Journal of Cleaner Production xxx (2016) 1–13

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Sustainable utilization of water resources in China: A system dynamics model

Yuhuan Sun*, Ningning Liu, Jixia Shang, Jingyu Zhang

School of Statistics, Dongbei University of Finance and Economics, Dalian, 116025, Liaoning, China

A R T I C L E I N F O

Article history:
Received 4 June 2015
Received in revised form
19 July 2016
Accepted 19 July 2016
Available online xxx

Keywords:
Water resources
System dynamics
Sustainable utilization
Water demand–supply gap

A B S T R A C T

Water resources play an important role in demographic, social, and economic development. The present study divides the macroeconomic factors that affect the sustainable use of water resources into five major subsystems: economy, population, water supply and demand, land resources, and water pollution and management. It then constructs a feedback loop and stock-flow chart of the systems with the system dynamics model to simulate water supply and demand conditions and future changes in the gap between supply and demand from 2005 to 2020. Further, this study designs different development programs to simulate the changes to the key variables by changing the value of important model parameters. It is found that a balanced development program can achieve not only steady economic growth, provide a demographic dividend, and protect arable land resources, but also maximize the sewage treatment rate and improve the reutilization efficiency of water. Moreover, we find that the fundamental way in which to bridge the gap between the supply and demand of water resources is to improve water supply rather than control demand.

1. Introduction

Water resources play a vital role in people's daily lives as well as in agricultural irrigation, fish farming, and manufacturing. Water is not only an indispensable natural resource, but also an irreplaceable economic resource. However, the water shortage problem has become more serious in China over the past five decades. According to the *China Water Resources* website, China is desperately short of freshwater, with the volume of per capita freshwater being only one quarter of the world's average. Among all 669 cities in China, 440 cities have a lack of water, while 110 have severe water shortages. Not only is daily water demand increasing, water pollution and waste are also serious issues. Hoekstra (2013) noted that water pollution affects the health of residents seriously, while Bian et al. (2014), using a DEA model, confirmed that water use efficiency in China is lower than that in many other countries (see also Che and Han, 2014). Meanwhile, An et al. (2016) used a two-stage DEA model, finding that a decentralized production system leads to more water waste than centralized production, even though the former system is the most popular industrial mode. Wu et al. (2016) also used a two-stage DEA model to analyze the efficiency of reusing water resources. Moreover, Dalin et al. (2015) stated that the uneven distribution of water resources has led to their unsustainable utilization. Only by balancing the supply and demand of water resources, reducing water pollution, and building a warning system to encourage the sustainable utilization of water resources nationally can sustainability improve.

Previous research on water resources can be categorized into four types: surface and ground hydrology, water resources carrying capacity, sustainable utilization of water resources, and water pollution and management. First, surface and groundwater hydrology studies are typically associated with modeling climate change theoretically. Liang et al. (1994) proposed the variable infiltration capacity model and used hydrologic and meteorological data to obtain good simulation results. Christensen et al. (2004) predicted the impact of climate change on the Colorado River Basin in the 21st century, finding that water demand is expected to exceed water inflow volume, which would result in reservoir degradation. Similarly, Hagemann et al. (2013) used a multiple global climate-hydrological model to research the Colorado River Basin and found that climate change was not the only factor that had lead to the uncertainties in the changes of the hydrological cycle.

Second, studies of water resources carrying capacity mainly use assessment methods such as the EPI (Wang et al., 2013), CCRR (Song

* Corresponding author.
E-mail addresses: yhsun602@163.com (Y. Sun), liunn0724@163.com (N. Liu), xueyin_china@163.com (J. Shang), maimi1990@126.com (J. Zhang).

http://dx.doi.org/10.1016/j.jclepro.2016.07.110
0959-6526/

et al., 2011), information diffusion theory (Feng and Huang, 2008), cluster analysis (Wang et al., 2014), the fuzzy synthetic evaluation method (Hou and Tang, 2014; Meng and Chen, 2013), and system dynamics theory (Feng et al., 2008, 2009; Yang et al., 2015a). The system dynamics model helps clarify the relationships between the impact factors and water resources carrying capacity, whereas other methods focus on choosing indicators to measure water resources carrying capacity. However, both types of studies focus on the city or regional scale instead of the national scale.

Third, research on the sustainable utilization of water resources has drawn inconclusive findings. Hannouche et al. (2016) concluded that it is now time to apply concepts of integrated and sustainable management of water resources because of the growing agricultural practice and population needs. Lambooy (2011) introduced several tools to reduce water consumption by enterprises, such as the global water tool and water footprint tool. Pahl-Wostl et al. (2013) found that policymaking based on scientific findings should play an important role in the sustainable utilization of water resources at the global scale. Liu et al. (2010) introduced an effective water resources sustainable utilization project in the Hai Hua Ecological Industry Pilot Zone that operated at the individual firm, inter-firm, and regional levels. Chinese scholars have also used evaluation systems and methods to analyze the sustainable utilization of water resources. For example, Jin et al. (2012) examined sustainable utilization in Yunnan Province and Ling et al. (2012) built a series of comprehensive assessment indicators covering fields from ecological security to supply and demand conditions.

Finally, research on water pollution and management evaluates different water pollution control techniques, and control from source is considered to be a better approach, particularly compared with the “treatment after pollution” method (Gani and Scrimgeour, 2014; Zhang et al., 2014). Innovative approaches to sharing water use data have been encouraged to evaluate water pollution and management (Laituri and Sternlieb, 2014). For example, Ai and Yue (2014) discussed the application of big data to water resources and proposed a framework for this purpose. However, a lack of data means that the application of big data is still in the theoretical stage.

Recent research on water resources across these four domains has adopted diverse methods and models. However, it mostly focuses on the district or county levels, and seldom examines the national scale, preventing us from understanding the overall utilization of water resources at the macro level. To bridge this gap in the body of knowledge on this topic, this study uses a system dynamics model to build a comprehensive assessment and management system for understanding water resources use at the national scale in China. We examine the following five subsystems that influence the sustainable utilization of water resources: economy, population, water supply and demand, land resources, and water pollution and management. Then, we build a system dynamics model to analyze the influence of the variables of each subsystem on the supply and demand of water. Finally, suggestions from the perspectives of the economy, demographics, resources, and the environment are put forward to promote the sustainable utilization of water resources in the long-term.

2. Basic theory of system dynamics

System dynamics, a discipline based on systems science and computer simulation techniques to study systems with dynamic complexity, was first put forward by Forrester (1958) as both a tool to solve problems and a kind of a system mindset. This scientific method is a combination of theory and computer science, which allows for the research of systematic feedback structure and behavior. For instance, Meadows (1972) established a global model for analyzing industries, pollution, population, and other important factors by using the system dynamics model. From its birth in the 1950s, the system dynamics model become widely applied globally and gained more comprehensive development as a consequence in the fields of policy development, project management, learning organization, logistics and supply chains, and a company's strategic areas at both the macro and the micro levels. The standard system dynamics approach runs as follows: first, specify the problems and clarify the boundaries of the system; second, put forward a dynamic hypothesis, write the formulation, and conduct the simulation test; and finally, finish the policy design and evaluate. Every causal loop in system dynamics models should have at least one stock, otherwise no cumulant will appear. Only the flow can change the stock value, as all variables change over time.

As system dynamics theory has developed, the application range has enlarged as well to include industry, finance, medical science, education, resources and the environment, real estate, and many other fields. Among these fields, resources and the environment is the field to which system dynamics applies most (Yang et al., 2015b). For instance, Movilla et al. (2013) used system dynamics to analyze the photoelectric energy market in Spain. Based on a system dynamics model, Tan et al. (2012) formulated a cultivated land pressure index as the object variable and then built population, cultivated land, and grain subsystems to analyze their impact on cultivated land pressure in Hubei province. Xie et al. (2014) set up a system dynamics model to analyze the water resources carrying capacity of the Luanhe River Basin. The authors found a decreasing trend for the water resources carrying capacity in the basin and showed that current economic growth was not sustainable. Zhou et al. (2013) used a system dynamics model to analyze the characteristics and balance of water and land resources when planting three kinds of crops: winter wheat, summer corn, and cotton.

Compared with other common methods for analyzing water resources (e.g., principal component analysis, analytic hierarchy process, fuzzy evaluation), which are typically single equation econometric models that have strict conditions and are more adaptable to short-term quantitative research and forecasting, system dynamics is suitable for the qualitative and quantitative analysis of complex systems. The subjective qualitative analysis of the decision maker is the first step, and this is followed by the quantitative analysis (Forrester, 1958). With the help of modern computer technology, economic or societal problems, especially the sustainable utilization of water resources, can be studied in depth by using simulation techniques. Indeed, researchers can formulate feasible policy based on the estimation and simulation results provided by the system dynamics model. Indeed, system dynamics can reflect the complex relationship between large numbers of variables in huge systems and thus it is widely applied to complex nonlinear systems, and it can make better mid- or long-term predictions. Therefore, this study uses a system dynamics model to analyze the sustainable utilization of water resources in China.

3. Development of system dynamics

3.1. Selection of variables in the model

This study chooses water resources in China as the research object and the period 2005–2020 as the research period. Following Feng et al. (2008, 2009), Wu et al. (2013), and Yang et al. (2015a, 2015b) and considering the availability of data, this study selects as the model variables five major variables, including those related