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Review

The state-of-the-art system dynamics application in integrated water resources modeling

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ABSTRACT

In recent years, water resources management has become more complicated and controversial due to the impacts of various factors affecting hydrological systems. System Dynamics (SD) has in turn become increasingly popular due to its advantages as a tool for dealing with such complex systems. However, SD also has some limitations. This review contains a comprehensive survey of the existing literature on SD as a potential method to deal with the complexity of system integrated modeling, with a particular focus on the application of SD to the integrated modeling of water resources systems. It discusses the limitations of SD in these contexts, and highlights a number of studies which have applied a combination of SD and other methods to overcome these limitations. Finally, our study makes a number of recommendations for future modifications in the application of SD methods in order to enhance their performance.

1. Introduction

Water is a crucial resource in virtually all aspects of human life and activity, and obtaining a reliable source of clean water has been a challenging task for thousands of years. In more recent times, the ever increasing demand arising from dramatic population growth as well as industrialization and improving living standards has led to new and more complex problems, such as imbalances between water supply and demand (Rayan et al., 2001; Saif and Almansoori, 2014), waste water management issues (Maryam and Büyükgüngör, 2017; Vafaeifard et al., 2016), soil and water contamination (Haruna et al., 2016; Saleh and Danmaliki, 2016; Saleh et al., 2017), and broader environmental problems (Kirschke et al., 2017).

All these growing problems greatly increase the need for us to try to understand and predict the behavior of water resources systems and their users. However, the complexity and uncertainty involved in such systems makes this a highly challenging task. While the introduction of mathematical modeling along with the advent of computers in the 1960s paved the way for far greater accuracy as well as allowing more factors to be brought into consideration, both decision-makers and experts on water resources continue to seek new models which can provide better decisions and underpin long-term sustainable development.

As modeling approaches have become more holistic, their level of complexity has also increased dramatically because of the multiplicity of interactions between the different factors involved, uncertainties in both the linear and nonlinear relationships between these factors, and the dependencies and restrictions within diverse sub-systems as well as interactions between these sub-systems (Arshady, 2010; Chen and Wei, 2014; Mirchi, 2013). Various methods have been suggested to deal with these growing levels of complexity in water system modeling. However, while some of these have been partially successful, watershed models still suffer from various problems in terms of approach, application, and their ability to offer users a holistic and reliable understanding of the systems involved (Madani and Mariño, 2009; Mirchi, 2013).

Many conventional modeling techniques are based on linear causal thinking and consequently cannot provide the mental and structural framework required to tackle problems of this level of complexity. System Dynamics (SD), on the other hand, is a method for investigating the behaviors of a complex system over time by converting the whole system into an interconnected series of stocks and flows which affect each other through feedback loops. It can thus provide decision-makers with a powerful contextual tool (Kelly et al., 2013; Mirchi et al., 2012). While SD was initially suggested by Forrester (1958) for simulating

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industrial and urban dynamics (Forrester, 1961, 1969), there has been substantial growth in the application of SD to the planning and management of water resources systems over the past two decades due to its advantages over conventional methods (Khan et al., 2009; Madani and Mariño, 2009; Mirchi et al., 2012; Winz et al., 2009). SD offers an integrated combination of materials, structures, science, information, functions and experiences; it thus facilitates horizontal linkages between the natural and social sciences (Saysel et al., 2002; Wang, 1995a). SD can deal with complicated, nonlinear, high-order, multi-feedback and unstable system issues. It is also a perfect method for studying the law of motion of complicated systems (Chen and Wei, 2014). The existence of feedback loops enables it to provide insights into the possible consequences of system perturbations. In sum, SD is a highly appropriate framework for sustainable water resources planning and management (Madani and Mariño, 2009; Mirchi et al., 2012; Simonovic, 2009).

Using SD in the area of water resources has moreover a number of additional advantages. Developing a model based on SD allows users to understand the parameters that can most affect a system or its sub-systems. SD further offers the benefits of rapid model development and ease of model expansion, the capability to capture interactions between model components which involve individual variables and parameters, and inherent flexibility and transparency (Khan et al., 2009; Simonovic, 2000). Flexibility and transparency are desirable attributes especially for identifying the effects of basic elements on the overall dynamics of a system – which is particularly advantageous when modeling social or economic elements (Xu et al., 2002). In addition, the SD approach is capable of modeling different systems on a variety of scales ranging from local (Khan et al., 2009; Stave, 2003; Xin et al., 2009) to national (Simonovic and Rajasekaram, 2004; Yang et al., 2008) to global (Davies and Simonovic, 2011; Hoekstra et al., 2012; Simonovic, 2002a, b, 2003). These advantages, in addition to the relatively short time needed to run SD models, make SD a method of choice for modeling complex systems, especially when an integrated point of view is required.

Although SD has become more and more popular recently, there are surprisingly few studies that provide useful insights into its application to water resources modeling. Mirchi et al. (2012) reviewed the main concepts of SD and categorized its previous applications to water resources management into three types of modeling approach: (I) predictive simulation models; (II) descriptive integrated models; and (III) participatory and shared vision models. Chen and Wei (2014) reviewed previous research into the application of SD in the field of water security and classified this into three categories: (I) flood control and disaster mitigation; (II) water resources security; and (III) water environment security. All these studies are useful guides to SD methodology and its application to water security. However, finding the best studies on a specific application of SD is still a challenging task, and there remains a big gap with regard to studies taking an integrated view on modeling.

The current review aims to fill this gap. It seeks to contribute to ongoing efforts in the scientific community to identify and test methods which can effectively deliver high levels of integrated modeling. To this end, it summarizes previous state-of-the-art research that has used SD to tackle a range of different challenges in water system modeling, especially in the last decade. It further reviews various examples of the combined application of SD with other methods, and highlights the advantages of this approach. Finally, it points up certain limitations and deficiencies of the SD approach, and puts forward suggestions for ways to counter these so as to improve the effectiveness of system dynamics in integrated water resources modeling.

2. System dynamics: overview

SD concepts were initially introduced by Forrester (1961, 1969) as a modeling and simulation method for industrial management and decision-making. Based on feedback control theory (Lingling et al., 2012) and system thinking concepts (Ford, 1999; Richmond, 1993), the SD approach has proven to be suitable not only for business and strategy problems (Barlas, 2007; Senge and Sterman, 1992; Sterman, 2000) but also for the simulation of complicated environmental and water system problems (Ford, 1999; Mulligan et al., 2004; Simonovic, 2002a, 2009; Wang, 1995b; Yang et al., 2008).

According to Richardson (2011), SD is founded on certain simple but important concepts: boundaries and hierarchy, feedback loops, and level and rate (state and flow). The first of these, system boundaries, are a key factor in understanding complex systems. They are crucial in identifying the internal and external dynamics of a system and in determining whether given sub-systems are open or closed. Open systems are not aware of their past behavior, whereas in closed systems, recent actions control future outcomes. The second element – choosing the proper level of hierarchy – is another key factor in effective model development: the right level for a given model is determined by the purpose of the modeling. "*The model should be able to address issues at hand*", as Simonovic (2009) emphasized in his book.

However, probably the most important property of SD, and the one which really sets it apart from other available modeling techniques, is the third element: the feedback loop concept. This element of SD facilitates simulating the behavior of complicated systems, particularly when the aim is to model and predict long-term outcomes and achieve sustainability.

The last concept above (rate) enables SD to quantitatively simulate almost all engineering processes, as the variables of the latter can be categorized into two classes: stocks and flows. Stocks represent the current state of the system, and are the basis for decisions, actions and delays in systems. In turn, flows change stocks. The mathematical presentation of the stock-flow relationship is shown in Equation (1) below:

$$Stock_t = Stock_{ts} + \int_{ts}^{t} (Inflow_s - Outflow_s) ds \tag{1}$$

where $Inflow_s$ and $Outflow_s$ are the value of inflow and outflow at any given time s between initial time ts and current time t.

To model a problem using the SD method, it is often broken down into different spatially aggregated and temporally dynamic sub-systems. These sub-systems are used to develop a network of stocks, flows, and their feedback relationships. Feedback loops can be instantaneous or delayed in time (Tidwell et al., 2004). The structure of a system derives from the totality of the relationships between the system's components, that may generate various dynamic behaviors such as exponential growth or decline over time. However, the ability of the SD method to successfully provide an efficient and accurate model of the existing system depends on recognizing the main components and feedback loops between them within the system (Forrester, 2007; Gohari et al., 2013; Madani and Mariño, 2009; Martinez-Moyano and Richardson, 2013; Mirchi et al., 2012; Simonovic, 2009).

In general, models using SD are developed in two main stages. The first stage is the development of a Causal Loop Diagram (CLD), while the second stage involves converting the latter into a Stock and Flow Diagram (SFD). Table 1 below is a summary outline of the development of a model using SD (Wolstenholme and Coyle, 1983). For more details on water resources modeling using SD, see: (Ahmad and Simonovic, 2000, 2004; Mirchi et al., 2012; Simonovic, 2009).

3. Application of SD in water resources modeling

The many models applied to deal with the various problems that arise in water resources planning and management can be categorized in a number of different ways, either based on the method or approach they use, alternatively on the types of problems they address, or by looking at scope and purpose. Mirchi et al. (2010) suggested that catchment models can be classified into four categories based on their