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System dynamics simulation for optimal stream flow regulations under consideration of coordinated development of ecology and socio-economy in the Weihe River Basin, China

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ABSTRACT

A system dynamics model (SDM) is developed to assess the dynamic changes in water resources and the impacts of different policies and measures in the Weihe River Basin. The purpose of the model is to enhance understanding of the dynamic behavior of this interactive system and to provide decision support to promote the sustainable utilization of water resources and the coordinated development of socio-economic conditions and the ecological environment in the Weihe River Basin. Six scenarios are designed to simulate the variations in and the effects of key variables based on changing the values of parameters in the model. The simulation results show that the SDM developed in this study can provide deep insight into the actual system and accurately reflects the dynamic behaviour of the basin. The results of the scenario-based projections suggest that improving water efficiency is the most effective means of supporting rapid socio-economic development and improving the quality of the ecological environment.

1. Introduction

The Water Resources Development Report indicates that many countries face water scarcity, and adequate freshwater resources are critical for socio-economic development, particularly in developing countries (UNWWAP, 2016). In the future, one-third of the world's population will experience a high degree of water insecurity, which will pose a series of problems in areas including economic development, food security, environmental health and population welfare (Vorosmarty, 2000; Alcamo et al., 2003; Taylor, 2009). At present, watershed-scale water resources management is becoming more and more challenging due to physical water scarcity, which occurs under natural conditions, and social water scarcity, which is caused by socio-economic conditions and policies (UNDP, 2006). Integrated water resources management aims to maintain a balance between the use of resources by humans and protection of the ecological environment (Dudgeon et al., 2006; Tan et al., 2013). However, water resources issues are made complex by the interactions and dynamic feedbacks between socio-economic conditions and the ecological environment; thus, the potential consequences of individual policies are difficult to assess (Sterman, 2012; Sivapalan, 2015).

The interactions and the feedbacks between systems have been widely recognized in the context of sustainable development. Many studies have shown that decision making in water resource management systems is based on systems thinking, which enables the understanding and analysis of complex dynamic feedbacks in socio-economic and biophysical processes (Davies and Simonovic, 2011; Gohari et al., 2013; Gain and Giupponi, 2015; Sivapalan, 2015). Therefore, system dynamics is most useful for improving our understanding of systems and testing the effects of various policies, and it can be used to evaluate the impacts of alternative management measures or to determine adaptive development patterns and reduce the adverse effects of decision making (Kelly et al., 2013; Sivapalan, 2015).

System dynamics models (SDMs) represent useful learning tools and include high level modelling software platforms. Such models promote systems thinking and enable model users to carry out knowledge integration. Meanwhile, SDMs have enormous advantages in model development and strategy analysis (Kelly et al., 2013). Compared with

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other methods, SDMs can accurately simulate feedbacks, controls, delays and nonlinear effects, and these features address the deficiencies in traditional water resources system management models that are based on linear simplifications and mechanical methods (Mirchi et al., 2012). Some recent studies have successfully used SDMs to carry out simulations and predictions in many watersheds (Qin et al., 2011; Susnik et al., 2012; Zarghami and Akbariyeh, 2012; Liu et al., 2015; Chapman and Darby, 2016; Kotir et al., 2016). The developed watershed-scale water management models are applied to the economic processes associated with agricultural production in most studies, whereas the effects of socio-economic and ecological processes on water resources management remain unclear (Cai et al., 2011; Johnston and Kummu, 2012).

In this study, we present a watershed-scale water resources management model to support the sustainable development of the Weihe River Basin (WRB) in China. The model developed here is used to simulate the interactions and feedback processes among socio-economic conditions, the ecological environment and the water resources in the river basin and to predict the impacts of watershed management measures on future development. Thus, adaptive measures that promote sustainability are identified. Because the Weihe River is the main supply source of renewable water resources in the region and is also a typical seasonal river, it is of great significance in the development of northwest China. Several previous studies have developed comprehensive models to assess the availability of water resources (Wang et al., 2008, 2009; Zhao et al., 2016). However, these studies rarely consider the impacts of development patterns and policy measures on water availability in the WRB. Hence, the establishment of a water management model that integrates ecological and socio-economic processes will contribute to food production, socio-economic development and environmental health in the WRB.

The main objectives of this study include: (i) dynamic assessment of the water resources of the WRB in China in response to increased population and decreased water abundance; (ii) evaluating the effects of different development patterns and water management measures on the balance between water supply and demand in the future; (iii) identifying adaptation measures to permit the establishment of a sustainable development pattern.

2. Study area and data sources

2.1. Site description

The WRB is located in northwest China. The area of the WRB is approximately 1.35×10^5 km^2, and the length of the main stream of the Weihe River is 818 km. The river originates in the Niaoshu Mountains, and it flows through a number of cities, including four cities in Gansu Province (Tianshui, Dingxi, Pingliang, and Qingyang), one city in the Ningxia Hui Autonomous Region (Guyuan) and five cities in Shaanxi Province (Baoji, Xianyang, Xi'an, Weinan and Tongchuan). The Weihe River is the largest tributary of the Yellow River (Fig. 1). The average annual precipitation within the basin as a whole is approximately 500–800 mm/yr, and this precipitation is usually concentrated in summer and autumn. The average annual temperature ranges from 7.8 to 13.5 °C.

The Weihe River is the "mother river" of the Guanzhong Region, which is the primary agricultural and industrial region in northwest China (Chang et al., 2015). Several water conservancy projects (i.e., the Hanjiang-to-Weihe River Water Transfer Project) have been built to expand the water supply. More available water resources is in need of development to meet balance between supply and demand of water resources including socio-economic and ecological environmental systems. In particular, the Guanzhong Region is the core area of the "Guanzhong-Tianshui economic zone" and the Guanzhong city group, which plays an essential role in regional development and the implementation of national strategies (Han et al., 2016).

2.2. Data sources

The data in this study were collected from the literature and field surveys. The main types of data used in this study describe population, the economy, household life, land resources, hydrology, water use, wastewater discharge and treatment, and the ecological environment. The population, economic, household life, land resource, wastewater and ecological environment data were collected from the statistical yearbooks of each region (SXBS and SXITNBSC, 2001–2015; GSDY and GSITNBSC, 2001–2015; NXBS and NXITNBSC, 2001–2015). The hydrological and water use data were obtained from the Water Resources Bulletin and the studies of (Song and Li, 2004; Wang et al., 2009). The data in the year 2000 were used as initial values to build the WRB-SDM. Some key parameters and values are provided in Table 1.

3. Methodology

3.1. System dynamics model

System dynamics modeling relies on the development of computer technology, which is mainly used to takes a systematic view of complex dynamic changes. It is mainly derived from cybernetics, systems science and information science. Forrester (1958) first proposed the use of system dynamics to improve industrial management. System dynamics modelling can clearly reflect the interactions between the variables in large-scale systems, and it displays good performance in predicting changes in nonlinear dynamic systems. Given the ongoing system dynamics theory and support technology, system dynamics model has been fully applied in many fields.

A SDM contains four submodels that represent stocks, flows, converters and connectors. Stocks are like reservoirs that accumulate physical and non-physical quantities. Flows represent the behaviour of stocks, and they control changes in the values of stocks (i.e., increases or decreases). Converters are functions that are used to define the status of flows. Connectors reflect the interactions between the parameters and produce the decisions (or activities) of the system. The level equation is the core of this model, and this equation is written as follows (Sterman, 2000):

$$Stock(t) = \int_{t_0}^{t} [Inflow(s) - Outflow(s)]\,ds + Stock(t_0)$$

where t_0 is the initial time, t is the current time, Stock(t_0) is the initial value of the stock, Inflow(s) and Outflow(s) are flow rates into and out of a stock between the t_0 and t. Inflow (s) and Outflow (s) have the units of Stock (t) divided by time.

3.2. Dynamic simulation model settings and description

In general, the steps involved in building an SDM can be summarized as follows. First, the purpose of the model is clarified. Second, the boundaries of the system are delineated. Third, a feedback flow diagram is drawn. Fourth, the numerical functions of the model are expressed. Fifth, the operation, calibration and evaluation processes of the model are developed. Finally, the integrated model is proposed.

In this paper, an integrative model that combines water resources, socio-economic and ecological environmental systems is built. As a case study, the WRB is chosen as the model boundary. A professional system dynamics software package, Vensim PLE (www.vensim.com), is used to simulate the integrated system. The simulation period extends from 2000 to 2030, and a time step of one year is used. The design of the WRB-SDM includes seven subsystems that represent the population, the economy, the livelihoods of people, land resources, water supply and demand, recycled water, and the ecological environment (see Fig. 2). It consists of 11 level stocks, 97 auxiliary variables and 23 constant parameters.