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Research article

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

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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

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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

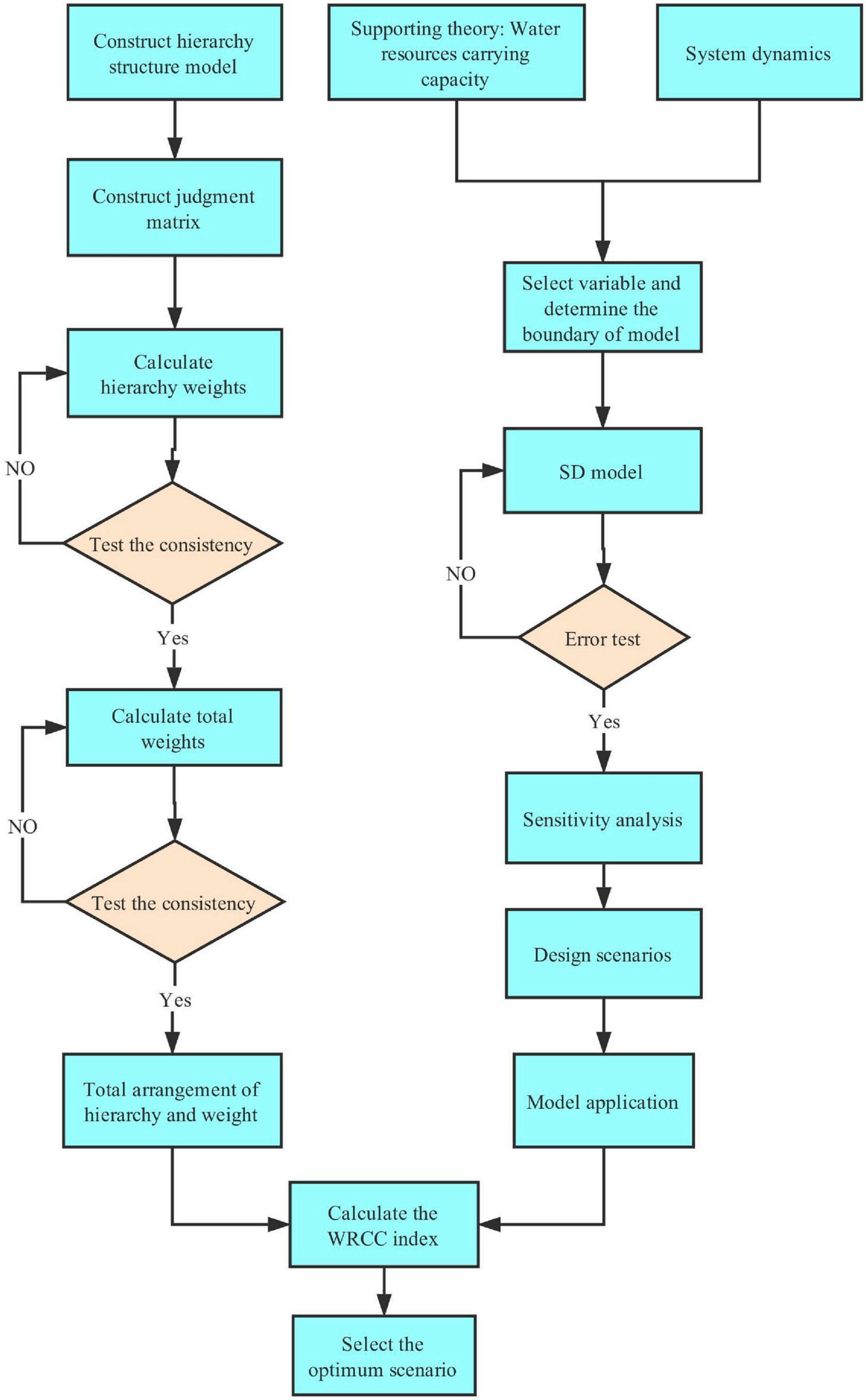

Fig. 1. Flowchart of the research methodology on the WRCC in Xi'an.

information regarding the population (rural and urban), per capita annual income of urban residents and rural households, and gross domestic product in addition to other information, while the data on water resources included the total volume of water resources, total volume of surface water resources and total volume of groundwater resources, and the data on wastewater discharge and treatment was composed of the total volume of industrial water, the volume of wastewater discharge, and the total volume of domestic and industrial sewage disposal.

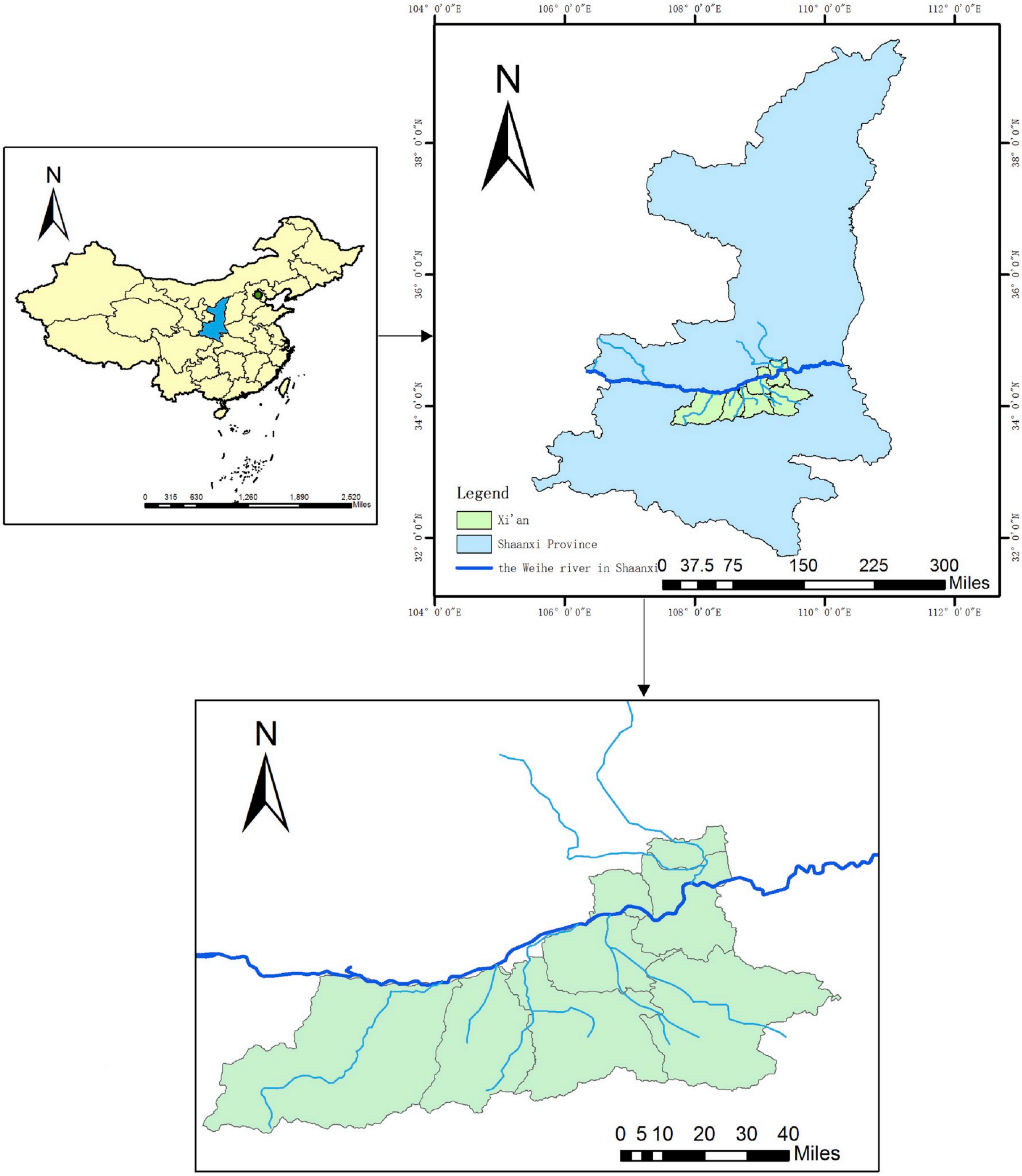

Fig. 2. Administrative map of Xi'an.

3.2. Analytic hierarchy process

In this study, the impacts of different indexes on the WRCC vary; hence, the index weights need to be determined. At present, two methods are utilized to calculate such weights: subjective weighting and objective weighting. In the former, the weight of each index is determined by an expert evaluation (e.g., an AHP or expert investigation); in the latter, the weight of each index is calculated by a numerical method, which does not depend on the subjective judgment of a researcher. Because the index selected for the evaluation index system involves multiple systems and multiple factors, an AHP is applied to determine the weight of each evaluation index. An AHP, a structured multi-attribute decision method developed by Thomas L. Saaty in the 1970s, is applicable to multi-objective, multi-criterion, and multi-actor decisions (Saaty, 1990). AHP models also address quantification problems by integrating the subjective judgments of researchers and by combining qualitative data with quantitative data.

The key steps involved in the AHP method are as follows:

(1) Clarify the scope of the problem, understand the factors involved in the problem, and determine the relationships between the various factors. Based on a preliminary analysis of the evaluation system, the system structure is divided into a hierarchical tree structure, which generally consists of three hierarchies: the top is the object hierarchy, the middle is the rule hierarchy, and the bottom is the index hierarchy.

(2) As the hierarchical model determines the subordinate relationships between the upper and lower elements, each element is pair-wise compared by a judgment matrix, as shown in Eq. (1), and the corresponding level is confirmed by assigning a numerical value (Table 1).

Table 1
Scale of preference between two elements.

Numerical scale	Definition
1	Equal significance between the two elements
3	Slight significance of one element compared to the other
5	Strong significance of one element compared to the other
7	Dominance of one element over the other
9	Absolute dominance of one element over the other
2, 4, 6, 8	Intermediate values between two neighboring levels
Reciprocals	If index i has one of the above numbers assigned to it when compared to index j, then j has the reciprocal value when compared to i

$$A = (b_{ij})_{n\times n} \tag{1}$$

where A is the judgment matrix; n is the number of factors for the pair-wise comparison; and b_{ij} is the ratio of the factor U_i to the importance of U_j relative to a criterion. In addition, Eq. (1) has the following properties: $b_{ij} = 1/b_{ji}$, $i \neq j$; i, j = 1, 2, 3, …, n; $b_{ij} \geq 0$; $b_{ii} = 1$; etc.

(3) Calculate the maximum eigenvalue ($\lambda_{\max}$) of each judgment matrix and its corresponding eigenvectors. The relative weights of the elements in the index (bottom) hierarchy relative to the weights of the elements in the object (top) hierarchy can be obtained by normalizing the eigenvectors, which correspond to the maximum eigenvalue. Then, the judgment matrix is tested based on the consistency ratio (CR). The CR and the consistency index (CI) are calculated by Eq. (2) and Eq. (3), respectively.

$$CR = CI/RI \tag{2}$$

$$CI = (\lambda_{\max} - n)/(n-1) \tag{3}$$

where CI is the consistency index, and RI is the random consistency index, which can be acquired from Table 2 in Appendix B.

(4) Integrate the judgments over the various hierarchies to obtain an overall priority ranking for the alternatives. Complete the entire process from the object hierarchy to the index hierarchy.

3.3. SD model

SD, which constitutes a subject of analytical information feedback systems, was introduced by Jay Forrester in the 1960s and popularized by the Club of Rome's Limits to Growth in the 1970s (Forrester and Warfield, 1971). SD is a well-established system simulation method for understanding, visualizing and analyzing complex dynamic feedback systems that exhibit nonlinear, multi-feedback and time-varying properties. Compared with other commonly used methods, SD models can be applied not only to simulations of microscale systems but also to simulations of macroscale social systems to address systematic problems (Leal et al., 2006). In this study, SD was applied to simulate the long-term behavior of a complex water resources system, to further analyze both how a system evolves over time and how past and current behaviors influence the future WRCC, and to investigate the interrelations between different subsystems of the system. The water resources system and the coordination between the water supply and the water demand in particular display long-term behavioral characteristics for which the SD model is adequately suited; thus, the SD model was applied in Xi'an.

There are four basic types of variables in the SD model: a level variable (L), a rate variable (R), an auxiliary variable (A) and an information arrow. Level variables describe the cumulative effect of the system that reflects the accumulation of information over time; these variables are denoted with the symbol “▭”. Rate variables reflect the speed of the system's cumulative effect and the changes in level variables over time, thereby representing the speed of change in the system or the amplitude of a decision; these variables are denoted with the symbol ““○═⧖═▶○””. Auxiliary variables are intermediate variables that run through the decision-making process, while information arrows indicate the existence of a certain relationship between two variables linked by an arrow. In the SD model, the level equation constitutes the core equation describing the dynamic behavior of the system. In other words, the level equation seeks the integral expressed as the integral form shown in Eq. (4):

$$L(t) = L_0 + \int_0^t \left(\sum X_i - \sum X_o\right) dt \tag{4}$$

where $L(t)$ is the value of the level variable L at a time t; L_0 is the initial value of L; X_i is the input flow of L; and X_o is the output flow of L. The above equation indicates that the value of the level variable at the time t is equal to its initial value plus the accumulation of the net inflow over the time period [0, t]; this formula is denoted with the symbol ““○═⧖═▶▭”” in the flowchart. All of the abovementioned symbols can be found in Fig. 3 through Fig. 8 in Appendix A.

4. Establishing the evaluation index system and SD model for the WRCC in Xi'an

4.1. Evaluation index system

Water resources constitute an enormous and complex system that is influenced and restricted by numerous aspects, such as the water environment, water resources, society, and economy (Davies and Simonovic, 2011; Henriques, 2007). Consequently, the application of a single-criterion evaluation method to establish an evaluation index system of the WRCC will inevitably lead to inaccurate results. Therefore, to better reflect the status of the WRCC, a multi-factor assessment method should be employed. The selected evaluation indicators should reflect the actual conditions of the study area, and the indicators should also characterize both the changes in the water environment and the impacts of socio-economic development on the WRCC (Liu et al., 2012). For this purpose, we drew on both domestic and international research achievements, consulted with selected experts, and considered the actual water resources situation in Xi'an as well as the availability of statistical data. Eventually, an evaluation index system composed of a total of 16 evaluation indexes for the WRCC in Xi'an was established (Table 3); furthermore, the system was divided into four major components, i.e., economy subsystems, water resources subsystems, water environment subsystems and society subsystems. The selected indicators are commonly utilized regulatory indicators of relevant management departments involved with the water resources status, water consumption, economic development, wastewater discharge, and sewage treatment; additionally, the selected indicators are in accordance with established principles of integrity, comparability, dynamics and practicability.

4.2. SD model formulation

The SD model of the WRCC was employed to comprehensively simulate the socio-economic/water resources compound system involving the economy, society, water resources, water environment, land resources and policy in Xi'an. The interactions among the population, GDP, industrial structure, and other socio-economic factors were considered to highlight the feedback relationships between the water resources and various socio-economic factors (e.g., water consumption, sewage discharge and investment in environmental protection). Additionally, the SD model is based on detailed parameter estimations and numerical equations, thereby reducing uncertainties and improving the accuracy of the model. The WRCC is typically studied by using

Table 3
The basic composition of the evaluation index system and the weight values of each evaluation index.

Object hierarchy	Rule hierarchy	Index hierarchy	Indicator description	Weighted value
WRCC in Xi'an	Subsystem index for water resources	Water consumption per 10,000 RMB of GDP U_1	Reflects the regional water consumption	0.0576
		Total available water resources U_2	Reflects the amount of total available water resources	0.0939
		Recycling rate of industrial wastewater U_3	Reflects the water consumption of regional industry	0.0341
		Ratio of water supply to water demand U_4	Reflects the level of water supply capacity	0.144
	Subsystem index for society	Urbanization rate U_5	Reflects the level of urbanization	0.0786
		Total population U_6	Reflects the regional population	0.0914
		Coverage of green areas in developed areas U_7	Reflects the level of regional greening	0.0108
		Cultivated areas U_8	Reflects the regional development of agriculture	0.0922
	Subsystem index for the economy	Industrial water consumption U_9	Reflects the water consumption of regional industry	0.0514
		Irrigation water consumption U_{10}	Reflects the water consumption of regional irrigation	0.0499
		Urban domestic water demand U_{11}	Reflects the water consumption of regional irrigation	0.0356
		GDP U_{12}	Reflects the level of regional economic development	0.1203
		The amount of water pollution U_{13}	Reflects the pollution status of the water environment	0.0311
	Subsystem index for the water environment	Treatment rate for sewage U_{14}	Reflects the level of sewage treatment in the area	0.027
		The volume of COD emissions U_{15}	Reflects the pollution status of the water environment	0.034
		Investment in environmental protection U_{16}	Reflects the investment in regional environmental protection	0.0481

computer-aided SD simulations. Thus, in this study, an SD model capable of engaging in complex decision-making processes and conducting comprehensive research on the regional WRCC was established. In this case, we used the administrative area of Xi'an as the model boundary. The following development scenarios were relatively easy to implement; this was beneficial for the management units insomuch that problems related to undefined responsibilities were avoided (Zhang et al., 2014). Moreover, the WRCC is influenced by many factors defined by both connections and restrictions among them; therefore, based on the WRCC evaluation index system described above, the actual social development state in Xi'an, and the effects of the social, economic and water environments on the WRCC, the WRCC system was divided into six subsystems. The main variables and the functions used in this study (in Vensim language) are summarized in Table 4 in Appendix B.

4.2.1. Population subsystem

Representing the integration of social groups, the population constitutes one of the leading factors in socio-economic development, and thus, the population can have a significant impact on water resources (Falkenmark and Widstrand, 1992; Sinding, 2009). The total population is determined by the birth population, death population, and net migration population. The birth population is determined mainly by the birth rate, while the water resources constrain the rate of population growth (Yuan and Tol, 2004). In addition, the death population and net migration population are determined by the death rate and net migration rate, respectively (Fig. 3 in Appendix A). When designing the population subsystem, some auxiliary variables were introduced to study the influences of these factors on the population. The population subsystem is linked to the other subsystems that profoundly affect the development of the socio-economy and influence the water environment. For instance, because non-agricultural populations and tertiary industries are key population drivers (Chen and Shi, 2014; Su et al., 2014), government policy factors were introduced to study the influences of these factors on the migration population. Furthermore, labor migration behavior in China is significantly affected by the urban-rural income gap; the greater the income gap between urban and rural residents, the more migrant laborers are drawn to cities. Thus, an income factor was also introduced.

4.2.2. Economy subsystem

The economic subsystem is an important component of the overall system and has a substantial impact on both the state of water resources and the performances of other subsystems (Fig. 4 in Appendix A). According to the method of industrial classification, the internal structure of the economic subsystem is divided into three parts: primary industry, secondary industry and tertiary industry. Each industry is affected not only by its growth rate but also by the available water resources. When the water demand exceeds the water supply, the economic growth rate slows down correspondingly. The behavior and characteristics of the water resources system impact the economic industrial structure, and various industries exhibit immense differences in their demand for water resources, while different industrial structures of the economic system form different water demand structures (Zhang et al., 2016). The GDP constitutes the core indicator of economic accounting and represents the regional level of socio-economic development (Ju et al., 2013). Thus, the regional GDP is the most significant variable in the economic subsystem, which consists of the combined value of agriculture, industry and tertiary industry. The function of the economic subsystem mainly reflects the following aspects: the level of economic development in Xi'an and the impacts of economic development on the water resources and water quality in the study area. Economic development is constrained by limited water resources, while water resources ensure the stable development of the economy. In addition, the relationships between the economic subsystem and other systems are similar to those of the population industry.

4.2.3. Water resource supply subsystem

The purpose of the water resource supply subsystem is to estimate the supply capability of local water resources. This subsystem provides the domestic water required by the population to meet the basic living requirements; in addition, it also supplies the fundamental material base for the economic subsystem and sustains the healthy development of the water environment subsystem (Fig. 5 in Appendix A). However, these three subsystems (i.e., the economic, water environment, and population subsystems) also have negative effects on water resources. For instance, excessive increases in the population, economic development and ecological water demand will aggravate the water supply burden, thereby leading to an imbalance between the water supply and water demand (Cai et al., 2016). In this study, the internal structure of the water resource supply subsystem is divided into three parts: total surface water resources, total underground water resources and recycled water resources. The total quantity of available water resources signifies the total water resources actually provided to consumers, which is estimated based on the utilization rate of water resources.

4.2.4. Land resources subsystem

The relationship between water resources and land resources is mainly reflected by the mutual influence of their utilization (Keeley and Faulkner, 2008). The functions of the land resource subsystem in the overall system determine two main aspects: the influences of changes in the effective irrigation area on the water resource demand subsystem and the effects of the WRCC at the city scale (Fig. 6 in Appendix A). The land resource subsystem was classified into four types: cultivated areas, constructed regions, land used for construction and land used for green areas. Among these variables, cultivated areas exhibit the highest influence on the water resource demand subsystem; the agricultural water demand varies markedly with changes in cultivated areas. Moreover, the urban ecological water demand will grow as the areas of green land and external transportation land increase.

4.2.5. Water environment subsystem

The quality of the water environment is a reflection of the sustainability of urban development, and it directly affects the quality of human life and the sustainable utilization of water resources (Kilkis, 2016). The urban water environment is closely related to the residential environment in addition to industrial development and human health; consequently, the degradation and destruction of the urban water environment will result in widespread economic losses and security risks. The water environment subsystem (Fig. 7 in Appendix A) reflects the pollution load in the study area, in this subsystem, the main evaluation indexes are the volume of chemical oxygen demand (COD) emissions and the amount of water pollution. The volume of COD emissions is determined by the volume of COD production and the treatment rate of sewage. To a certain extent, the treatment rate of sewage can be further improved by increasing the amount of investment in sewage management projects. There are two sources for the volume of COD production: the urban population and industry. In this study, however, the non-agricultural population and the secondary industry are utilized as substitutes for the urban population and industry, respectively. The amount of water pollution refers to the difference between the volume of total sewage discharged and the volume of sewage disposal. The sources of the volume of total sewage discharged are similar to those of the volume of COD production. Specifically, the sewage discharged from the tertiary industry is considered in the calculation of the volume of total sewage discharged.

4.2.6. Water resource demand subsystem

The water resource demand subsystem forms the core component of the entire system, and it includes five parts: domestic water demand, industrial water demand, agricultural water demand, urban ecological water demand and tertiary industrial water demand (Fig. 8 in Appendix A). The domestic water demand reflects the quantity of water used in the population's daily life; domestic water is also important in terms of the consumption of water resources and the source of water pollution. However, because the water quotas are different for urban and rural residents, the urban domestic water demand and rural domestic water demand are calculated separately. The agricultural water demand is the water consumed for agricultural irrigation, animal husbandry, fishery, forestry and fruit irrigation (Cai et al., 2015). The water demand of animal husbandry consists of two sectors: large animals (e.g., pigs, cows and goats) and poultry. Notably, agricultural water consumption accounts for the largest portion of water consumption in Xi'an. The urban ecological water demand is the sum of the water demand of green areas, environmental sanitation and surface evaporation, and thus, it is mainly influenced by the area of green land, the whole water area, the area of roads and the total annual precipitation (Altunkaynak et al., 2005; Wei et al., 2015); the water demand of green areas and environmental sanitation will grow as the areas of roads and green land increase. The water demand of surface evaporation refers to the amount of water that is used to maintain a certain water level in an urban water area. Due to the effects of evaporation, most artificial sources of water may shrink without a supplementary source of water; in contrast, when local precipitation exceeds evaporation, there is no water demand of surface evaporation. According to the official report released by the Water Resources Bulletin of Shaanxi Province (2005–2015), the urban ecological water demand in Xi'an is mainly impacted by urban environmental sanitation, and the proportion of ecological water has gradually increased over time. Due to the regional industrial scale and because the proportion of the urban industrial structure greatly affects the industrial water demand (Dong, 2008; Yu et al., 2011), the portion of this subsystem involving an industrial water demand consists of two components: industrial water consumption and tertiary industrial water consumption.

4.3. Model verification and sensitivity analysis of the model

A simulation model is a system that abstracts the real world into an information structure. Hence, the quality of a model simulation depends upon whether it can properly represent the real-world system (Wang et al., 2017b). Therefore, testing the validity of such a model through a historical examination and sensitivity analysis before running the simulation is indispensable.

4.3.1. Error test

The historical data from 2005 to 2015 were fed into the model. Then, the simulation results were compared with the actual values. The accuracy of the model provided the basis for the corresponding judgment to verify the correlation between the simulated and actual values. Due to the large number of parameters in the model, only several representative stock variables were selected for the test. Table 5 in Appendix B shows that the error of each indicator in the model was no more than 10%, which falls within the acceptable range. The simulation results of the model matched well with the actual values, indicating that the model effectively reflected the reality and provided a good foundation for forecasting the development trend.

4.3.2. Sensitivity analysis

In this study, sensitivity tests were performed to control the optimization of the system and ascertain which parameter variations more greatly influenced the behaviors of each subsystem. We examined the sensitivities of seven variables (representing each subsystem) to changes in 14 parameters. Each parameter was manually increased by 10% annually during the simulation period. The sensitivity of a variable relative to a test parameter can be calculated using Eq. (5).

$$S_t = \left| \frac{(Y_t' - Y_t)/Y_t}{(X_t' - X_t)/X_t} \right| \tag{5}$$

where S_t is the sensitivity of a variable relative to a test parameter at time t; Y_t and Y_t' are the values of the variable before and after the adjustment of the parameter at time t, respectively; X_t and X_t' are the values of the parameter before and after the adjustment at time t, respectively. If $0.15 \geq S_t \geq 0.1$, the variable is more sensitive; if $0.1 \geq S_t \geq 0.05$, the variable is less sensitive; if $S_t \geq 0.15$ or $S_t \leq 0.05$, the variable is very sensitive or not sensitive, respectively.

The results of the analysis (Table 6 in Appendix B) reveal that the sensitivities of the various parameters were quite different for each subsystem. For instance, the rate of secondary industrial production growth greatly influenced the total water demand but had little effect on the total population. Therefore, the parameters were modified for different purposes when the various scenarios were formulated. According to the results from the error test and sensitivity analysis, the SD model was considered valid. Moreover, most of the parameters were either less sensitive or not sensitive, indicating that the constructed model was robust.

4.4. Quantitative evaluation of the WRCC

4.4.1. Data normalization

The calculation of the WRCC can be cumbersome if the units and dimensions of the selected evaluation indicators are different. Hence, all evaluation indicators must be normalized to quantify the WRCC (Zhang et al., 2014). In this study, the various WRCC evaluation indicators were normalized to determine their individual scores. Some of the indicators had positive impacts on the WRCC, and thus, these indicators (e.g., the total volume of available water resources and recycling rate of industrial wastewater) were termed as a development index. In contrast, some of the indicators had negative impacts, and thus, these indicators (e.g., the volume of water consumption per 10,000 RMB of the GDP and the volume of COD emissions) were termed as a constraint index. The remaining indicators (e.g., the total population and urbanization rate) were termed as a coordination index. When a coordination index is closer to the average value, it is regarded as more beneficial for enhancing the WRCC.

Eq. (6) and Eq. (7) were used to normalize the data for the development and constraint indexes, respectively.

$$S_{ih} = \frac{V_{ih} - \min\limits_{h=1}^{m} V_{ih}}{\max\limits_{h=1}^{m} V_{ih} - \min\limits_{h=1}^{m} V_{ih}} \tag{6}$$

$$S_{ih} = \frac{\max\limits_{h=1}^{m} V_{ih} - V_{ih}}{\max\limits_{h=1}^{m} V_{ih} - \min\limits_{h=1}^{m} V_{ih}} \tag{7}$$

For the coordination index, Eq. (8) was applied.

$$S_{ih} = \frac{1 - |V_{ih} - V_{ih}^{*}|}{\max\limits_{h=1}^{m} V_{ih} - \min\limits_{h=1}^{m} V_{ih}} \tag{8}$$

where S_{ih} is the score of the i-index in the h-scheme; V_{ih} is the simulation value of the i-index in the h-scheme; and V_{ih}^{*} is the average value of V_{ih} in this study.

4.4.2. Calculation of the WRCC index

After normalizing the data, the scores of all indexes were weighted and summed to reflect the overall performance of the WRCC in Xi'an. The WRCC index was calculated by Eq. (9), which represents the weighted summation of all indicators in the evaluation system.

$$R_h = \sum_{i=1}^{n} U_i S_{ih} \tag{9}$$

where U_i is the weighted value of the i-index determined by Table 3, and R_h is constrained to be less than or equal to 1. Note that since each scenario run started in 2016, the value of the WRCC index in 2015 is the average value of the simulation results in 2016. According to the different scales of the WRCC, the WRCC index was divided into five types (Table 7).

4.5. Scenario management

To promote the coordinated development of the water environment and socio-economy and to improve the WRCC in Xi'an, five scenarios were proposed. Detailed information on each of the schemes is shown in Table 8 in Appendix B.

Table 7
The status of the WRCC in Xi'an.

WRCC index	Carrying status
0.8–1.0	Excellent
0.6–0.8	Positive
0.4–0.6	Normal
0.2–0.4	Poor
0–0.2	Weak

4.5.1. Business as usual

To facilitate comparisons with the other scenarios, the business-as-usual (BAU) condition was used to estimate the future trend of the WRCC under the current social development pattern.

4.5.2. High economic scheme

Owing to the relatively backward status of development in Shaanxi Province and the pressure for future development, a high economic scheme (HES) was employed to emphasize economic development in Xi'an (Shi, 2008). In this scheme, economic development remains the priority for the foreseeable future. To simulate this situation, the feedback effects of the economic subsystem in the model were enhanced by appropriately amplifying the parameters related to economic development (e.g., the rate of secondary industrial production growth and the rate of tertiary industrial production growth) and by slightly adjusting the others.

4.5.3. Readjusted industrial structure scheme

In the readjusted industrial structure scheme (RISS), the development of the primary and secondary industries is slowed while the development of the tertiary industry is accelerated. The development of the tertiary industry has become a hallmark for evaluating the level of economic development in modern society. In comparison with other industries, the tertiary industry in Xi'an has great advantages with regard to both its output value and its industrial structure (Yang and Zheng, 2006). Xi'an's Thirteenth Five-Year Plan recently noted that the rate of contribution of the tertiary industry to urban economic growth had increased annually, and its development has been used to determine the trend of future economic development in Xi'an. However, a rational industrial structure is conducive to the sustainable utilization of water resources (Bao et al., 2006). As various industries differ in their consumption of water resources, any adjustment of the industrial development pattern will change the regional water demand on a large scale.

4.5.4. Resource-environment protected scheme

The resource-environment protected scheme (REPS) emphasizes the protection of water resources and the water environment with the particular goal of conserving water and controlling pollution. For years, water resource problems have dramatically influenced the socio-economic development of urban areas, and thus, effective remediation strategies for reducing the emissions and background levels of pollution in the environment are urgently needed (Chen et al., 2017). Major issues include the inefficient utilization of water resources, the irrational water consumption structure and the implementation of unreasonable management strategies. Water consumption by farming irrigation dominates the total water demand in Xi'an, and thus, the REPS was enacted to control the increase in the water demand by suitably reducing various water quotas and improving the water-use efficiency (Xiong, 2006).

4.5.5. Comprehensive scheme

The comprehensive scheme (CS) integrates the abovementioned scenarios, i.e., focusing on the development of tertiary industry, readjusting the industrial structure, suitably reducing the water-use quotas of different industries, and increasing investments in environmental protection.

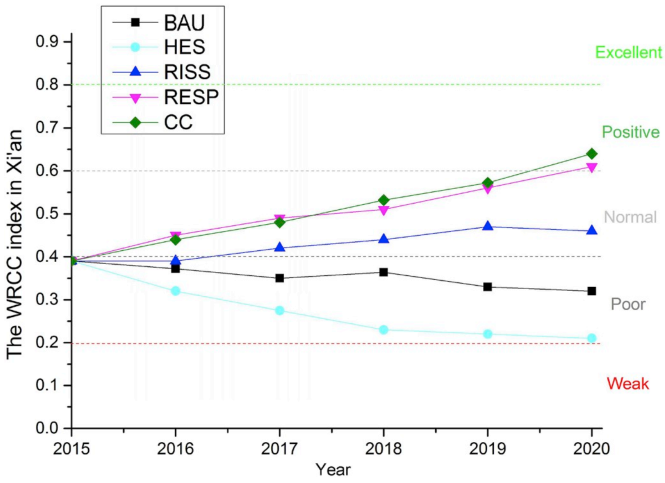

Fig. 9. The dynamic trends of the WRCC index in different scenarios.

5. Results and discussion

5.1. Simulation results under the different scenarios

According to the descriptions provided above, the five scenarios were simulated using the Vensim software, and we obtained the dynamic changes in the stock variables. After normalizing the data and performing calculations, the trend of the WRCC in Xi'an from 2015 to 2020 was obtained (Fig. 9).

5.1.1. BAU scenario

To date, the WRCC index exhibited a downward annual trend. Specifically, prior to 2015, the CC in the region shifted from a normal status to a poor status; however, the CC has not recovered to its original state. Moreover, the ratio of the water resources supply to the water resources demand in the study area decreased from 1.41 to 0.91 during the simulation period, and the GDP grew slowly to 877.96 billion yuan. The industrial water consumption is predicted to rise to 4.77×10^8 t by 2020, and the water demand of farming irrigation will have decreased from 9.0×10^8 t in 2005 to 5.9×10^8 t in 2020 (Fig. 10d and e).

5.1.2. HES scenario

As shown in Fig. 10a, the regional economy is predicted to exhibit extensive development. By 2020, the GDP of Xi'an will reach 976.55 billion yuan. The per capita disposable income of urban households in Xi'an will exceed 63,752 yuan. The above results suggest that the HES scenario better promotes economic development; however, as a result, the total water demand of the city will grow quickly. Fig. 10b shows that the ratio of the water resources supply to the water resources demand will reach only 0.87 by 2020; additionally, the industrial water consumption in Xi'an will increase rapidly from 3.96×10^5 t in 2015 to 4.77×10^5 t in 2020. These conditions will result in severe water shortages in the city. In terms of the water environment, the volume of COD emissions will dramatically increase from 7.3×10^4 t in 2015 to 9.6×10^4 t in 2020 (Fig. 10c). Furthermore, following this scheme, Fig. 9 shows a sharp downward trend in the WRCC index of the study area from poor to nearly weak.

5.1.3. RISS scenario

Based on the RISS simulation scenario, the GDP of the city is expected to reach 942.72 billion yuan, and the proportion of tertiary industrial in the GDP will increase to 68%. Remarkably, the ratio of the water resources supply to the water resources demand will increase to 1.32. Fig. 10d shows that industrial water consumption will have decrease from 3.96×10^8 t in 2015 to 3.89×10^8 t in 2020; the continuous increasing trends observed in the BAU and HES scenarios were preliminarily controlled. As shown in Fig. 9, the WRCC index steadily recovered from a poor status and ascended to a normal carrying status by 2016.

5.1.4. REPS scenario

According to Fig. 10d, in the REPS scenario, the growth trend in industrial water consumption will level off. With additional investments dedicated to controlling pollution and advancements in science and technology, the volume of COD emissions will have decreased from 6.7×10^4 t in 2015 to 5.5×10^4 t in 2020. Fig. 9 shows that the CC status will become positive in 2020.

5.1.5. CS scenario

As shown in Fig. 10a and d, in the CS scenario, the GDP will have increased from 627.4 billion yuan in 2015 to 941.9 billion yuan in 2020, and the industrial water consumption will have decreased from 3.96×10^8 t in 2015 to 3.85×10^8 t in 2020. By 2020, the WRCC index will achieve a positive status in Xi'an.

5.2. Comparison of the scenarios

The results from the BAU scenario implied that the conflict between the supply and demand of urban water resources would continue to increase, and the water environment situation was not optimistic. Given these conditions, the existing development trend cannot meet the requirements necessary for sustainable socio-economic and water environment development in Xi'an.

In the HES scenario, economic growth was higher than that in BAU; specifically, by 2020, the GDP value increased by 9% more than that in the BAU scenario, though the water resource constraints and water environmental pollution became more serious in the HES scenario. Specifically, the volume of COD emissions exceeded 9.6×10^4 t, which is 1.34 times higher than the volume of COD emissions in the BAU scenario. The explanation for this is straightforward: excessive economic growth resulted in continuous increases in the cost of water resources and further environmental degradation. The HES scenario was also inadequately suited for sustainable development conditions, especially at a time when the Chinese government is strengthening the construction of an ecological civilization. Thus, the industrial structure had to be adjusted to maintain sustainable urban development.

Through adjustments to the industrial structure, the economic performance of Xi'an was better in the RISS scenario than that in the BAU scenario, but the economic performance of Xi'an was slightly worse than that in the HES scenario. In terms of improving the WRCC, the results showed that the RISS scenario was more effective than the abovementioned scenarios. As the development of the primary and secondary industries slowed, the ratio of the water resources supply to the water resources demand increased by an average of 17.6% compared with the BAU scenario. However, the integral improvement of the WRCC was not significant, and the CC status was merely maintained at a normal level (i.e., the WRCC index was kept below 0.47). This result was observed because environmental and water resource management policies were not considered in this scenario. Therefore, the improvement of the WRCC should be considered from multiple perspectives.

In the REPS scenario, the WRCC of the study area improved remarkably (i.e., the WRCC index increased to 0.61). By 2020, the amount of water consumption decreased to 83% of the simulation results from the BAU scenario. However, one drawback in the REPS scenario was the exclusion of socio-economic progress, which resulted in a low economic growth performance compared with the other scenarios. Accordingly, a more comprehensive solution should be offered.

In the CS scenario, the WRCC index greatly improved. The GDP was also higher in the CS scenario than it was in most other scenarios (except for the HES scenario). In summary, the CS scenario was effective in all regards.

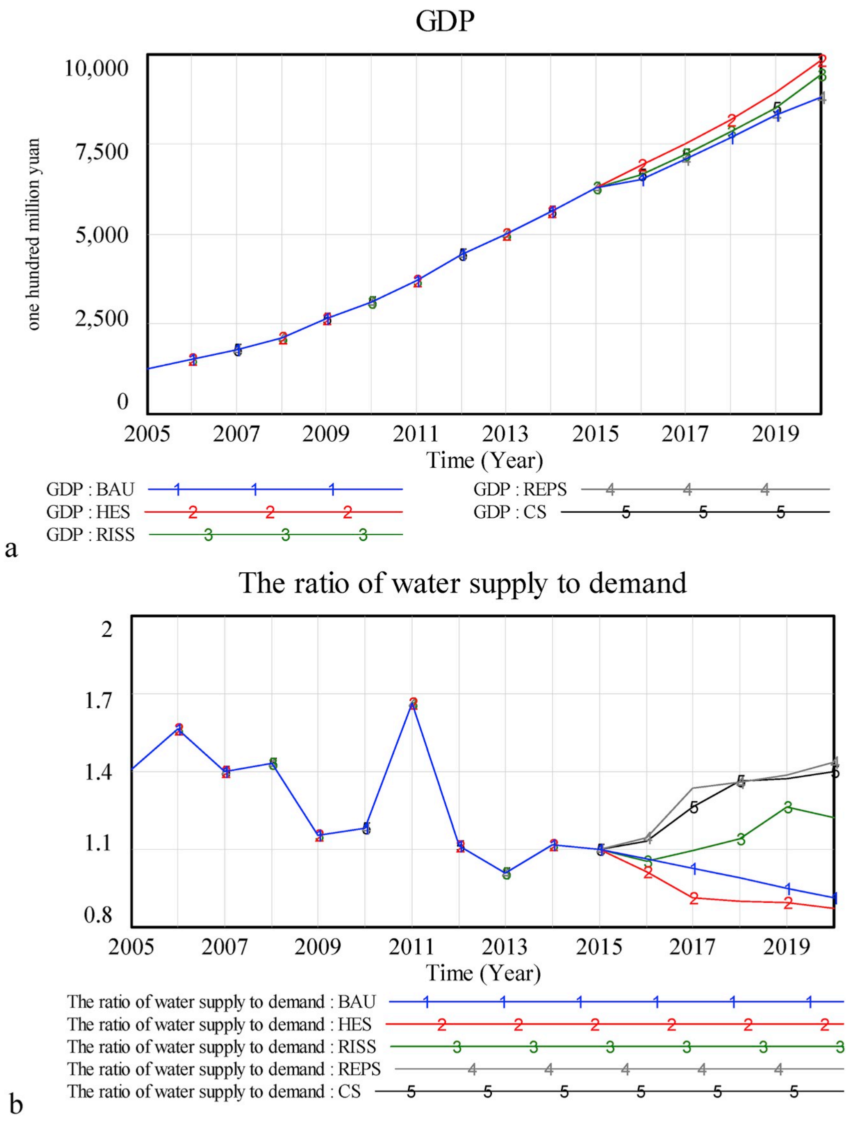

Fig. 10. Simulated development trends for the (a) GDP, (b) ratio of the water supply to the water demand, (c) volume of COD emissions, (d) industrial water consumption and (e) water demand of farming irrigation.

5.3. Policy implications

The demand for water resources will increase as the economy and population continue to grow. Under such conditions, more efficiently monitoring the exploitation rate of water resources and appropriately reducing the water quotas of various industries can effectively reduce the overall water consumption. Specifically, the changes in the water demand of farming irrigation present a markedly decreasing trend; however, the main reason for this is that cultivated areas have been shrinking on a yearly basis as a consequence of urban expansion rather than increases in the effective irrigation coefficient. Moreover, simulation results show that the water demand of farming irrigation is still the largest portion of the total water demand in Xi'an. Thus, the water demand of farming irrigation needs to be restricted. Much of the agricultural irrigation infrastructure is outdated; this leads to a low irrigation efficiency. According to Xi'an's Thirteenth Five-Year Plan, the effective irrigation coefficient reached 0.705 in 2015, which was a remarkable achievement compared with the coefficient value of 0.6 in 2010; however, there is still plenty of room for improvement. At present, agricultural development mainly depends on surface irrigation and traditional sprinkler irrigation in areas throughout northern China (Li et al., 2012). If micro-irrigation, micro-sprinkler irrigation or other advanced water-saving irrigation technologies are widely popularized and applied, then the effective irrigation coefficient will reach 85–90%, and agricultural water consumption will be further reduced. Though the agricultural sector has reduced its irrigation water quota and has introduced several water-saving policies in recent years, it remains in a backward state. Thus, the local government should accelerate the development and implementation of advanced irrigation and water-saving technologies. These proposals also cater to the requirements of Xi'an's Thirteenth Five-Year Plan that promote agricultural modernization.

Based on the status quo in Xi'an, there is little room for exploiting new water resources. In addition to some water diversion projects being constructed, the local government has recently promoted a project consisting of rainwater collection systems. Although rainwater utilization has made a relatively small contribution to the available amount of water resources in Xi'an, this practice has the potential to represent an important water supply source in the future. After years of construction, the city already boasts a large capacity for treating circulating water. However, the construction of infrastructure in Xi'an lacks reasonable and scientific planning, which greatly limits the utilization of recycled water. At present, the development and utilization of reclaimed water in Xi'an is still in its infancy. The annual average percentage of industrial water recycled reached only 70%, and the ratio of water reused

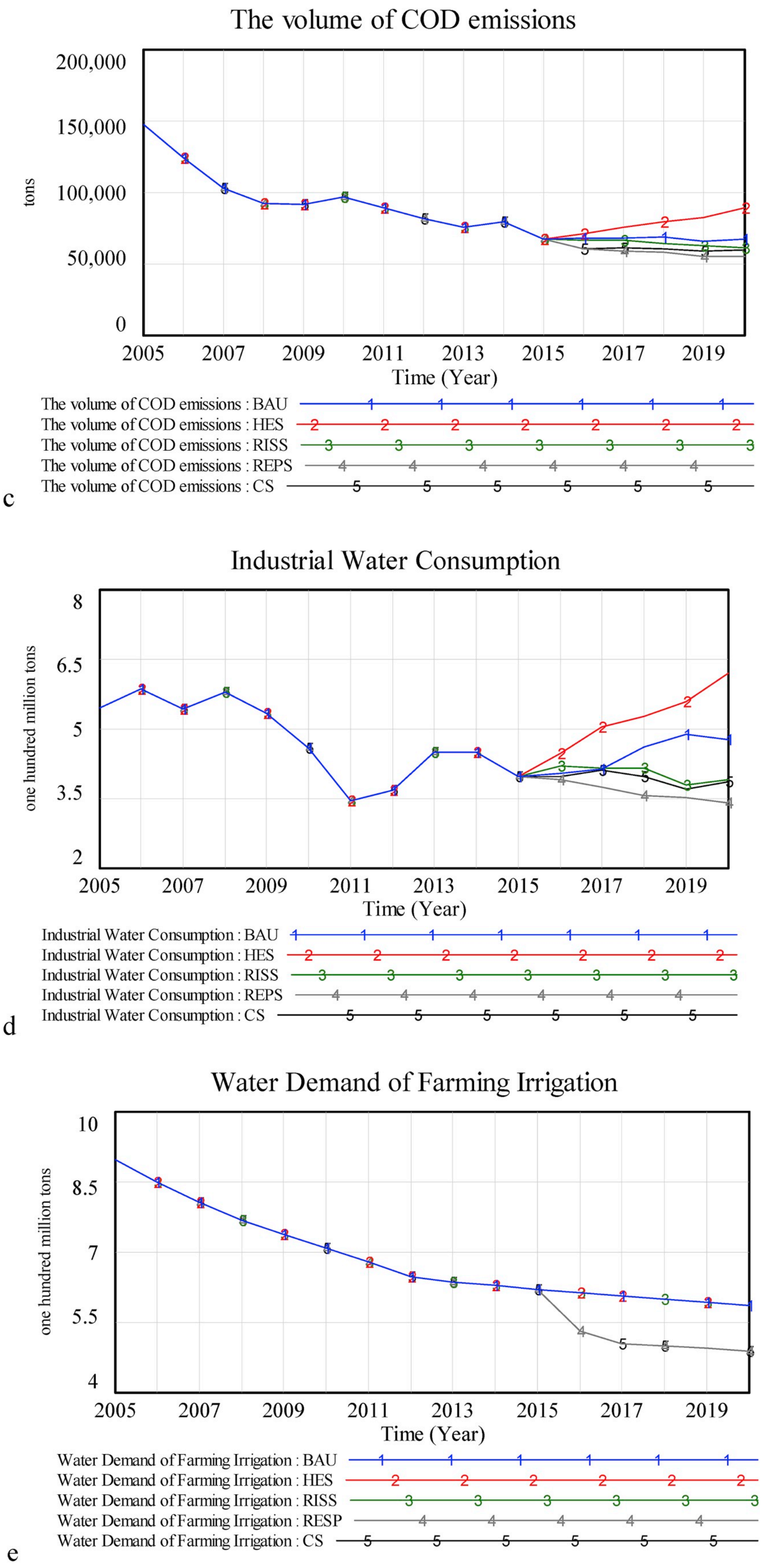

Fig. 10. (*continued*)

from other sources, such as water for residential and agricultural use, is low. Because the coverage of the reclaimed water network is inadequate, most reclaimed water can be drained away only from the canal. Therefore, strengthening the management of circulating water, expanding the coverage of reclaimed water pipe networks and improving the repetitive utilization rate of water resources are good solutions for bridging the gap between the water supply and water demand in the study area.

Over recent decades, traditional industries, such as the chemical industry, textile industry, and machinery industry, have become the dominant drivers of economic growth in Xi'an. However, most of these industries consume high volumes of water and produce considerable amounts of pollution. Although Xi'an has diversified somewhat over the last few years, its economic development model is still highly energy-intensive and environmentally damaging. Because the output and water-use efficiency of the tertiary industry are higher than those of other industries, vigorously developing the tertiary industry would help maintain rapid economic growth, and such development would avoid excessive increases in the amount of water consumption. Consequently, the blind pursuit of rapid economic growth is not desirable, and attempts to accelerate transformations in various industries are inevitable. Nevertheless, the experiences of many developed countries indicate that water consumption will decrease even as the GDP grows with the promotion of industrial reforms and improvements to water efficiency and recycling policies.

5.4. Limitations and future research directions

Furthermore, the following limitations exist in this research:

(1) The WRCC is a complex, multi-factor system. Though this research involves various elements, the socio-economic/water resources compound model constructed herein is still a simplified model. During the modeling process, some factors and some relationships among the subsystems are oversimplified or are not considered; these include changes in the water price, interactions between the socio-economy and water environment, and impacts of climate change on water resources (Cai et al., 2011a,b).

(2) The constructed model is limited because some of the data are difficult to collect, especially data on wastewater discharge. Therefore, the relevant simulation results are difficult to verify. In addition, because of the different statistical standards of each department, the uncertainty of the SD model was exacerbated.

Research on the WRCC involves the disciplines of economics, water management, environmental management and water resource management. With the help of more advanced methods and technologies, researchers will obtain more scientific and reasonable results. To conduct a more comprehensive study in the future, an SD model should be combined with a hydrological model or other relevant model.

6. Conclusions

In this paper, according to the characteristics of the WRCC in Xi'an, an assessment system incorporating 16 individual indexes was established by the AHP method. Then, a socio-economic/water resources compound model consisting of six subsystems was constructed. After performing a validity test and a sensitivity analysis, the test results demonstrated that the model adequately captured the essence of the integrated water resources system in Xi'an. We formulated five scenarios to simulate the dynamic trend of the WRCC under different social development modes. After performing calculations, analyses and comparisons of the simulation results, we chose the optimal scenario. The presented analysis allowed us to draw the following conclusions.

First, the SD model was used to simulate the outcomes of five different designed scenarios. The results indicated that the current social development pattern in Xi'an cannot meet the requirements necessary for sustainable urban development. The HES scenario highlighted the promotion of economic development, but it exhibited a dismal performance with regard to improving the WRCC, which was certainly not a suitable solution. In terms of economic development, the RISS scenario was slightly inferior to the HES scenario; specifically, the improvement of the WRCC was better than the abovementioned scenarios, yet the improvement was still not sufficient. The REPS scenario focused only on the protection of the water environment and the conservation of resources while ignoring economic growth. Combining the advantages of the above scenarios, the CS scenario significantly improved the WRCC in Xi'an, and the WRCC index achieved a positive carrying status. Second, agricultural water consumption currently accounts for an excessive proportion of the total water demand. The key to changing this situation is improving the irrigation efficiency and increasing the amount of investment in the agricultural irrigation infrastructure. Third, an adjustment of the industrial structure in Xi'an is urgently needed; accordingly, the government should not emphasize economic growth. In contrast, accelerating the development of the tertiary industry is a feasible solution for reducing urban water consumption.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2018.09.085.

References

Alcamo, J., Flörke, M., Märker, M., 2007. Future long-term changes in global water resources driven by socio-economic and climatic changes. Hydrol. Sci. J. 52, 247–275. https://doi.org/10.1016/j.apenergy.2012.08.002.

Altunkaynak, A., Özger, M., Çakmakci, M., 2005. Water consumption prediction of Istanbul city by using fuzzy logic approach. Water Resour. Manag. 19, 641–654. https://doi.org/10.1007/s11269-005-7371-1.

Bakker, K., 2010. Privatizing Water: Governance Failure and the World's Urban Water Crisis. Cornell University Press. http://www.jstor.org/stable/10.7591/j.ctt7z9jv.

Bao, C., Fang, C., Chen, F., 2006. Mutual optimization of water utilization structure and industrial structure in arid inland river basins of Northwest China. J. Geogr. Sci. 16, 87–98. https://doi.org/10.1007/s11442-006-0109-z.

Cai, J., Varis, O., Yin, H., 2016. China's water resources vulnerability: a spatio-temporal analysis during 2003–2013. J. Clean. Prod. 142 (4), 2901–2910. https://doi.org/10.1016/j.jclepro.2016.10.180.

Cai, X., Zhang, X., Noël, P.H., Shafiee-Jood, M., 2015. Impacts of Climate Change on Agricultural Water Management: a Review, vol. 2. Wiley Interdisciplinary Reviews Water, pp. 439–455. https://doi.org/10.1002/wat2.1089.

Cai, Y.P., Huang, G.H., Tan, Q., Liu, L., 2011a. An integrated approach for climate-change impact analysis and adaptation planning under multi-level uncertainties. Part II. Case study. Renew. Sustain. Energy Rev. 15, 3051–3073. https://doi.org/10.1016/j.rser.2011.03.014.

Cai, Y.P., Huang, G.H., Wang, X., Li, G.C., Tan, Q., 2011b. An inexact programming approach for supporting ecologically sustainable water supply with the consideration of uncertain water demand by ecosystems. Stoch. Environ. Res. Risk Assess. 25, 721–735. https://doi.org/10.1007/s00477-011-0477-5.

Chen, J., 2007. Rapid urbanization in China: a real challenge to soil protection and food security. Catena 69 (1), 1–15. https://doi.org/10.1016/j.catena.2006.04.019.

Chen, W., Shi, M., 2014. Demand Effects of Population Ageing on Service Industry Growth. Population Research (in Chinese).

Chen, Z., Zhang, R.R., Han, S.S., 2017. An enhanced environmental multimedia modelling system (FEMMS): Part I–development and model verification. Environ. Eng. Manag. J.(EEMJ) 16 (2).

Cheng, H., Hu, Y., Zhao, J., 2009. Meeting China's water shortage crisis: current practices and challenges. Environ. Sci. Technol. 43, 240. https://doi.org/10.1021/es801934a.

Clarke, A.L., 2002. Assessing the carrying capacity of the Florida keys. Popul. Environ. 23, 405–418. https://doi.org/10.1023/A:1014576803251.

Davies, E.G.R., Simonovic, S.P., 2011. Global water resources modeling with an integrated model of the social–economic–environmental system. Adv. Water Resour. 34, 684–700. https://doi.org/10.1016/j.advwatres.2011.02.010.

Dong, K., 2008. The dynamic optimization model of industrial structure with energy-saving and emission-reducing constraint. J. Sustain. Dev. 1, 27. https://doi.org/10.5539/jsd.v1n2p27.

Falkenmark, M., Widstrand, C., 1992. Population and water resources: a delicate balance. Popul. Bull. 47, 1–36.

Feng, L.H., Zhang, X.C., Luo, G.Y., 2008. Application of system dynamics in analyzing the carrying capacity of water resources in Yiwu City, China. Math. Comput. Simulat. 79 (3), 269–278. https://doi.org/10.1016/j.matcom.2007.11.018.

Forrester, J.W., Warfield, J.N., 1971. World dynamics. IEEE Trans. Syst. Man Cybern. 2, 558–559.

Garfì, M., Ferrer-Martí, L., Bonoli, A., Tondelli, S., 2011. Multi-criteria analysis for improving strategic environmental assessment of water programmes. A case study in semi-arid region of Brazil. J. Environ. Manag. 92, 665–675. https://doi.org/10.1016/j.jenvman.2010.10.007.

Han, D., Currell, M.J., Cao, G., 2016. Deep challenges for China's war on water pollution. Environ. Pollut. 218 (218), 1222–1233. https://doi.org/10.1016/j.envpol.2016.08.078.

Henriques, C., 2007. Hydrology and water resources management in East Anglia and North West England in the context of climate and socio-economic change. J. Med. Microbiol. 56, 1161–1166.

Iliadis, L.S., Maris, F., 2007. An Artificial Neural Network model for mountainous water-resources management: the case of Cyprus mountainous watersheds. Environ. Model. Software 22, 1066–1072. https://doi.org/10.1016/j.envsoft.2006.05.026.

Ju, J.Y., Zhu, R.X., Geng, L., 2013. Forecasting and analysis the demand of agricultural mechanization for economic development. Adv. Mater. Res. 697, 3512–3515. https://doi.org/10.4028/www.scientific.net/AMR.694-697.3512.

Keeley, A., Faulkner, B.R., 2008. Influence of land use and watershed characteristics on protozoa contamination in a potential drinking water resources reservoir. Water Res. 42, 2803–2813. https://doi.org/10.1016/j.watres.2008.02.028.

Kessler, J.J., 1994. Usefulness of the human carrying capacity concept in assessing ecological sustainability of land-use in semi-arid regions. Agric. Ecosyst. Environ. 48, 273–284. https://doi.org/10.1016/0167-8809(94)90109-0.

Khanna, P., Babu, P.R., George, M.S., 1999. Carrying-capacity as a basis for sustainable development a case study of National Capital Region in India. Prog. Plann. 52, 101–166. https://doi.org/10.1016/S0305-9006(99)00004-5.

Kilkis, S., 2016. Sustainable development of energy, water and environment systems index for Southeast European cities. J. Clean. Prod. 130, 222–234. https://doi.org/10.1016/j.jclepro.2015.07.121.

Leal, N.A.C., Legey, L.F., Gonzálezaraya, M.C., Jablonski, S., 2006. A system dynamics model for the environmental management of the Sepetiba Bay Watershed, Brazil. Environ. Manag. 38, 879. https://doi.org/10.1007/s00267-005-0211-5.

Liu, H., 2012. Comprehensive carrying capacity of the urban agglomeration in the Yangtze River Delta, China. Habitat Int. 36, 462–470. https://doi.org/10.1016/j.habitatint.2012.05.003.

Liu, J., Dong, S., Mao, Q., 2012. Comprehensive evaluation of the water resource carrying capacity for China. Geogr. Nat. Resour. 33, 92–99. https://doi.org/10.1134/S1875372812010155.

Li, Z., Zhao, W., Sun, W., et al., 2012. Application prospect of sprinkler irrigation technology in water-short areas of northern China. Trans. Chin. Soc. Agric. Eng. 28 (6), 1–6. https://doi.org/10.3969/j.issn.1002-6819.2012.06.001.

Long, T.R., Jiang, W.C., He, Q., 2004. Water resources carrying capacity: new perspectives based on eco-economic analysis and sustainable development. J. Hydraul. Eng. 35, 38–45. https://doi.org/10.3321/j.issn:0559-9350.2004.01.008. (in Chinese).

Peng, H., Zhou, H., 2011. A fuzzy-dependent chance multi-objective programming for water resources planning of a coastal city under fuzzy environment. Water Environ. J. 25, 40–54. https://doi.org/10.1111/j.1747-6593.2009.00187. x.

Saaty, T.L., 1990. How to make a decision: the analytic hierarchy process. Eur. J. Oper. Res. 48, 9–26. https://doi.org/10.1016/0377-2217(90)90057-I.

Safavi, H.R., Mehrparvar, M., Szidarovszky, F., 2016. Conjunctive management of surface and ground water resources using conflict resolution approach. J. Irrigat. Drain. Eng. 142, 05016001. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000991.

Shang, Y., You, B., Shang, L., 2016. China's environmental strategy towards reducing deep groundwater exploitation. Environ. Earth Sci. 75 (22), 1439. https://doi.org/10.1007/s12665-016-6110-7.

Shi, X.H., 2008. Construct an open system to bring in capital, promote western economic development——take Shaanxi Province as an example. J. Shaanxi Admin. Sch. https://doi.org/10.3969/j.issn.1673-9973.2008.02.016. (in Chinese).

Sinding, S.W., 2009. Population, poverty and economic development. Phil. Trans. Roy. Soc. Lond. 364, 3023–3030. https://doi.org/10.1098/rstb.2009.0145.

Song, X.M., Zhan, C.S., 2011. Assessment of water resources carrying capacity in tianjin city of China. Water Resour. Manag. 25 (3), 857–873. https://doi.org/10.1007/s11269-010-9730-9.

Su, S., Hu, Y., Luo, F., et al., 2014. Farmland fragmentation due to anthropogenic activity in rapidly developing region. Agric. Syst. 131, 87–93. https://doi.org/10.1016/j.agsy.2014.08.005.

Tan, Q., Huang, G.H., Cai, Y.P., 2013. Multi-source multi-sector sustainable water supply under multiple uncertainties: an inexact fuzzy-stochastic quadratic programming approach. Water Resour. Manag. 27, 451–473. https://doi.org/10.5194/hess-18-1793-2014.

Tzeng, G.H., Huang, J.J., 2011. Multiple attribute decision making: methods and applications. Eur. J. Oper. Res. 4 (4), 287–288. https://doi.org/10.1201/b11032.

Walter, A., Cadenhead, N., Lee, V.S.W., Dove, C., Milley, E., Elgar, M.A., 2012. Water as an essential resource: orb web spiders cannot balance their water budget by prey alone. Ethology 118, 534–542. https://doi.org/10.1111/j.1439-0310.2012.02041. x.

Wang, C., Xu, L., Fu, X., 2017a. Studies on Water Resources Carrying Capacity in Tuhai River Basin Based on Ecological Footprint. https://doi.org/10.1088/1755-1315/64/1/012030. 012030.

Wang, D., He, Y., Liang, J., et al., 2013. Distribution and source analysis of aluminum in rivers near Xi'an City, China. Environ. Monit. Assess. 185 (2), 1041–1053. https://doi.org/10.1007/s10661-012-2612-2.

Wang, D., Ma, G., Song, X., Liu, Y., 2017b. Energy price slump and policy response in the coal-chemical industry district: a case study of Ordos with a system dynamics model. Energy Pol. 104, 325–339. https://doi.org/10.1016/j.enpol.2017.02.014.

Wang, S., Yang, F.L., Xu, L., Du, J., 2013. Multi-scale analysis of the water resources carrying capacity of the Liaohe Basin based on ecological footprints. J. Clean. Prod. 53, 158–166. https://doi.org/10.1016/j.jclepro.2013.03.052.

Wei, S., Yang, H., Song, J., Abbaspour, K.C., Xu, Z., 2015. System dynamics simulation model for assessing socio-economic impacts of different levels of environmental flow allocation in the Weihe River Basin, China. Eur. J. Oper. Res. 221, 248–262. https://doi.org/10.1016/j.ejor.2012.03.014.

Wu, W., Xu, Z., Yin, X., et al., 2014. Assessment of ecosystem health based on fish assemblages in the Wei River basin, China. Environ. Monit. Assess. 186 (6), 3701–3716. https://doi.org/10.1007/s10661-014-3651-7.

Xia, J., Chen, Y.D., 2001. Water problems and opportunities in the hydrological sciences in China. Hydrol. Sci. J. 46, 907–921. https://doi.org/10.1080/02626660109492885.

Xiong, Y., 2006. Research on the forecast models for agricultural water demand in the Shaanxi Province. Ground Water. https://doi.org/10.3969/j.issn.1004-1184.2006.01.004. (in Chinese).

Xi, X., Poh, K.L., 2015. A novel integrated decision support tool for sustainable water resources management in Singapore: synergies between system dynamics and analytic hierarchy process. Water Resour. Manag. 29 (4), 1329–1350. https://doi.org/10.1007/s11269-014-0876-8.

Xue, L., Qiu, G., 2013. Issues of water resources and environment in Xi'an with rapid urbanization. Inner Mong. Environ. Sci. 1–8https://doi.org/10.3969/j.issn.1007-0370.2013.09.001. (in Chinese).

Yang, X., Zheng, J., 2006. Competitive advantages of the service industry in Xi'an and its development strategy. J. Xian Shiyou Univ. https://doi.org/10.3969/j.issn.1008-5645.2006.02.004. (in Chinese).

Yuan, Z., Tol, R.S.J., 2004. Implications of desalination for water resources in China — an economic perspective. Desalination 164 (3), 225–240. https://doi.org/10.1016/S0011-9164(04)00191-2.

Yu, Q., Zhong, D., Guo, J., 2011. Proposing a Clean and Water-saving Industrial Structure in China, International Conference on Multimedia Technology. pp. 4032–4037. https://doi.org/10.1109/ICMT.2011.6002931.

Zhang, B., Chen, Z.M., Zeng, L., Qiao, H., Chen, B., 2016. Demand-driven water withdrawals by Chinese industry: a multi-regional input-output analysis. Front. Earth Sci. 10, 13–28. https://doi.org/10.1007/s11707-015-0505-8.

Zhang, Z., Lu, W.X., Zhao, Y., Song, W.B., 2014. Development tendency analysis and evaluation of the water ecological carrying capacity in the Siping area of Jilin Province in China based on system dynamics and analytic hierarchy process. Ecol. Model. 275, 9–21. https://doi.org/10.1016/j.ecolmodel.2013.11.031.

Zhu, Y.Z., Xia, J., Tan, G., 2002. A primary study on the theories and process of water resources carrying capacity. Prog. Geogr. 21, 180–188. https://doi.org/10.11820/dlkxjz.2002.02.011. (in Chinese).