of system dynamics. *Journal of the operational research society* 50, 440-449.

Richardson, G. P. (2011). Reflections on the foundations of system dynamics. *System Dynamics Review* 27, 219-243.

Richardson, G. P., and Pugh, A. (1981). Introduction to System Dynamics Modeling with DYNAMO. Productivity Press. (Now available from Pegasus Communications, Waltham, MA.), Cambridge, MA.

Richmond, B. (1993). Systems thinking: critical thinking skills for the 1990s and beyond. *System Dynamics Review* 9, 113-133.

Richmond, B. (1994). System Dynamics/systems thinking: Let's just get on with it. *In* "International Systems Dynamics Conference, Sterling, Scotland".

Richmond, B., and Peterson, S. (2001). "An introduction to systems thinking," High Performance Systems., Incorporated. Hanover, NH, USA.

Rittel, H. W., and Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy sciences* 4, 155-169.

Roberts, N., Andersen, D. F., Deal, R. M., Garet, M. S., and Shaffer, W. A. (1983). "Introduction to computer simulation: the system dynamics approach," Addison-Wesley Publishing Company.

Robinson, J., Brush, S., Douglas, I., Graeldel, T. E., Graetz, D., Hodge, W., and Liverman, D. (1994). Land-Use and Land-Cover Projections. *In* "Changes in Land Use and Land Cover: A Global Perspective, " (W. Meyer and B. Turner, eds.). Cambridge University Press., Cambridge, UK.

Robles-Morua, A., Halvorsen, K. E., Mayer, A. S., and Vivoni, E. R. (2014). Exploring the application of participatory modeling approaches in the Sonora River Basin, Mexico. *Environmental Modelling & Software* 52, 273-282.

Robson, C. (2011). "Real World Research (Third Edition)," John Wiley and Sons, Chichester, UK.

Röckmann, C., Ulrich, C., Dreyer, M., Bell, E., Borodzicz, E., Haapasaari, P., Hauge, K. H., Howell, D., Mäntyniemi, S., and Miller, D. (2012). The added value of participatory modelling in fisheries management–what has been learnt? *Marine Policy* 36, 1072-1085.

Rodela, R., Cundill, G., and Wals, A. E. J. (2012). An analysis of the methodological underpinnings of social learning research in natural resource management. *Ecological Economics* 77 6–26.

Rodgers, C., Paul L.G. Vlek, L. G. P., Eguavoen, I., and Arntz, C. (2007). GLOWA Volta Phase II completion report Center for Development Research, Bonn, Germany.

Rogers, K., Roux, D., and Biggs, H. (2000). Challenges for catchment management agencies: lessons from bureaucracies, business and resource management Rogers, Water SA, vol. 26(4), pp 505-511.

Roling, N. G., and Wagemakers, M. A. E. (2000). "Facilitating sustainable agriculture: participatory learning and adaptive management in times of environmental uncertainty," Cambridge University Press.

Roudier, P.; Durcharne, A.; Feyen, L. (2014). Climate change impacts on river discharge in West Africa: A review. *Hydrology and Earth System Sciences,* 18: 2789-2801.

Rounsvell, M.D.A, T.P Dawson, and P.A Harrison. 2010. A conceptual framework to assess the effects of environmental change on ecosystem services. *Biodiversity and Conservation* 19 (10):2823-2842.

Rousseau, D. (2014). Systems Philosophy and the Unity of Knowledge. *Systems Research and Behavioral Science* 31, 146-159.

Ruth, M., and Hannon, B. (2012). "Modeling Dynamic Economic Systems (Second Edition)," Springer Science+Business Media, LLC New York, USA.

Ruth, M., and Hannon, B., eds. (1997). "Modelling Dynamic Economic Systems." Springer New York, USA.

Ruth, M., and Pieper, F. (1994). Modeling spatial dynamics of sea-level rise in a coastal area. *System Dynamics Review* 10, 375-389.

Safavi, H. R., Golmohammadi, M. H., and Sandoval-Solis, S. (2015). Expert knowledge based modeling for integrated water resources planning and management in the Zayandehrud River Basin. *Journal of Hydrology* 528, 773-789.

Sahin, O., Stewart, R. A., and Porter, M. G. (2016). Water security through scarcity pricing and reverse osmosis: a system dynamics approach. *Journal of Cleaner Production* 88, 160-171.

Santhi, C., Arnold, J. G., Williams, J. R., Dugas, W. A., Srinivasan, R., and Hauck, L. M. (2001). validation of the swat model on a large RWER basin with point and nonpoint sources1. Wiley Online Library.

Sarantakos, S. (2005). "Social Research (third edition)," Third/Ed. Palgrave Macmillan, New York, USA.

Saravanan, V., McDonald, T., Mollinga, P. (2009). Critical review of Integrated Water Resources Management: Moving beyond polarised discourse. Natural Resources Forum 33, 76–86. http://dx.doi.10.1111/j.1477-8947.2009.01210.x.

Sayer, J. A., and Campbell, B. (2002). Research to integrate productivity enhancement, environmental protection, and human development. *Ecology and Society* 5.

Sayer, J., and Campbell, B. M. (2004). "The science of sustainable development: local livelihoods and the global environment," . Cambridge, Cambridge University Press.

Scheff, T. J., Phillips, B. S., and Kincaid, H. (2015). "Goffman unbound: A new paradigm for social science," Routledge.

Schimel, D., Hibbard, K., Costa, D., Cox, P., and van der Leeuw, S. (2015). Analysis, Integration and Modeling of the Earth System (AIMES): Advancing the post-disciplinary understanding of coupled human–environment dynamics in the Anthropocene. *Anthropocene* 12: 99–106.

Schlüter, M., Hinkel, J., Bots, P. W., and Arlinghaus, R. (2014). Application of the SES Framework for Model-based Analysis of the Dynamics of Social-Ecological Systems. *Ecology and Society* 19, 36.

Schlüter, M., McAllister, R. R. J., Arlinghaus, R., Bunnefeld, N., Eisenack, K., Hölker, F., Milner-Gulland, E. J., Müller, B., Nicholson, E., Quaas, M., and Stöven, M. (2012). New horizons for managing the environment: A review of coupled social-ecological systems modeling. *Natural Resource Modeling* 25, 219-272.

Schneider, U. A., Havlík, P., Schmid, E., Valin, H., Mosnier, A., Obersteiner, M., Böttcher, H., Skalský, R., Balkovič, J., and Sauer, T. (2011). Impacts of population growth, economic development, and technical change on global food production and consumption. *Agricultural Systems* 104, 204-215.

Scholten, L., Scheidegger, A., Reichert, P., and Maurer, M. (2013). Combining expert knowledge and local data for improved service life modeling of water supply networks. *Environmental Modelling & Software* 42, 1-16.

Scholz, R. W. (2011). "Environmental literacy in science and society: from knowledge to decisions," Cambridge University Press, Cambridge, UK.

Scholz, R., Binder, C. R., and Land, D. J. (2011). The HES Framework. In "Environmental literacy in science and society: from knowledge to decisions" (R. Scholz, ed.). Cambridge University Press, Cambridge, UK.

Schoon, M. L., and Cox, M. E. (2012). Understanding disturbances and responses in social-ecological systems. *Society & Natural Resources* 25, 141-155.

Schröter, D., Polsky, C., and Patt, A. G. (2005). Assessing vulnerabilities to the effects of global change: an eight step approach. *Mitigation and Adaptation Strategies for Global Change* 10, 573-595.

Schwandt, T. A. (2007). "The Sage dictionary of qualitative inquiry (3rd. Ed). ," Sage Publications, Incorporated.

Scoones, I. (1999). New ecology and the social sciences: What Prospects for a Fruitful Engagement? 28: 479-507.

Scoones, I. (2004). Climate Change and the Challenge of Non-equilibrium Thinking. *IDS Bulletin* 35, 114-119.

Sedlacko, M., Martinuzzi, A., Røpke, I., Videira, N., and Antunes, P. (2014). Participatory systems mapping for sustainable consumption: Discussion of a method promoting systemic insights. *Ecological Economics* 106, 33-43.

Seidl, R. (2015). A functional-dynamic reflection on participatory processes in modelling projects. *Ambio* 44, 750-765.

Senge, P. (1990). "The Fifth Discipline," Doubleday, New York.

Senge, P. M. (2006). "The Fifth Discipline: The art and practice of the learning organization" *Second edition*, Random House, New South Wales, Australia.

Senge, P., Smith, B., Schley, S., and Laur, J. (2008). " The necessary revolution," Doubleday, New York, USA.

Sevaldson, B. (2008). A System Approach to Design Learning. *Systemisches Denken und Integrales Entwerfen/System thinking and Integral Design*, 22-33.

Silberstein, R. (2006). Hydrological models are so good, do we still need data? *Environmental Modelling & Software* 21, 1340-1352.

Simonovic, S. P. (2002). World water dynamics: global modeling of water resources. *Journal of Environmental Management* 66, 249-267.

Simonovic, S. P. (2009). "Managing water resources: methods and tools for a systems approach," Earthscan James & James, London.

Simonovic, S. P., and Fahmy, H. (1999). A new modeling approach for water resources policy analysis. *Water resources research* 35, 295-304.

Simonovic, S. P., Fahmy, H., and El-Shorbagy, A. (1997). The use of object-oriented modeling for water resources planning in Egypt. *Water Resources Management* 11, 243-261.

Singh, B. K. (2010). Understanding Complexity: Reductionist or Holistic Approach? *Complexity* 16, 58-59.

Sivapalan, M. (2015). Debates—Perspectives on socio-hydrology: Changing water systems and the "tyranny of small problems"—Socio-hydrology. *Water Resources Research* 51, 4795-4805.

Smit, B., and Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. *Global environmental change* 16, 282-292.

Sood, A., Muthuwatta, L., and McCartney, M. (2013). A SWAT evaluation of the effect of climate change on the hydrology of the Volta River basin. *Water international* 38, 297-311.

Stave, K. (2010). Participatory system dynamics modeling for sustainable environmental management: Observations from four cases. *Sustainability* 2, 2762-2784.

Stave, K. (2015). System dynamics for environmental applications. *In* "Handbook of Research methods and Applications in Environmental Studies" (M. Ruth, ed.). Edward Elgar Publishing Limited, Cheltenham, UK.

Stave, K. A. (2003). A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. *Journal of Environmental Management* 67, 303-313.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., and de Wit, C. A. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science* 347, 1259855.

Steffen, W., Sanderson, A., Tyson, P., Jäger, J., Matson, P., Moore III, B., Oldfield, F., Richardson, K., Schellnhuber, H. J., Turner, B. L. I., and Wasson, R. J. (2005). "Global Change and the Earth System: A Planet Under Pressure," Springer Berlin Germany.

Sterling, S. (2003). System Thinking as the basis for paradigm shift in Education: Exploration in the context of sustainability, University of Bath, Bath, UK.

Sterman, J. D. (1984). Appropriate summary statistics for evaluating the historical fit of system dynamics models. *Dynamica* 10, 51-66.

Sterman, J. D. (2000). " Business dynamics: systems thinking and modeling for a complex world. ," Irwin McGraw-Hill, Boston, MA.

Sterman, J. D. (2002). All models are wrong: reflections on becoming a systems scientist. *System Dynamics Review* 18, 501-531.

Sterman, J. D. (2010). Does formal system dynamics training improve people's understanding of accumulation? *System Dynamics Review* 26, 316-334.

Sterman, J. D. (2012). Sustaining Sustainability: Creating a Systems Science in a Fragmented Academy and Polarized World. *In* "Sustainability Science: The Emerging Paradigm 21 and the Urban Environment, DOI 10.1007/978-1-4614-3188-6_2" (M. P. Weinstein and R. E. Turner, eds.). Springer Science+Business Media, LLC.

Sterman, J. D., and Sweeney, L. B. (2007). Understanding public complacency about climate change: Adults' mental models of climate change violate conservation of matter. *Climatic Change* 80, 213-238.

Stoorvogel, J., Antle, J. M., Crissman, C., and Bowen, W. (2004). The tradeoff analysis model: integrated bio-physical and economic modeling of agricultural production systems. *Agricultural Systems* 80, 43-66.

Sullivan, H. I. (2010). Unbalanced Nature, Unbounded Bodies, and Unlimited Technology: Ecocriticism and Karen Traviss' Wess' har Series. *Bulletin of Science, Technology & Society* 30, 274-284.

Sušnik, J., Vamvakeridou-Lyroudia, L. S., Savić, D. A., and Kapelan, Z. (2012). Integrated System Dynamics Modelling for water scarcity assessment: Case study of the Kairouan region. *Science of the total environment* 440, 290-306.

Swart, R. J., Raskin, P., and Robinson, J. (2005). The problem of the future: sustainability science and scenario analysis. *Global environmental change* 14, 137-146.

Sweeney, L. B., and Sterman, J. D. (2000). Bathtub dynamics: initial results of a systems thinking inventory. *System Dynamics Review* 16, 249-286.

Terrasson, I., Fisher, M.J.W., Andah, W., and Lemoalle, J. (2009). Yields and water productivity of rain-fed grain crops in the Volta basin, West Africa. *Water International* 34: 104-118.

Tesch, R. (1990). "Qualitative research: analysis types and software tools." Falmer Press, New York.

Thom, D., Seidl, R., Steyrer, G., Krehan, H. and Formayer, H. (2013). Slow and fast drivers of the natural disturbance regime in Central European forest ecosystems. *Forest Ecology and Management* 307: 293-302.

Thompson, J., and Scoones, I. (2009). Addressing the dynamics of agri-food systems: an emerging agenda for social science research. *Environmental Science & Policy* 12, 386-397.

Thompson, J., Millstone, E., Scoones, I., Ely, A., Marshall, F., Shah, E., Stagl, S., and Wilkinson, J. (2007). "Agri-food System Dynamics: pathways to sustainability in an era of uncertainty." STEPS Working Paper 4, Brighton: STEPS Centre.

Thompson, P. B. (2007). Agricultural sustainability: what it is and what it is not. *International Journal of Agricultural Sustainability* 5, 5-16.

Thwink (2015) Finding and resolving the root causes of sustainable problems. Available: http://www.thwink.org/index.htm [accessed on January 16, 2015]

Tidwell, V. C., Passell, H. D., Conrad, S. H., and Thomas, R. P. (2004). System dynamics modeling for community-based water planning: Application to the Middle Rio Grande. *Aquatic Sciences* 66, 357-372.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., and Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature* 418, 671-677.

Troyer, M. E. (2002). A spatial approach for integrating and analyzing indicators of ecological and human condition. *Ecological indicators* 2, 211-220.

Turner, B. L., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., Eckley, N., Hovelsrud-Broda, G. K., Kasperson, J. X., Kasperson, R. E., and Luers, A. (2003). Illustrating the coupled human–environment system for vulnerability analysis: three case studies. *Proceedings of the National Academy of Sciences* 100, 8080.

Turner, M. G., Romme, W. H., Gardner, R. H., O'Neill, R. V., and Kratz, T. K. (1993). A revised concept of landscape equilibrium: disturbance and stability on scaled landscapes. *Landscape ecology* 8, 213-227.

Turner, S.P. (2015). Internal and External Influences on Water Resource Decision Making. *Society & Natural Resources*:1-15. DOI: 10.1080/08941920.2015.1058996.

Tuuli, M. M. (2009). Empowerment and Control Dynamics in Project teams: a multilevel examination of antecedents and job perfoamnce quencequences, PhD thesis, The University of Hong Kong, PhD thesis.

Tzanopoulos, J., Mouttet, R., Letourneau, A., Vogiatzakis, I. N., Potts, S. G., Henle, K., Mathevet, R., and Marty, P. (2013). Scale sensitivity of drivers of environmental change across Europe. *Global environmental change* 23, 167-178.

UNEP (2002). Global Environment Facility-Volta River Basin Preliminary Transboundary Diagnostic Analysis. Final Report. *In* "A Programme of the Governments of the Volta River Countries, with the assistance of the Global Environment Facility (the United Nations Environment Programme)

UNEP (United Nations Environment Programme)-GEF (Global Environment Facility) Volta Project. (2013). Volta Basin transboundary diagnostic analysis. UNEP/GEF/Volta/RR 4/2013. Accra, Ghana: United Nations Environment Programme (UNEP).

Vallejo, R. (2009). Problems and Perspectives of Dryland Restoration. *In* "Land Restoration to Combat Desertification Innovative Approaches, Quality Control and Project Evaluation" (S. Bautista, J. Aronson and R. V. Vallejo, eds.), pp. 13-22. Fundación Centro de Estudios Ambientales del Mediterráneo – CEAM, Valencia, Spain.

Van Cauwenbergh, N., Biala, K., Bielders, C., Brouckaert, V., Franchois, L., Garcia Cidad, V., Hermy, M., Mathijs, E., Muys, B., and Reijnders, J. (2007). SAFE—A hierarchical framework for assessing the sustainability of agricultural systems. *Agriculture, ecosystems & environment* 120, 229-242.

Van de Giesen, N.; Andreini, M.; van Edig, A.; Vlek, P. (2001). Competition for water resources of the Volta Basin. In: Regional management of water resources, proceedings of a symposium held during the sixth IAHS scientific assembly at Maastricht, the Netherlands, July 2001. Wallingford, UK: IAHS Publication 268: 199-205.

Van den Belt, M. (2004). "Mediated modeling: a system dynamics approach to environmental consensus building," Island Press, Washington DC, USA.

van den Belt, M., Kenyan, J. R., Krueger, E., Maynard, A., Roy, M. G., and Raphael, I. (2010). Public sector administration of ecological economics systems using mediated modeling. *Annals of the New York Academy of Sciences* 1185, 196-210.

van Vliet, Nathalie, Ole Mertz, Andreas Heinimann, Tobias Langanke, Unai Pascual, Birgit Schmook, Cristina Adams, Dietrich Schmidt-Vogt, Peter Messerli, and Stephen Leisz. 2012. Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers: A global assessment. *Global environmental change* 22 (2):418-429.

Vennix, J. A. M. (1996). "Group model building: Facilitating team learning using system dynamics," Chichester: John Wiley & Sons, Ltd.

Vennix, J. A. M. (1999). Group model-building: tackling messy problems. *System Dynamics Review* 15, 379-401.

Venot, J.P, Andreini, M, and Pinkstaff, C. B. (2011). Planning and corrupting water resources development: The case of small reservoirs in Ghana. *Water Alternatives* 4, 399.

Ventana Systems Inc. (2014). Vensim Ventana Systems Inc. Vol. 2014.

Videira, N., Antunes, P., and Santos, R. (2009). Scoping river basin management issues with participatory modelling: The Baixo Guadiana experience. *Ecological Economics* 68, 965-978.

Videira, N., Antunes, P., Santos, R., and Gamito, S. (2003). Participatory modelling in environmental decision-making: the ria Formosa natural park case study. *Journal of environmental assessment policy and management* 5, 421-447.

Videira, N., Antunes, P., Santos, R., and Lopes, R. (2010). A participatory modelling approach to support integrated sustainability assessment processes. *Systems Research and Behavioral Science* 27, 446-460.

Videira, N., Lopes, R., Antunes, P., Santos, R., and Casanova, J. L. (2012). Mapping maritime sustainability issues with stakeholder groups. *Systems Research and Behavioral Science* 29, 596-619.

Videira, N., Schneider, F., Sekulova, F., and Kallis, G. (2014). Improving understanding on degrowth pathways: An exploratory study using collaborative causal models. *Futures* 55, 58-77.

Videira, N., van den Belt, M., Antunes, R., and Santos, R. (2011). Integrated Modeling of Coastal and Estuarine Ecosystem Services. *2011 Elsevier Inc*.

Voinov, A. (2008). "System Science and Modelling for Ecological Economics (Firth Edition)," Elsevier Inc. , London, UK.

Voinov, A., and Bousquet, F. (2010). Modelling with stakeholders. *Environmental Modelling & Software* 25, 1268-1281.

Voinov, A., and Gaddis, E. J. B. (2008). Lessons for successful participatory watershed modeling: a perspective from modeling practitioners. *Ecological modelling* 216, 197-207.

Voinov, A., Kolagani, N., McCall, M. K., Glynn, P. D., Kragt, M. E., Ostermann, F. O., Pierce, S. A., and Ramu, P. (2016). Modelling with stakeholders–Next generation. *Environmental Modelling & Software* **77**, 196-220.

Voinov, A., Seppelt, R., Reis, S., Nabel, J. E., and Shokravi, S. (2014). Values in socio-environmental modelling: Persuasion for action or excuse for inaction. *Environmental Modelling & Software* 53, 207-212.

Von Bertalanffy, L. (1969). "General system theory: Foundations, development, applications," Braziller, NewYork.

Von Wirén-Lehr, S. (2001). Sustainability in agriculture--an evaluation of principal goal-oriented concepts to close the gap between theory and practice. *Agriculture, ecosystems & environment* 84, 115-129.

Wagner, S., Kunstmann, H., and Bárdossy, A. (2006). Model based distributed water balance monitoring of the White Volta catchment in West Africa through coupled meteorological-hydrological simulations. *Advances in Geosciences* 9, 39-44.

Walker, B. (2005). A Resilience Approach to Integrated Assessment. *The Integrated Assessment Journal* 5 77–97.

Walker, B. H., and Salt, D. A. (2006). "Resilience thinking: sustaining ecosystems and people in a changing world," Washington D.C: Island Press.

Walker, B. H., Carpenter, S. R., Rockstrom, J., Crépin, A. S., and Peterson, G. D. (2012). Drivers," Slow" Variables," Fast" Variables, Shocks, and Resilience. *Ecology and Society* 17, 30.

Walker, B., Carpenter, S., Anderies, J., Abel1b, N., Cumming, G., Janssen, M., Lebel, L., Norberg, J., Peterson, G. D., and Pritchard, R. (2002). Resilience management in social-ecological systems: a working hypothesis for a participatory approach. *Conservation Ecology* 6, 14.

Walker, B., Gunderson, L., Kinzig, A., Folke, C., Carpenter, S., and Schultz, L. (2006). A handful of heuristics and some propositions for understanding resilience in social-ecological systems. *Ecology and Society* 11, 13.

Walker, L. R. (1999). "Ecosystems of disturbed ground," Elsevier Science. Amsterdam, The Nethelands

Walker, W.E., Harramoes, P., Rotmans, J., van der Sluijs, J.P., van Asselt, M.B.A., Janssen, P., Krayer von Krauss, M.P., 2003. Defining uncertainty. A conceptual basis for uncertainty management in model-based decision support. *Integrated Assessment* 4, 5-17.

Wang, X.-j., Zhang, J.Y, Liu, J.F., Wang, G.Q., He, R.M., Elmahdi, A., and Elsawah, S. (2011). Water Resources Planning and Management Based on System Dynamics: A Case Study of Yulin City. *Environment, development and sustainability* 13, 331-351.

Water Resources Group (2009). Charting Our Water Future: Economic frameworks to inform decision-making. 2030 Water Resource Group, Melbourn, Australia.

Weil, H. B. (1980). The Evolution of an Approach for Achieving Implemented Results from System Dynamics Projects. *In* "Elements of the system dynamics method" (J. Randers, ed.). MIT Press, Cambridge, MA.

Welsh, W. D., Vaze, J., Dutta, D., Rassam, D., Rahman, J. M., Jolly, I. D., Wallbrink, P., Podger, G. M., Bethune, M., and Hardy, M. J. (2013). An integrated modelling framework for regulated river systems. *Environmental Modelling & Software* 39, 81-102.

Widlok, T., Aufgebauer, A., Bradtmöller, M., Dikau, R., Hoffmann, T., Kretschmer, I., Panagiotopoulos, K., Pastoors, A., Peters, R., and Schäbitz, F. (2012). Towards a theoretical framework for analyzing integrated socio-environmental systems. *Quaternary International*. 274, 259–272.

Williams, D. R., and Patterson, M. E. (2007). Snapshots of what, exactly? A comment on methodological experimentation and conceptual foundations in place research. *Society and Natural Resources* 20, 931-937.

Williams, L. R. T. (2008). Matauranga and mainstream knowledge working together. *In* "Paper presented at Whakanuia Te Wiki o Te Reo (Celebration of Māori language week), Division of Sciences", University of Otago, Dunedin, New Zealand, 21-28 July.

Williams, T. O., Smakhtin, V., Biney, A. C., and Mul, L. M. (2016). "The Volta River Basin: Water for Food, Economic Growth and Environment " Routledge, Earthscan Series on Major River Basins of the World.

Wilson, G., and Bryant, R. L. (1997). "Environmental Management: New Directions for the twenty-first century," Routledge, London, UK.

Winz, I., Brierley, G., and Trowsdale, S. (2009). The use of system dynamics simulation in water resources management. *Water resources management* 23, 1301-1323.

Wolcott, H.F. (2001). "Writing up qualitative research (2nd.edn.). Sage Poblication, California, USA

Wolstenholme, E. F. (1990). "System enquiry: a system dynamics approach," John Wiley & Sons, Inc. New York, NY, USA.

Wolstenholme, E. F. (1999). Qualitative vs quantitative modelling: the evolving balance. *Journal of the Operational Research Society*, 422-428.

World Bank (2010). "World Bank (2010). Economics of Adaptation to Climate Change synthesis report Ghana," The World Bank, Washington, DC.

World Bank. (2007). World Development Report 2008. Agriculture for Development. The World Bank, Washington, DC. 386 p.

Worster, D. (1993). "The Wealth of Nature: Environmental History and the Ecological Imagination," Oxford University Press, Oxford, UK.

Wu, G., Li, L., Ahmad, S., Chen, X., and Pan, X. (2013). A dynamic model for vulnerability assessment of regional water resources in arid areas: a case study of Bayingolin, China. *Water Resources Management* 27, 3085-3101.

Wu, J. (2013). Landscape sustainability science: ecosystem services and human well-being in changing landscapes. *Landscape ecology* 28, 999-1023.

Xu, Z., Takeuchi, K., Ishidaira, H., and Zhang, X. (2002). Sustainability analysis for Yellow River water resources using the system dynamics approach. *Water resources management* 16, 239-261.

Yohe, G., and R.S.J. Tol. 2002. Indicators for social and economic coping capacity—moving toward a working definition of adaptive capacity. *Global environmental change* 12 (1): 25–40.

Youkhana, E., and Laube, W. (2006). "Cultural, Socio-Economic and Political Constraints for Virtual Water Trade: Perspectives from the Volta Basin, West Africa." Center for Development Research, Department of Political and Cultural Change Research Group, Bonn, Germany.

Young, O. R., and Steffen, W. (2009). The Earth System: Sustaining planetary life-support systems. *In* "Principles of Ecosystem Stewardship: Resilience Base Natural Resource Management in a Changing World" (F. S. Chapin, P. G. Kofinas and C. Folke, eds.), pp. 295-315. Springer, New York.

Young, O. R., Lambin, E. F., Alcock, F., Haberl, H., Karlsson, S. I., McConnell, W. J., Myint, T., Pahl-Wostl, C., Polsky, C., and Ramakrishnan, P. (2006). A portfolio approach to analyzing complex human-environment interactions: institutions and land change. *Ecology and Society* 11, 31.

Yunlong, C., and Smit, B. (1994). Sustainability in agriculture: a general review. *Agriculture, ecosystems & environment* 49, 299-307.

Ziegler, R., and Ott, K. (2011). The quality of sustainability science: a philosophical perspective. *Millennium consumption goals: a fair proposal from the poor to the rich* 7, 31. Available at: https://sspp.proquest.com/the-quality-of-sustainability-science-a-philosophical-perspective-32d0fc1b7573 (Accessed March 1, 2012).

APPENDIX 1: Expert Survey and Interview Questionnaire

Project Title: An Application of Systems Thinking and Dynamic Modelling Approach to Support Strategic Decision Making and Sustainable Water Resources Management in the Volta River Basin, West Africa

Interview Date _____Time _____

Informant ID number or name if interview is willing to give) ____

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SECTION A

PROFILE OF KEY EXPERTS

</div>

Please give us a little background information about yourself and the work you do.

A1   Gender (*tick one*)

              □ Male
              □ Female

A2   How old are?_____

A3   Your highest academic qualification is (for technical experts only):
              □ Diploma
              □ Bachelors degree
              □ Masters degree
              □ PhD Degree
              □ Other (please specify)_____

A3   What is your field/area of specialisation?_____

A4   Your current job title_____

A5   Which institution/organization do you currently work for?_____

A6   How long have you been working in your current organization?_____

A7   How long have you been working/doing research in the Volta River Basin?_____Years

<div align="center">

SECTION B

</div>

I am now going to ask you some questions about the key biophysical/environmental, socioeconomic and policy and institutional drivers that underpin agricultural production and sustainability in the Volta River Basin

B1   *Think about the <u>BIOPHYSICAL/ENVIRONMENTAL AND SOCIO-ECONOMIC DRIVERS OF CHANGE</u> within the Volta River Basin (**1 being very important, 2 being important, 3 being less important and 4 being not at all important**), how <u>IMPORTANT</u> do you think the following factors are in terms of driving change and influencing water resource management and agricultural production within the basin?*

Environmental & Biophysical Drivers

Driver of Change/Rating Scale	1	2	3	4	If possible, please give reason for your rating
Biodiversity loss (V_S)					
Change in cropping pattern (V_S)					
Change in length of growing season (V_S)					
Change in temperature (V_S)					
Crop yield growth (V_S)					
Deforestation (V_S)					
Droughts-intensity & duration (V_F)					
Floods-intensity & duration (V_F)					
Ground & surface water availability (V_S)					
Land productivity (V_S)					
Land use/cover change (V_S)					
Land/soil degradation (V_S)					
Pest & disease occurrence (V_F)					
Precipitation variability (V_F)					
Pollution (V_S)					
Soil erosion (V_s)					
Soil fertility (V_S)					
Use of fertilizer (V_S)					
Please add any biophysical/environmental other driver(s) of change you think is (are) important but are not on this list					

Economic & Technological Drivers

Driver of Change/Rating Scale	1	2	3	4	If possible, please give reason for your rating
Access to financial credit(V_F)					
Agricultural intensification (V_S)					
Agricultural market access (V_S)					
Availability of arable land (V_S)					
Availability of off-farm employment (V_S)					
Change in consumption patterns (V_S)					
Change in farm size/structure (V_S)					
Cost of inputs (V_F)					
Household income growth (V_S)					
Infrastructure conditions (V_S)					
Innovation & technological change (V_S)					
Labour availability (V_S)					
Livelihood & income diversification (V_S)					
Small-scale mining (V_S)					
Please add any biophysical/environmental other driver(s) of change you think is (are) important but are not on this list					

Socio-demographic Drivers

Driver of Change/Rating Scale	1	2	3	4	If possible, please give reason for your rating
Access to health care (V_S)					
Change in age structure (V_S)					
Change in fertility (V_S)					
Change in mortality (V_S)					
Change in traditional values & practices(V_S)					
Education level (V_S)					

Driver of Change	1	2	3	4	
In/out migration (V$_F$)					
Inequality (e.g., gender, age, class) (V$_S$)					
Land Abandonment (V$_F$)					
Population density (V$_S$)					
Population growth (V$_S$)					
Poverty level (V$_S$)					
Social Conflicts (V$_F$)					
Urbanisation (V$_S$)					
Please add any biophysical/environmental other driver(s) of change you think is (are) important but are not on this list					

Policy & Institutional Drivers

Driver of Change/Rating Scale	1	2	3	4	If possible, please give reason for your rating
Policy & institutional Drivers					
Availability of extension services(V$_S$)					
Availability of funds for investments (V$_F$)					
Level of investment (V$_S$)					
Production subsidies (V$_F$)					
Property rights issues (V$_S$)					
Please add any biophysical/environmental other driver(s) of change you think is (are) important but are not on this list					

SECTION C

I will also like to know your view and observation concerning the impacts of the drivers of change we just talked about, and what you thinking the future will play out in the context of changing socio-economic and environmental conditions in the Volta River Basin.

C1   What specific types of **POLICIES OR STRATEGIES** do you think could assist the people in responding to this [these] changes?

C2   Who else should I speak to?--

C3   What are the key documents I should read?

C4   Given all we have discussed so far, is there anything else that you would like to add, remember your comments are completely confidential.

Thank you for your time. Your comments have been insightful and will be used to inform more proactive community planning. If you would like to receive information about the results of this research, please provide me with an e-mail or contact number or address where you can be reached. Thank you again for your time and comments.

*TOTAL DURATION OF INTERVIEW*_____

Thank you very much for taking part in this survey/interview

APPENDIX 2: Questionnaire: <u>Participatory Modelling Workshop Evaluation</u>

Project Title: An Application of Systems Thinking and Dynamic Modelling Approach to Support Strategic Decision Making and Sustainable Water Resources Management in the Volta River Basin, West Africa

We would like to know the extent to which this workshop has met your expectations. Summary information of your responses will be important in our analysis of the research information. Please fill in your response circles completely using either a pen or pencil and return this evaluation to the person designated to collect them in your group. Thanks

This study adheres to the Guidelines of the ethical review process of The University of Queensland. Whilst you are free to discuss your participation in this study with project staff (contactable on **+61404650811** or j.kotir@uq.edu.au), if you would like to speak to an officer of the University not involved in the study, you may contact Dr Annie Ross, the Ethics Officer on **+61 3365 1450; or +61 3365 6084**; or annie.ross@uq.edu.au.

For further enquiries, my contact details are:
Email: j.kotir@uq.edu.au
Phone number: +61404650811

PART A: BACKGROUND AND DEMOGRAPHIC INFORMATION (please tick √ the appropriate box):

PART A

A1   Organisational affiliation:
      □ Government institutions
      □ NGO and civil society
      □ Research and academic institutions
      □ Private and consulting firms
      □ Local farmer group
      □ Tertiary Education
        Other (please specify)_____

PART B: STAKEHOLDER PERCEPTION ABOUT THE PARTICIPATORY MODELLING WORKSHOP /PROCESS

B1. To what extend do you agree or disagree (*1 being "**Agree**", 2 being "**disagree**", 3 being "**No Answer**"*) with each of the following statements regarding your opinion about this participatory modelling workshop you participated in?

Evaluation of the Modelling Process

Item no.	Statement/evaluation item	Scale		
1	My interest/views/ideas have been included in the model	1	2	3
2	The modelling process/workshop was open and transparent	1	2	3
3	Other stakeholders brought fresh ideas into the modelling process	1	2	3
4	The process has helped me to learn and improve my understanding of the basin's problems and their interrelationships	1	2	3
5	Participatory modelling process is a good method for planning and management	1	2	3
6	The process has helped me to understand other participants mental model	1	2	3
7	The modelling tools/software (i.e.,Vensim & Stella) were easy to learn and implement	1	2	3
8	The process has helped me to understand other participants mental model	1	2	3
9	The model building process has been useful to me	1	2	3
10	I will participate in future participatory modelling exercise/workshop	1	2	3

Evaluation of the Model Outputs

Item no.	Statement/evaluation item	Scale		
1	Visual representation of the basin's problems helps my understanding about how the system functions	1	2	3
2	The developed model is valid and represent the true structure of the Volta River Basin	1	2	3
3	The CLD and the simulation models are important system tools to represent and simplify complex environmental issues	1	2	3
4	The developed CLD and simulaion models are comprehensive and easy to understand	1	2	3
5	The developed simulation model can be used as a decision-making tool	1	2	3

Please provide, any relevant comment you have have regarding the modelling process and the outputs produced. confidential.

Thank you very much for taking part in this Participatory Modelling Workshop

APPENDIX 3: Detailed Stella Equations

Adult_Population(t) = Adult_Population(t - dt) + (Immigration + Maturation - Deaths - Emmigratoin) * dt
INIT Adult_Population = 6900368 * 0.70
INFLOWS:
Immigration = Adult_Population*actual_immgration_rate
Maturation = Children_population/maturation_delay
OUTFLOWS:
Deaths = Adult_Population*actual_death_rate
Emmigratoin = Adult_Population*emmigration_rate
Available__surface_water(t) = Available__surface_water(t - dt) + (Actual_surface_water_inflow + Run_off - Surface_water_withdrawal - Spill - Evaporation) * dt
INIT Available__surface_water = 37900000000
INFLOWS:
Actual_surface_water_inflow = Normal_surface_water_inflow*Effect_of_rainfall_on_surface_water_inflow
Run_off = Actual_precipitation*Actual_rainfall_runoff_ratio*Faction_of_runoff_to_reservoir
OUTFLOWS:
Surface_water_withdrawal = if Available__surface_water < (Domestic_water_demand+Agricultural_water_demand+Industrial_water_demand) then (Available__surface_water + Actual_surface_water_inflow) else (Domestic_water_demand+Agricultural_water_demand+Industrial_water_demand)
Spill = (Available__surface_water+net_flow)-Reservoir_storage_capacity
Evaporation = Available__surface_water*Evaporation_rate
Children_population(t) = Children_population(t - dt) + (Births - Maturation - Infant_deaths) * dt
INIT Children_population = 6900368 * 0.30
INFLOWS:
Births = Adult_Population*actual_birth_rate
OUTFLOWS:
Maturation = Children_population/maturation_delay
Infant_deaths = Children_population*actual_death_rate
Cropland_Area(t) = Cropland_Area(t - dt) + (Change_in_cropland_area) * dt
INIT Cropland_Area = 1306631
INFLOWS:
Change_in_cropland_area = if Required_minus_actual_cropland_area>Total_arable_land_minus_cropland_area then (Total_arable_land_minus_cropland_area/Delay_in_cropland_area_change) else (Required_minus_actual_cropland_area/Delay_in_cropland_area_change)
Crop_Yield(t) = Crop_Yield(t - dt) + (change_in_crop_yield) * dt
INIT Crop_Yield = 1309.3 {kg/ha}
INFLOWS:
change_in_crop_yield = suggested_minus_actual_crop_yield/delay_in_crop_yield_change
Actual_agricultural_water_demand_per_ha = Inital_agricultural_water_demand_per_ha*Effect_of_water_availability_on_agricultural_water_demand_per_ha
Actual_average_domestic_water_demand_per_capita = Inital_average_domestic_water_demand_per_capita*Effect_of_water_availability_on_domestic_water_demand
Actual_average_industrial_water_demand_per_capita = Inital_average_industrial_water_demand_per_capita*Effect_of_water_availability_on_industrial_water_demand
Actual_birth_rate = inital_birth_rate*(Effect_of_food_available_on_birth_rate)
Actual_death_rate = initial_death_rate*(effect_of_food_available_on_death_rate)
Actual_food_available_per_person = Food_available/Total_population
Actual_immgration_rate = inital_immigration_rate*effect_of_food_on_immigration_rate
Actual_outside_of_Ghana_precipitation = Normal_outside_of_Ghana_precipiation * (1-Percent_drop_in_precipitation)
Actual_precipitation = Normal_precipitation * (1-Percent_drop_in_precipitation)
Actual_rainfall_runoff_ratio = Normal_rainfall_runoff_ratio*Effect_of_rainfall_on_runoff
Agricultural_water_demand = Cropland_Area*Actual_agricultural_water_demand_per_ha {565000000}
Average_food_consumed_per_capita = 423 {kg/year}
Cost_per_ha = 2.44 {GHC}
Crop_price = 1.5{$}
Delay_in_cropland_area_change = 5
Delay_in_crop_yield_change = 1
Domestic_water_demand = total_population*Actual_average_domestic_water_demand_per_capita
effect_of_agricultural_water_demand_on_crop_yield = GRAPH(Actual_agricultural_water_demand_per_ha/Inital_agricultural_water_demand_per_ha)

(0.00, 0.00), (0.2, 0.202), (0.4, 0.397), (0.6, 0.593), (0.8, 0.795), (1.00, 1.00), (1.20, 1.20), (1.40, 1.34), (1.60, 1.38), (1.80, 1.39), (2.00, 1.39)

Effect_of_food_available_on_birth_rate = GRAPH(Actual_food_available_per_person/Initial_food_available_per_person)
(0.00, 0.00), (0.2, 0.509), (0.4, 0.749), (0.6, 0.899), (0.8, 0.974), (1.00, 1.00), (1.20, 1.00), (1.40, 1.00), (1.60, 1.00), (1.80, 1.00), (2.00, 1.00)

Effect_of_food_available_on_death_rate = GRAPH(Actual_food_available_per_person/Initial_food_available_per_person)
(0.00, 50.0), (0.2, 10.5), (0.4, 3.56), (0.6, 1.65), (0.8, 1.12), (1.00, 1.00), (1.20, 1.00), (1.40, 1.00), (1.60, 1.00), (1.80, 1.00), (2.00, 1.00)

Effect_of_food_on_emmigration_rate = GRAPH(Actual_food_available_per_person/Initial_food_available_per_person)
(0.00, 50.0), (0.2, 10.3), (0.4, 3.56), (0.6, 1.87), (0.8, 1.05), (1.00, 1.00), (1.20, 0.984), (1.40, 0.946), (1.60, 0.902), (1.80, 0.729), (2.00, 0.202)

Effect_of_food_on_immigration_rate = GRAPH(Actual_food_available_per_person/Initial_food_available_per_person)
(0.00, 0.00), (0.2, 0.423), (0.4, 0.764), (0.6, 0.909), (0.8, 0.965), (1.00, 1.00), (1.20, 1.06), (1.40, 1.14), (1.60, 1.26), (1.80, 1.43), (2.00, 1.59)

Effect_of_labour_on_crop_yield = GRAPH(labour/inital_labour)
(0.00, 0.505), (0.2, 0.696), (0.4, 0.8), (0.6, 0.867), (0.8, 0.874), (1.00, 1.01), (1.20, 1.04), (1.40, 1.07), (1.60, 1.14), (1.80, 1.14), (2.00, 1.14)

Effect_of_rainfall_on_runoff = GRAPH(Actual_precipitation/Normal_precipitation)
(0.00, 0.007), (0.2, 0.007), (0.4, 0.037), (0.6, 0.202), (0.8, 0.419), (1.00, 1.00), (1.20, 1.21), (1.40, 1.36), (1.60, 1.40), (1.80, 1.40), (2.00, 1.40)

Effect_of_rainfall_on_surface_water_inflow = GRAPH(Actual_outside_of_Ghana_precipitation/Normal_outside_of_Ghana_precipiation)
(0.00, 0.00), (0.2, 0.00), (0.4, 0.045), (0.6, 0.21), (0.8, 0.412), (1.00, 1.00), (1.20, 1.21), (1.40, 1.36), (1.60, 1.40), (1.80, 1.40), (2.00, 1.40)

Effect_of_water_availability_on_agricultural_water_demand_per_ha = GRAPH(Available__surface_water/initial_surface_water)
(0.00, 0.00), (0.2, 0.202), (0.4, 0.412), (0.6, 0.607), (0.8, 0.809), (1.00, 1.00), (1.20, 1.15), (1.40, 1.26), (1.60, 1.34), (1.80, 1.39), (2.00, 1.40)

Effect_of_water_availability_on_domestic_water_demand = GRAPH(Available__surface_water/initial_surface_water)
(0.00, 0.00), (0.2, 0.514), (0.4, 0.754), (0.6, 0.871), (0.8, 0.965), (1.00, 1.00), (1.20, 1.03), (1.40, 1.10), (1.60, 1.24), (1.80, 1.42), (2.00, 1.61)

Effect_of_water_availability_on_industrial_water_demand = GRAPH(Available__surface_water/initial_surface_water)
(0.00, 0.00), (0.2, 0.514), (0.4, 0.754), (0.6, 0.871), (0.8, 0.965), (1.00, 1.00), (1.20, 1.03), (1.40, 1.10), (1.60, 1.24), (1.80, 1.42), (2.00, 1.61)

Emmigration_rate = inital_emmigration_rate*effect_of_food_on_emmigration_rate
Evaporation_rate = 0.1
Faction_of_runoff_to_reservoir = 0.5
Food_available = Cropland_Area*Crop_Yield
Food_consumption = total_population*average_food_consumed_per_capita
Industrial_water_demand = total_population*Actual_average_industrial_water_demand_per_capita
Inital_agricultural_water_demand_per_ha = 565000000/1306631 {water/ha}
Inital_average_domestic_water_demand_per_capita = 235000000/6674376
Inital_average_industrial_water_demand_per_capita = 95000000/6674376
Inital_birth_rate = 41.87/1000
Inital_emmigration_rate = 3/1000
Inital_immigration_rate = 12/1000
Inital_labour = 6900368 * 0.60
Initial_death_rate = 8.10/1000
Initial_food_available_per_person = 248 {423 {kg/yr}
Initial_surface_water = 37900000000
Intal_crop_yield = 1814.3 {kg/ha}
Labour = Adult_Population*proportion_of_population_that_is_labour
Maturation_delay = 16
Net_farm_income = (Crop_Yield*crop_price)-cost_per_ha
Net_flow = (Run_off+Actual_surface_water_inflow)-(Surface_water_withdrawal+Evaporation)
Net_growth_rate = (actual_birth_rate+actual_immgration_rate)-(actual_death_rate+emmigration_rate)
Normal_outside_of_Ghana_precipiation = 1
Normal_precipitation = 500000000000
Normal_rainfall_runoff_ratio = 0.08

Normal_surface_water_inflow = 25900000000

Percent_drop_in_precipitation = 0 + STEP(0.1, 2000)

Proportion_of_population_that_is_labour = 0.6

Required_cropland_area = food_consumption/max(Crop_Yield, 0.0001)

Required_minus_actual_cropland_area = Required_cropland_area-Cropland_Area

Reservoir_storage_capacity = 150000000000

Suggested_crop_yield = Intal_crop_yield * min(effect_of_agricultural_water_demand_on_crop_yield, effect_of_labour_on_crop_yield)

Suggested_minus_actual_crop_yield = suggested_crop_yield-Crop_Yield

Total_arable_land = 1306631*1.25

Total_arable_land_minus_cropland_area = Total_arable_land-Cropland_Area

Total_population = Children_population+Adult_Population