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Systemic feedback modelling for sustainable water resources management and agricultural development: An application of participatory modelling approach in the Volta River Basin

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A B S T R A C T

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 is seen as 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 provides a holistic understanding of the key biophysical and socio-economic factors and processes, and the role the systemic feedbacks play in determining the basin's behaviour. An ex-post analysis of the process with stakeholders showed that the process contributed to the shared understanding of the basin's problems. Based on our experience we present some lessons for the design and application of a participatory modelling process.

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 resource 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 seen as 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 (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 (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; 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). 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

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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 a majority of system dynamics applications have not made adequate use of qualitative modelling tools (Mirchi et al., 2012). However, a number of 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 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 in order to improve our understanding and management of environmental/natural resource systems. 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. According to Kelly et al. (2013), models are built for a number of purposes including, prediction, forecasting, management and decision-making under uncertainty, for social learning, and for developing system understanding/experimentation. 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, highlighting some salient lessons in the light of recent progress in PM approach and systems thinking research.

2. Context of the study

The PM exercise was implemented in the VRB, which is one of Africa's most important river systems (or 'catchment'). It occupies an area of approximately 400,000 Km^2 within the sub-humid to semi-arid West African savannah zone (Fig. 1). The river basin is a transboundary watershed shared among six riparians West African countries: Burkina Faso, Ghana, Togo, Benin, Cote d'Ivoire, and Mali. The basin is made up of three sub-basin basins: the Black Volta, the White Volta, and the Oti river basin all flowing into the Atlantic Ocean. 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 depend on the availability of the water that flows through the river basin. The water resources in the entire river basin is mainly used for domestic, industrial, and agricultural purposes. However, demographic pressures, land use change, climate change, and increased competition for land and water are some of the multiple challenges confronting the Volta River basin (Mul et al., 2015; Williams et al., 2016).

3. Materials and methods

3.1. Participatory modelling approach

PM approach based on the principles of system thinking 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 (Stave, 2010. p. 2766). 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). Many proponents and practitioners of PM approach (e.g., Videira et al., 2009; Beall, 2010; Stave, 2010; Voinov and Bousquet, 2010; Röckmann et al., 2012; Videira 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, the clarifiation of stakeholders mental models, creating an environment for social learning, and increasing the credibility of model outputs and legitimacy of management decisions. Jointly developed models has the advantage of helping stakeholders with problem definition and evaluation of possible management or policy options (Beall, 2010). Detail overview of the PM process and guidelines for practitioners in environmental/natural resource management systems can be found in Voinov and Bousquet (2010), Hare (2011), and Voinov et al. (2016).

In practice, PM process is facilitated using different types of analytical and system tools. The most common tools frequently used include system dynamics, Bayesian belief networks, fuzzy cognitive mapping, and agent-based modelling (Voinov and Bousquet, 2010). The system tools used to construct the conceptual models in this study were causal loop diagrams (CLDs) based on the principles of systems thinking and system dynamics (see Forrester, 1961; Sterman, 2000).

CLDs comprised 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. 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) (Gohari et al., 2013).

According to Sedlacko et al. (2014) CLDs are perhaps the most utilised system visualisation and communication tools for dealing with environmental problems. We used CLDs in this study because of their ability to show cause-effect relationships between a set of