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A system dynamics simulation model for sustainable water resources management and agricultural development in the Volta River Basin, Ghana

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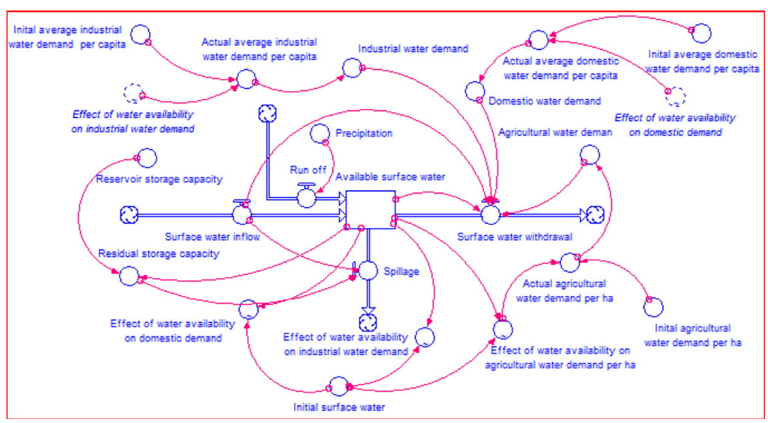
HIGHLIGHTS

- Management of water resources often overlooks feedback processes between key system components.
- Biophysical and socio-economic processes coupled and simulated using system dynamics approach.
- The importance of scenario analysis for long-term sustainable management is demonstrated.
- Population growth and various water demands will continue to increase.
- Development of water infrastructure more important than cropland expansion.

GRAPHICAL ABSTRACT



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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

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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.

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 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, and 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., 2015a), 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 management systems 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., 2015b; Sivapalan, 2015; Sahin et al., 2016). According to Girard et al. (2015), water planners need to anticipate how to adapt management practices and infrastructure 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 e.g., Qin et al., 2011; Sušnik et al., 2012; Dawadi and Ahmad, 2013; Gohari et al., 2013; Mirchi and Watkins, 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). As a consequence, 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 approaches 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.

The specific objectives of this study are 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; and (2) identify and evaluate the effects of different policy scenarios to support decision making for sustainable water resources management and agricultural development. Ultimately, the VRB-SD simulation model is expected to serve as a learning tool for policy makers to improve their understanding of the long-term dynamics of the basin, and as a decision support tool for exploring plausible management or policy strategies. Although desirable, accurate prediction of levels and volumes regarding the key system variables is not a primary aim of this paper.

2. The study context and scope

The VRB is located within the sub-humid to semi-arid West African savannah zone (Fig. 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 1600 mm/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).