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Innovative Applications of O.R.

System dynamics simulation model for assessing socio-economic impacts of different levels of environmental flow allocation in the Weihe River Basin, China

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ABSTRACT

This study develops a complex system dynamics model (SD) reflecting interactions between water resources, Environmental Flow (EF) and socio-economy using SD software package "Vensim PLE". The proposed model is employed to assess socio-economic impacts of different levels of EF allocation in the Weihe River Basin of China. Four alternative socio-economic growth patterns and four EF allocation schemes are designed to simulate those impacts. The results reveal that developed SD model performance well in reflecting the dynamic behavior of the system in the current study area. In the meanwhile, an optimal growth pattern considering both socio-economic growth and EF requirements are also found by comparing the different scenario simulation results.

1. Introduction

There is an increasing awareness and understanding of the importance of preserving some amount of water in a river to maintain the constant functions and services of the river system (Smakhtin et al., 2004; Tharme et al., 1998). The amount of water required to maintain the health of a river ecosystem is usually referred to as the 'Environmental Flow' (EF); however, there is no universally agreed definition of EF (IWMI, 2005). Tharme et al. (1998) defined environmental (or instream) flows as flows that are left in, or released into, a river system in order to maintain valued features of the ecosystem. Dyson et al. (2003) stated that an EF is the water regime provided within a river, wetland, or coastal zone to maintain ecosystems and their benefits. A variety of other alternative terms are used by different researchers, including 'minimum flows', 'environmental demand', 'instream flow requirements', and 'ecological acceptable flow regime', each describing a slightly different concept (IWMI, 2005; Song and Li, 2004). In general, a good EF definition is necessary in working out conceptual schemes to ensure that a river system remains environmentally, economically and socially healthy.

The problems of water scarcity and water quality, due to rapid socio-economic development (Vairavamoorthy et al., 2008; Wei et al., 2010) and climate change (Kashaigili et al., 2009), have become more serious in countries, resulting in an increase in water demand and reduction in EF. Allocating water resources efficiently, equally, and fairly for socio-economic development and a healthy river system has become one of the major concerns for sustainable development. Water resources, socio-economic development, and EF interact interdependently, and form a large system, which has complex, dynamic, diverse and nonlinear characteristics.

System dynamics (SDs) is a theory of system structure and an approach for representing such a complex system and analyzing its dynamic behavior (Forester, 1961). Comparing to the traditional methods, the SD simulation approach studies the dynamic, evolving, cause-effect interrelations, and information feedbacks that direct interactions in a system over time, and it does not require longitudinal (Panel and Time Series Cross-Section) data. SD is usually characterized as a "strategy and policy laboratory" and "socio-economic system laboratory" because it provides a tool to test the effects of various strategies and policies in a system, especially for socio-economic systems. In environmental and water resources management, SD has been applied to the following main fields: carrying capacity of water resources (Sun et al., 2007) and land resources (Chen et al., 1999); simulating problems in water use (Fedorovskiy et al., 2004); environmental impacts (Deaton and Winebrake, 2000); global modeling of water resources (Simonovic, 2002); interrelationships between environmental, ecological and economic resources (Costanza et al., 1998); reservoir operations (Ahmad and Simonovic, 2000); sustainable development (Xu et al., 2002); garbage disposal (Cai, 2006); water resources planning

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(Zhang et al., 2008); as well as water quality management (Rivera et al., 2006; Tangirala et al., 2003).

However, studies on the application of SD to simulate interrelations among socio-economic, water resources and EF (SEWEF) in a river basin have not been available in the literature. In order to fill this gap, a complex SEWEF system dynamic simulation model has been developed and employed for assessing socio-economic impacts of different levels of EF allocation in the Weihe River Basin in China. The main goals of the study include:

- Studying water availability-demand balances in the study area;
- analyzing water resources carrying capacity to socio-economic development;
- examining interrelations of water resources and socio-economic growth;
- demonstrating and evaluating impacts of various EF allocation alternatives on socio-economic development;
- investigating optimal and practical strategy to increase water carrying capacity in light of EF allocations, water availability and local socio-economic conditions.

2. Study area and data sources

2.1. Site description

The Weihe River basin in the Guanzhong region of Shaanxi Province was selected as our study area due to the serious conflicts between water use and EF allocation. The study area includes five municipalities – Baoji, Xianyang, Xi'an, Tongchuan and Wei'nan, and five main hydrological gages, namely Linjiacun, Weijiabao, Xianyang, Lintong and Huaxian (Fig. 1). The river is 818 km long with a watershed area of 1.36×10^5 km^2, the largest tributary of the Yellow River. It has 176 tributaries with a catchment area of over 100 km^2, among which 16 rivers have an annual runoff of over 1.0×10^8 m^3. The river is called the 'Mother River' of the Guanzhong region, which plays a great role in the development of West China and the health of the ecosystem of the Yellow River. However, since the late 1990s many parts of the river have lost their ecosystem functions, restricting as a consequence the sustainable development of the region socially and economically (Song and Li, 2004).

2.2. Data sources

Data sources include a literature review and a one-month site survey in April 2010. The main types of data include information on socio-economy (1999–2008), water resources and hydrology (1959–2000), water use (1995–2008), wastewater discharge and treatment (1999–2008), environment and ecology (1999–2008), as well as EF. Socio-economic data cover population (rural and urban), natural growth rates, industrial and agricultural gross domestic products, per capita disposable income of urban households, and per capita net income of rural households, irrigation areas, as well as consumer price index (CPI), which were collected from the Shaanxi Statistical Yearbooks (SXBS and SXITNBSC, 2000–2009) and the Xi'an Statistical Yearbook (XABS, 2008). Water resources and hydrological data, including surface water, ground water and river discharge, were collected mainly from previous studies (Song and Li, 2004; Wang et al., 2009) and different hydrological gages. Water use data, spanning rural and urban domestic daily water use, industrial water use, agricultural water use, the water consumption coefficients of these sectors, and the water saving ability of domestic and agricultural users were all collected from the Shaanxi Statistical Yearbooks (SXBS and SXITNBSC, 2000–2009), the site survey in 2004, and previous studies (Xing et al., 2006; Zhou, 2006). Wastewater discharge and treatment data include mainly domestic use and industrial waste water discharge, waste water treatment rates and reclaim rates taken from the Shaanxi Statistical Yearbooks (SXBS and SXITNBSC, 2000–2009). The environment and ecology data on urban green areas, and water and soil conservation areas are collected from the Shaanxi Statistical Yearbooks (SXBS and SXITNBSC, 2000–2009), and data on urban water surface areas, artificial water body areas, zonal vegetation areas and water quotas are taken from Wang et al. (2008). EF data on EF requirements were taken from the studies of Song and Li (2004).

3. Methods

3.1. Concept of SD

The basic building blocks of SD simulation are composed of four components: Stock ("state variable", "level", or "reservoir"), Flow ("Rate", "Control Variable" or "Processes"), Converter ("Auxiliary", or "Translation variable") and Connector (or "Information Arrow"). The SD simulation model consists of a set of nonlinear differential equations, such as level (or state) equations, flow equations, auxiliary equations, parameter equations, condition equations as well as initial value equations. Level equation is the core equation, which presents the dynamic behavior of a system, and it can be expressed as:

$$\frac{dX_i(t)}{dt} = f(X_i, R_i, A_i, C_i) \tag{1}$$

The differential equation can be expressed as follows:

$$X_i(t + \Delta t) = X_i(t) + f(X_i, R_i, A_i, C_i)^* \Delta t \tag{2}$$

where X_i(t) is a vector of state variables, *f*() is a vector-valued function, and R_i is a vector of flow variables, A_i is a vector of auxiliary variables, C_i is a vector of parameters, t is time variable, Δt is time difference. The above equations are solved numerically by a simulation procedure such as Euler, and Runge–Kutta.

The state Eq. (2) expresses three time points – past, present and future, in which the present state is a summary of past states, and the difference between current and last period, and the future state is an expression of the present state plus the change during the variation time period. Thus it states the dynamic variations of a system over time.

3.2. SD simulation process

In general, SD modeling and simulation process can be summarized as: (1) defining simulation objectives, (2) determining the system boundary, (3) designing a user-interfaced graphical structure of the system, (4) developing stock-flow diagrams, (5) formulating the mathematical model, (6) calibrating and validating the model, and (7) implementing the model.

3.3. Nominal to real value transformation

The original time series data of economic values, including industrial and agricultural gross domestic product, per capita incomes of households, etc., are calculated at current prices, which contain inflation and subsequently are called *current*(*nominal*)*values*. In order to compare them, the *nominal values* of a series are usually transformed to *real*(*constant*) *values*, i.e. values calculated at constant prices in a reference year (Wei et al., 2010). The method of transformation of *nominal* to *real values* is expressed by the following equation:

$$VR_{t+n} = VB_t^* ID_{t+1}^* ID_{t+2}^* \ldots {}^* ID_{t+n}, \quad n = 1, 2, 3, \ldots, N \tag{3}$$