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Water environment carrying capacity in Bosten Lake basin

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ABSTRACT

By combining a system dynamics (SD) model and an analytic hierarchy process (AHP), an evaluation index system for water environment carrying capacity (WECC) in the Bosten Lake basin was developed that considers mutual interactions among six subsystems of industry, agriculture, population, water supply, water ecology, and water pollution. The model was tested with data including water level, surface area, water volume, chemical oxygen demand (COD) concentration, total nitrogen (TN) concentration, and salinity concentration observed for 2002–2010. In addition, the model was applied to study and compare the trend of WECC under seven scenarios from 2002 to 2024. The results indicated that the WECC trends of industrial water consumption drop 0.5% each year (Scenario 2) and water transport from Bosten Lake to the Tarim River of 0.5 billion m^3 each year (Scenario 6) were the same as Scenario 1 (present mode), which means that Scenario 2 and Scenario 6 cannot improve the WECC of Bosten Lake. As for the other four scenarios, the effects on the WECC of Bosten Lake were in the order of increase ground water exploitation (Scenario 7) > water-saving irrigation investment (Scenario 4) > increase reed area (Scenario 5) > increase industrial water reutilization rate (Scenario 3). Although the four scenarios can improve the WECC of Bosten Lake, only Scenario 7, i.e. increasing ground water exploitation rate by 3%, can turn the carrying status of WECC from poor to good. In addition, population and concentrations of COD, TN, and salinity will improve in the improved scheme compared to the present mode. The sensitivity of three parameters including the growth rate of water demand per 10^4 USD, growth of reutilization rate in industrial water, and ecological water transport were analyzed. The results indicated that both growth rate of water demand per 10^4 USD and growth of reutilization rate in industrial water increased the WECC of Bosten Lake. Moreover, the WECC of Bosten Lake will be negatively affected when the water quantity of ecological water transport from Bosten Lake to the Tarim River exceeds 1 billion m^3. The results provide a scientific basis for a reasonable development pattern in protecting the WECC of Bosten Lake.

1. Introduction

Population, resources, environment and development (PRED) are the focus of attention in the world today. With rapid growth of population and speed up of industrialization processes, resources and environment face unprecedented pressure, especially water resources and the water environment (Yu et al., 2003; Zhou et al., 2017). In China, most lakes have serious water environment problems, such as shrinkage of water surface area, eutrophication, transformation from inland freshwater lakes into saltwater lakes, and organic pollution. To a certain extent, the deterioration of the water environment has constrained or affected the respective local/regional economic development (Zhou et al., 2017). To study the economy and society scale that water environments can support, the concept of water environment carrying capacity (WECC) was proposed. Carrying capacity originated in ecological fields and is defined as the maximum population size that a specific environment can support, and is applied in various fields due to resource shortages to produce more carrying capacity including land carrying capacity, forest carrying capacity, soil carrying capacity, water resources carrying capacity, water environment carrying capacity, etc. (Feng et al., 2008; Lin et al., 2011; Mei et al., 2010). Water environment carrying capacity is defined as "the largest population and economic scale that the water environment can support in a

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specific region during a period of time without an adverse impact on the local water environment" (Wei et al., 2014; Zeng et al., 1998). By studying the WECC of lakes, the society and economy scale that the water environment sustains and restrains can be discerned, and the findings can in turn be used to regulate the development plans in sustainable ways.

Research on WECC is inherently complex since it is a complex function of the water environment, population, economy, technology, planning scheme, etc., and different types of interactions and feedback mechanisms exist among them (Zhou et al., 2017; Handler et al., 2017; Xin et al., 2018). Numerous concepts and tools for modelling the effects and impacts of coupled human and natural systems on sustainable development have been proposed. The research methods of WECC can be summarized into four types: index complex evaluation method, multiple objective programming method, water footprint method, and system dynamics (SD) method. First, index complex evaluation methods such as the hierarchical multi-criteria method (Xia, 2013), fuzzy comprehensive evaluation method (Wang et al., 2010), project pursuit method (Wang et al., 2003), press-state-response framework (Wang, J. et al., 2013), and back propagation (BP) neural network (Yang and Tong, 2013) were applied in estimating water resources carrying capacity. Secondly, multiple objective programming such as multi-objective large system decomposition and coordination models were applied to study WECC in the Guanzhong region, Shaanxi (Jiang et al., 2001). Another widely used method in WECC is the water resources ecological footprint (WEF), and ecological pressure index (EPI) that was introduced as the ratio of the WEF to the WECC to compare the water resource supply and consumption in the future of Liao-Hun and Taizi Watersheds (Wang, S. et al., 2013). The SD method can simulate the socio-economic-environment system considering interactions among subsystems, and has been successfully applied to study water resources carrying capacity and water environment carrying capacity (Wang and Xue, 2017; Yang et al., 2015; Zhang et al., 2014). To date, the research on WECC has not formed a scientific theoretical system. The advantages and limitations of the above-mentioned methods are summarized in Table 1 (Li, 2008; Li et al., 2016; Mirchi et al., 2012; Wei et al., 2012). The combination of complex evaluation methods and system dynamics can overcome the limitations of the methods mentioned above, allowing consideration of the interactions among evaluation factors during the process of quantitative analysis of WECC. In addition, in previous WECC evaluation index systems, the water pollution level is represented by pollution load instead of water quality (Zhu et al., 2009), which is not reasonable as water quality can depict the water environment quality and visually represent the water environment status in a study area. In this paper, therefore, the concentrations of water quality indices such as chemical oxygen demand (COD), total nitrogen (TN), and salinity were considered in index system, and pollution factors of COD, TN and salinity were chosen to represent the water pollution system in the SD model, which help bridge the gap of overlook the water quality in the evaluation of WECC.

In this paper, the interactions among subsystems of socio-economic development, water resources, and pollution were considered for assessing WECC in the Bosten Lake basin by combination of a SD model with a complex evaluation method. In the proposed model, the coupling effects of six subsystems containing industry, agriculture, population, water resources, water ecology, and water pollution were taken into account. In the WECC comprehensive evaluation index system, water quality indicators of COD, TN, and salinity were integrated into water pollution subsystem. By an AHP method, the weights of each index in subsystems and each subsystem were identified. The SD model corresponding to the six subsystems was proposed by simulating the interactions among parameters and subsystems. Data collected from years 2002–2010 were used for calibration of the WECC model, which is applied to analyze and compare the development trend of WECC in Bosten Lake for seven development situations. The effects of different scenarios for improving WECC level and water quality were forecasted and compared, which can help basin managers make the most effective decisions to protect the water environment in Bosten Lake.

2. Materials and methods

2.1. Study area

Bosten Lake (41°56′ ~ 42°14′N, 86°40′ ~ 87°56′E) is the biggest inland freshwater lake in Xinjiang, China, which is located in the southern part of Tianshan Mountains and in Bohu County, Bayinguoleng Mongol Autonomous Profecture. The area of the lake is 968 km^2 (at a water level of 1047.5 m), and is about 55 km long, 25 km wide, with a mean depth of 7.38 m. Bosten Lake is the terminus of the Kaidu River and the headwaters of the Kongque River. Bosten Lake plays multiple roles in controlling floods in the Kaidu

Table 1
Summary of advantages and limitations of assessment methods for water environment carrying capacity.

Approach	Advantages	Limitations
Index complex evaluation method	- suitable for preliminary evaluation	- does not consider the coupling effects of influencing factors - subjective process of selecting the indicators and the assessment criteria which leads to being unable to provide comprehensive results involving population and economic data.
Multiple objective programming method	- considers various goals and values - integrates the thought of decision makers	- difficulty in determining the proper values of the model parameters
Water footprint method	- explicit definition - simplicity - wide applicability - vividly expresses the links between human consumption and water resources	- deviates from the actual situation analysis because of factor attributes
System dynamics method	- considers the interactions among the internal factors of the system - better reflects the nature of systems - can simulate dynamic differences between demographic changes and ecosystem capacity with different development strategies - flexible model and ease of sensitivity analysis	- difficult to establish rational equations and models