Journal of Environmental Management 230 (2019) 221–233

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Comprehensive evaluation and scenario simulation for the water resources carrying capacity in Xi'an city, China

Zhaoyang Yang[a], Jinxi Song[a,b,*], Dandong Cheng[b,c], Jun Xia[a], Qi Li[a], Muhammad Irfan Ahamad[a]

[a] Shaanxi Key Laboratory of Earth Surface System and Environmental Carrying Capacity, College of Urban and Environmental Sciences, Northwest University, Xi'an 710127, China

[b] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences, Yangling 712100, China

[c] University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Keywords:
Water resources carrying capacity
Analytic hierarchy process
SD model
Scenario analysis
Water management

ABSTRACT

The quantity and quality of water resources are of great importance in maintaining urban socio-economic development. Accordingly, substantial research has been conducted on the concept of the water resources carrying capacity (WRCC). In this study, analytic hierarchy process (AHP) and system dynamics (SD) models were combined to construct a multi-criteria evaluation system of the WRCC and a socio-economic/water resources SD model for Xi'an. The developmental trends of the society, economy, water supply/demand, and wastewater discharge were obtained from 2015 to 2020 using five scenarios designed for distinct purposes; these scenarios and trends were comprehensively evaluated using a combination of qualitative and quantitative analyses. The results indicated that the WRCC (0.32 in 2020) in Xi'an will shift from a normal to a poor state if the current social development pattern is maintained; therefore, we conclude that the socio-economic development of Xi'an is unsustainable. However, under a comprehensive scheme, the WRCC index (0.64 in 2020) will increase by 48% compared with the WRCC index under a business-as-usual scenario. Further, some practical suggestions, including the promotion of industrial reforms and the improvement of water-use efficiency and recycling policies, were provided for improving the regional WRCC.

1. Introduction

Water resources, which constitute an irreplaceable foundation of social development, are one of the most important natural resources for the survival of organisms (Walter et al., 2012). Coincident with the rapid development of contemporary society, the discrepancies between acute water shortages and increasing demands for water resources have become more prominent (Cai et al., 2011a,b; Safavi et al., 2016). In recent years, human activities have led to an enormous demand for water resources accompanied by water resource shortages and water quality degradation; these demands have led to water crises in many regions, particularly in urban areas (Tan et al., 2013; Wu et al., 2014). Nearly two-thirds of cities in China face different degrees of water shortages, and the groundwater in some areas is overexploited (Shang et al., 2016). Moreover, rapid urbanization has introduced many new pollution-related challenges, such as the need to collect and treat increasing volumes of city sewage (Chen, 2007). Over the last two decades, it has been estimated that more than 11,000 water quality-related emergencies have occurred. A recent example is the discovery of severe water contamination in the Jialing River caused by the discharge of wastewater from chemical plants containing high amounts of thallium (Han et al., 2016). Though cities represent a concentration of water resource demands, urban development has caused serious threats that have focused the public's attention on the importance of protecting existing water resources (Bakker, 2010). In 2014, Chinese Premier Li Keqiang publicly declared war on pollution in an economic overhaul, and the Chinese Central Government has since issued a series of policies in the field of pollution control and remediation (Han et al., 2016). Thus, quantitative and qualitative evaluations of whether available water resources can support socio-economic development are important for ensuring that the accessible water environment is not destroyed.

The carrying capacity (CC), originally a concept from the science of ecology, is used to reflect the maximum number of individual species

* Corresponding author. Shaanxi Key Laboratory of Earth Surface System and Environmental Carrying Capacity, College of Urban and Environmental Sciences, Northwest University, Xi'an 710127, China.
E-mail address: jinxisong@nwu.edu.cn (J. Song).

https://doi.org/10.1016/j.jenvman.2018.09.085
Received 15 February 2018; Received in revised form 21 September 2018; Accepted 22 September 2018

that a habitat can support (Kessler, 1994). The water resources carrying capacity (WRCC), which represents the extended application of the CC in the field of water resources, was first proposed by the Research Panel of Water Resource Soft Science in Xinjiang, China (Feng et al., 2008). Since its proposal, the concept of the WRCC has been researched abroad. Some studies concluded that the WRCC is a concept that focuses on sustainable socio-economic development within a region or basin (Clarke, 2002; Khanna et al., 1999), while others regarded it as the maximum threshold of water resources that an environment is capable of providing to maintain human activities (Zhu et al., 2002). The definition of the WRCC used in this study is the maximum sustainable socio-economic scale based on the available water resources and the maintenance of a healthy water environment (Song and Zhan, 2011). Currently, most studies combine the concept of the WRCC with the theory of sustainable development instead of regarding it as a separate research topic (Long et al., 2004; Zhu et al., 2002). Therefore, in this study, the WRCC is incorporated into a larger theoretical background of sustainable development and water management.

To date, many researchers have conducted extensive assessments of the WRCC by adopting a variety of methods, such as the conventional tendency method (Liu, 2012), the ecological footprint method (Wang et al., 2017a), the multi-objective analysis method (Garfí et al., 2011; Peng and Zhou, 2011), and the artificial neural network method (Iliadis and Maris, 2007). Through statistical analysis and calculation, the conventional tendency method selects indicators to characterize the WRCC based on the supply-demand balance of water resources; however, due to the lack of systematic analyses on the coupled relationships between different elements, an objective portrayal of the real situation of the WRCC using the conventional tendency method is difficult to achieve. The ecological footprint method describes the WRCC by establishing only the ecological footprint as a comprehensive index, making it simpler than other methods; however, this highly generalized conclusion is not appropriate for obtaining a specific and in-depth evaluation. As a planning method, multi-objective analysis incorporates the relationship between natural resources and the regional social economy; furthermore, the development goals of different periods are considered when researchers make decisions. However, the application of multi-objective analysis is limited due to the lack of an appropriate method for solving optimization problems. The artificial neural network method performs well in terms of nonlinear pattern recognition, but it is difficult to quantify the evaluation results in practical applications while utilizing this technique. Notably, in addition to the abovementioned limitations, these methods all adopt a static evaluation approach, which neglects dynamic changes in the WRCC (Wang et al., 2013). Multi-criteria decision-making (MCDM) methods have been proposed to determine the most preferred alternative by classifying those alternatives in a few categories and prioritizing them in a subjective order of preferences (Tzeng and Huang, 2011). Among the various MCDM methods developed to solve real-world decision problems, the analytic hierarchy process (AHP) is a widely used and well-known decision support tool. Therefore, to overcome the abovementioned deficiencies, we integrated evaluation and scenario simulations based on an AHP model and a system dynamics (SD) model, both of which have been widely used in research on the WRCC. For example, Xi and Poh (2015) proposed a novel integrated decision support tool that synergizes SD and AHP models to diversify Singapore's water supply sources and relieve the risks of urban flooding. Furthermore, Zhang et al. (2014) assessed the maximum population and socio-economic scale that the water resource system of the Siping area can support.

In this study, we focused on quantitatively evaluating the WRCC and seeking optimal development scenarios based on a synthetic simulation of the socio-economic/water resources compound system. With the aid of SD and AHP methods, both a WRCC evaluation index system and an SD model were established. Moreover, five reasonable scenarios, each of which contained a unique emphasis, were proposed to improve the WRCC. Under these different scenarios, the development trend of the WRCC in the study area was obtained. Through a comparative analysis, the optimal scenario was selected as a solution to coordinate the development of both the regional socio-economy and the water environment. Thus, this study provides a reliable reference for improving the WRCC. The details of each chapter are organized as follows: sections 2 and 3 introduce the case study area, the methods and the acquisition of related data; section 4 establishes the multi-criteria evaluation system and SD model for the WRCC in Xi'an, verifies the model, performs a sensitivity analysis, and constructs various scenarios based on specific parameters; section 5 provides and compares the simulation results under the different scenarios, discusses policy implications, and identifies future research opportunities and limitations; finally, section 6 presents the main conclusions. Fig. 1 shows a flow chart of the methodology proposed in this study.

2. Study area

The study area is Xi'an (107.4–109.49°E, 33.42–34.45°N), the capital of Shaanxi Province and the largest city in Northwest China (Fig. 2). Xi'an, which is a major industrial city in Shaanxi Province that acts as a major national trade center and manufacturing base (Wang et al., 2013), is located in the center of the Guanzhong Plain to the south of the Qinling Mountains, and it spans a total area of 10,108 km^2. In recent years, the average annual precipitation was 500–750 mm, and the average annual evaporation was 800–1000 mm. The total volume of water resources in the region is $22.48 \times 10^8\ m^3$, of which $18.74 \times 10^8\ m^3$ (83.4%) is surface water. The regional volume of water resources per capita is only 270 m^3, which is less than one-seventh of the national average and one-quarter of the provincial average. Moreover, the per capita volume of water resources of Xi'an is well below the critical value of 1000 m^3, which is internationally recognized as the standard for a region to maintain economic and social development (Alcamo et al., 2007).

The economy of Xi'an has developed rapidly in recent years, and this rapid development has had dramatic effects on the water environment. According to reports in the Xi'an Statistical Yearbook (2015), approximately 4.26×10^6 t of industrial wastewater and 1.43×10^7 t of untreated domestic sewage are discharged annually into water bodies. Accordingly, the deterioration of the aquatic environment is the result of surface water pollution, and the excessive exploitation of groundwater has led to ground subsidence. Both the shortage of water resources and the deterioration of the water environment have severely restricted sustainable social and economic development in Xi'an (Cheng et al., 2009). In China, although the total volume of water resources is vast, the average accessible amount of water resources is low and is unevenly distributed in time and space (Xia and Chen, 2001). Thus, both social and natural factors produce severe water shortages in Xi'an, thereby posing an imminent problem for the government (Xue and Qiu, 2013).

3. Data sources and methods

3.1. Statistical data

Two major sources of data were employed for this paper, namely, the Xi'an Statistical Yearbook (2005–2015) and the Shaanxi Province Water Resources Bulletin (2005–2015), which are published by the Xi'an Bureau of Statistics and the Shaanxi Province Department of Water Resources, respectively. In addition, other information was collected from the industrial water-use quota of Shaanxi Province and the official website of the Shaanxi Provincial Bureau of Statistics; these data included information on the socio-economy, water resources, and wastewater discharge and treatment. The socio-economic data included