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Analysing complex behaviour of hydrological systems through a system dynamics approach

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Abstract

The interaction among various water cycle components consists of complex, non-linear, and bidirectional (interdependent) biophysical processes which can be interpreted using feedback loops in a system dynamics (SD) environment. This paper demonstrates application of an SD approach with two case studies using a specialised software tool, Vensim. The first case study simulates water balance in a rice field system on a daily basis under aerobic conditions with provision of supplemental irrigation on demand. A physically based conceptual water balance model was developed and then implemented using Vensim to simulate the processes that occur in the field water balance system including percolation, surface runoff, actual evapotranspiration, and capillary rise. The second case study simulates surface–groundwater dynamic interactions in an irrigation area where river water and groundwater are two key sources of irrigation. The modelled system encompasses dynamically linked processes including seepage from the river, evaporation from a shallow watertable, groundwater storage, and lateral flow from upland to lowland areas. The model can be applied to simulate responses of different irrigation management scenarios, to develop strategies to improve water use efficiency and control watertable, to prevent salinization in upland, and to reduce the cost of groundwater abstraction in lowland areas. The discussed applications of the SD approach conclude that it helps to conceptualize and simulate complex and dynamic water system processes deterministically which are otherwise partly simulated by conventional hydrologic and stochastic modelling approaches. It is recognised that conceptualization and implementation phases of this approach are challenging, however, the latter is greatly assisted by modern computer softwares.

Keywords: System dynamics; Causal loop diagrams; Dynamic simulation; Irrigation; Salinity; Soil water balance; Groundwater; Surface–groundwater interaction; Aerobic rice; China; Vensim

1. Introduction

System dynamics (SD) is the theory of system structures and an approach for representing complex systems and analysing their dynamic behaviour (Forrester, 1961). System dynamics deals with study of how the behaviour of complex system changes through time. The key objectives of this approach include: (i) to elucidate endogenous structure of the system under study, (ii) to see how different elements of the system actually relate to one another, and (iii) to experiment with changing relations within the considered system when different alternatives are simulated. In SD, the relation between structure and behaviour is based on the concept of information feedback and control (Simonovic, 2000). Moreover, causal loop diagrams represent major feedback mechanisms, which reinforce (positive feedback loop) or counteract (negative feedback loop) a given change in a system variable (Sterman, 2000). The field of SD was pioneered during 1950s when the principles of feedback and control were introduced to the study of economic and business management problems by J.W. Forrester and his colleagues at the Massachusetts Institute of Technology, USA (Forrester, 1995).

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A system dynamics based water resource model allows users to understand the most sensitive parameters for improving the water use efficiency at system scale. Its merits include the increased speed of model development, the ease of model improvement, and the ability to simulate the interactions between the model components, inherent flexibility and transparency.

In this paper a review of alternative approaches for understanding complex behaviour of water systems is presented. This is followed by two case studies on application of SD approach in water resources management using the Vensim environment which present a comprehensive way of developing policy and management models.

2. Approaches for understanding water systems behaviour

In addition to system dynamics analysis other modelling approaches to address the complex problems of water resource planning and management include Bayesian Networks (BNs), Genetic Algorithms (GAs), decision trees as well as some empirical approaches like Artificial Neural Networks (ANN).

Bayesian Networks (also known as Belief Networks, Bayesian Belief Networks, Causal Probabilistic Networks or Knowledge Maps) are a powerful modelling methodology that can simulate the stochastic nature of physical phenomenon (an event that involves conditions of uncertainty) in a consistent, efficient, and mathematically sound way (Charniak, 1991; Pearl, 1988). The main purpose of building a BN is to estimate the probability of unobservable events (Honari et al., 2006). The BNs were first developed by the artificial intelligence and machine learning researchers (Pearl, 1986, 1988; Jensen, 1996) and successfully applied in the fields of medical diagnosis (Andreassen et al., 1991; Hamilton et al., 1994) and system reliability studies (Cooper and Herskovits, 1992; Heckerman et al., 1995; Yu et al., 1999). The mathematical background of the approach is extensively explored by the abovementioned references and by Neapolitan (1990), Lauritzen (1996), Cowell et al. (1999), Pearl (2000), Todd (2000), Jensen (2001), and Acid et al. (2005). The August 2007 special issue of Journal of Environmental Modelling and Software includes a number of articles (relevant references include Ticehurst et al., 2007; Pollino et al., 2007; de Olalla et al., 2007; Henriksen et al., 2007; Castelletti and Soncini-Sessa, 2007) covering a range of topics on application of BNs in water resources modelling and management. For example, Castelletti and Soncini-Sessa (2007) applied BNs to couple farmer behaviour with real-time reservoir control and socio-economics for participatory river basin planning. Henriksen et al. (2007) carried out public participation modelling using BNs in the management of groundwater contamination. Their key finding was that BNs could be valuable decision making tools in situations where physically based groundwater models are not sufficiently accurate. Ticehurst et al. (2007) presented an application of BNs for assessing the sustainability of coastal lakes using an integrated model framework. The authors concluded that BNs are suitable for rapid integration of complex and diverse processes for integrated catchment management. The main benefit of the BNs is that BNs can be used to model the system components for which knowledge is limited, incomplete, random, uncertain, or unstructured. However, BNs cannot be used to explore dynamically varying stocks and flows under changing system boundaries; therefore, system dynamics approach is necessary to explore such water management problems.

The ANNs are powerful, adaptive, and non-linear statistical data modelling approach used for a number of tasks such as prediction, classification, and clustering. They are based on simplified abstract models of brain neural connections. The concept was first proposed in the 1940s (McCulloch and Pitts, 1943), made limited progress in the 1950s and 1960s (Rosenblatt, 1958), and experienced a resurgence in popularity in the 1980s (Rumelhart and McClelland, 1986). Since then, ANNs have generated considerable interest across a number of disciplines as evidenced by approximately 22,500 journal articles and 13,800 conference papers published in the field during the period 1999–2003, primarily investigating neural networks in fields such as fluid dynamics, psychology, engineering, medicine, computer science, and business (Gyan et al., 2004). The ANN is a non-linear black-box modelling approach which requires relatively long-term historical data to train the network to mimic output of a complex system.

The GAs were invented in the 1960s by John Holland at the University of Michigan. Holland's research in GAs focused on formalizing the concept of adaptation as exhibited in the nature (Holland, 1975). More recently, the GAs widespread application is for optimisation or domain-specific practical problem solving. While simple GAs perform particularly well on a variety of problems, they are sometimes susceptible to premature convergence, typically when population size is too small (Mitchell, 1998).

The abovementioned approaches due to their characteristics like acyclic topology, data demand, and lack of feedback loop mechanisms are not applicable to all complex systems especially to the more dynamic and more structured problems of water resources planning and management. None of the above approaches allow deterministic exploration of the dynamic behaviour of systems where the causes and effects can change based on the time dependent boundaries of the systems. Therefore, there is a need to build further insights into the use of the system dynamics approach to analyse biophysical problems and integrate them with the social and economic aspects to derive policy implications of natural resource management decisions.

The SD approach is an appropriate technique for simulating complex problems in integrated water resources and seeking best management solutions while keeping track of the whole system response. The inherent flexibility and transparency is particularly helpful for the development of simulation models for complex water resource systems which involve subjective variables and parameters. The flexibility allows application of the hierarchical decomposition in the model development and the transparency raises the possibility of practitioners' involvement in the model development, increasing their confidence on