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Comprehensive evaluation of the water environment carrying capacity of a river basin: a case study of the Weihe River Basin in China

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ABSTRACT

By combining the analytic hierarchy process (AHP) and system dynamics (SD) models, a compound index system is established for simulating and evaluating the water environment carrying capacity (WECC) of the Weihe River Basin. The development tendencies of the population, economy, water resource demand and supply, water environment, water pollution, and water management were obtained from 2005 to 2040 by applying the five scenarios designed in this study. The results indicate that the comprehensive solution scenario was the optimal scenario, and the WECC would upgrade from a 'general' status to a 'good' status. Moreover, the blind pursuit of rapid economic growth is inadvisable, and it will compromise the sustainability of the river basin area. The river basin area should divert local development modes toward increased sustainability, emphasizing the coordinated development of society, the economy, and the environment.

Key words: Analytic hierarchy process (AHP), Scenario analysis, System dynamics, Water environment carrying capacity

HIGHLIGHTS

- By using an integrated application of the AHP and SD models, the WECC evaluation index and simulation scenarios were established.
- Obtaining the development tendencies of the WECC under different scenarios.
- The comprehensive solution scenario was the optimal scenario.
- The water resources would reach a balance between supply and demand in 2030.
- Strengthening the WECC requires the coordinated development.

1. INTRODUCTION

With the rapid economic development and the acceleration of population growth and urbanization, numerous pollutants have been generated and discharged into rivers, placing severe pressure on water resources and the general environment (Hanjra *et al.*, 2012; Zhou *et al.*, 2019). In China, most rivers suffer from aquatic destruction, such as the overexploitation of water resources, eutrophication, and aquatic pollution. In some instances, the deterioration of aquatic environments has restricted regional socio-economic development (Mulali *et al.*, 2014; Zhang *et al.*, 2019). Thus, it is urgent to assess the maximum socio-economic scale that the river water environments can maintain (Wang *et al.*, 2018). The water environment carrying capacity (WECC) is an effective

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means to reflect the ability of a water environment system to support human social development, utilizes the carrying capacity as the link, and combines water environment problems with social and economic development. In addition, the WECC can be used to discuss the response mechanism between human activities and the water ecological environment. Moreover, the WECC considers the interaction between the natural environment and the human society, and seeks to establish a sustainable development path in which human society and natural ecosystems can live in harmony (Yang *et al.*, 2015). As a standard to assess whether the social economy is coordinated with the water environment system, the WECC plays a vital role in the comprehensive development and development scale of a country or a region (Wang *et al.*, 2017a).

The concept of WECC, which originated in ecological fields (Odum *et al.*, 1971), has been proposed to initiate a balanced development mode that guarantees socio-economic prosperity without contaminating the health of local aquatic environments. Although various interpretations and definitions of WECC exist, there is no widely accepted definition to date. In this study, the WECC is defined as 'the maximum socio-economic scale that a specific water environment can maintain and guarantee a healthy water environment in a certain time phrase' (Wang *et al.*, 2018; Yang *et al.*, 2019; Zhou *et al.*, 2020). Currently, most studies have combined the WECC with sustainable development theory, emphasizing the sustainable bearing capacity of water resources and the environment on human society and the economy (Li *et al.*, 2016; Nakajima & Ortega, 2016; Świąder *et al.*, 2020). The quantitative evaluation of the WECC of a river basin cannot only explore the limit of the WECC, but also seek the optimal social and economic development scale that water resources and the environment of a river basin can support.

Researchers have conducted extensive evaluations of the WECC, and these studies can be generally categorized into five types based on their methods: comprehensive index evaluation methods (Widodo *et al.*, 2015), multi-objective decision methods (Peng & Zhou, 2011), ecological footprint methods (Świąder *et al.*, 2020), artificial neural network methods (Wu *et al.*, 2019), and emergy methods (Dang & Liu, 2012). First, comprehensive index evaluation methods include the fuzzy comprehensive evaluation (Prato, 2009; Wang *et al.*, 2010; Wu & Hu, 2020), principal component analysis (Zheng, 2019), and the press-state-response framework (Wang & Xu, 2015). Comprehensive index evaluation methods are suitable for preliminary calculations, but these methods often neglect the coupling relationship between affecting factors (Wang *et al.*, 2019). Second, multi-objective decision methods require multiple criteria to evaluate and optimize the scheme. This method is primarily composed of an analytic hierarchy process (AHP) (Garfi *et al.*, 2011; Lu *et al.*, 2017), multiple objective programming (Li *et al.*, 2016; Zheng, 2019), and the technique for order preference by similarity to an ideal solution (TOPSIS) methodology (Irankhahi *et al.*, 2017; Wang *et al.*, 2020). This method can consider a wider range of goals; however, it is inadequate for choosing appropriate parameter values. Third, ecological footprint methods are widely used for the evaluation of WECC in urban areas (Luo *et al.*, 2018; Świąder *et al.*, 2020) and other regions (Peng *et al.*, 2019). This method evaluates the WECC through a simple and directly applicable index but lacks necessary detail and precision explanation, which restricts its potential for broader usage (Wang *et al.*, 2018). Fourth, artificial neural network analysis is a tool used for identifying patterns in complex data, such as those related to ecological data (Noble & Tribou, 2007). Khanna *et al.* (1999) applied this method to calculate the ecological carrying capacity of the National Capital Region in India. Wu *et al.* (2019) proposed a prediction model based on artificial neural networks and predicted the ecological capacity for Tianjin. This method has superior performance in nonlinear mode recognition, but its evaluation results are difficult to quantify in actual practice (Zhang *et al.*, 2014). Finally, emergy-based methods assess environmental and economic products and services and provide information on ecological processes (Pizzigallo *et al.*, 2008; Giannetti *et al.*, 2010) by presenting emergy indicators to reflect ecological and economic efficiency. However, this method has difficulty developing a threshold for system sustainability.

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To overcome the limitations of the above methods, some researchers have combined the AHP with system dynamics (SD) to evaluate the WECC. The AHP is a flexible and practical multi-criteria decision-making method that was proposed by Thomas L. Saaty in the 1970s (Saaty, 1990). As one of the most widely used methods for determining index weight, the AHP can organize a complex and multi-attribute problem into a hierarchical structure (Wang *et al.*, 2019). The SD model is a method used to describe complex systems and analyze their dynamic behavior, which was initially proposed by Forrester (1958) as a simulation approach for improving industrial management and decision-making. The SD model is a mature system simulation for dealing with nonlinear, multi-level, multi-feedback, time-varying system problems, and policy simulations. Compared with other commonly used approaches, the SD model can be applied to solve dynamic problems by simulating both microscale and macroscale systems (Leal *et al.*, 2006). The combination of the AHP and SD method has been proved to be efficient, not only for operational and strategic issues (Sterman, 2000; Barlas, 2007), but also for the simulation of environmental and socio-economic development issues (Evan & Slobodan, 2011; Han *et al.*, 2017; Wang *et al.*, 2018). For example, Xi & Poh (2015) proposed a novel integrated decision support tool that synergizes the SD and AHP models for sustainable water resource management in Singapore. Furthermore, Wang *et al.* (2018) established the WECC evaluation index system for the Bosten Lake Basin by combining the SD and AHP models.

In this study, a quantitative evaluation of the WECC is investigated, and the optimal development scenario based on a comprehensive simulation of the socio-economic system is proposed. By using an integrated application of the AHP and SD models, the WECC evaluation index system and simulation scenarios of a river basin are established. Furthermore, the development tendencies of the WECC under different scenarios are obtained, and the optimal and practical scenarios that coordinate socio-economic development and the aquatic environment are identified.

The remainder of this paper is organized as follows. Section 2 introduces the study area and analysis methods. Section 3 establishes the WECC index system, describes six subsystems that influence the socio-economy and environment, and designs representative scenarios. Section 4 validates the model and tests the sensitivity; it also presents the primary findings of this research, as well as provides a discussion on these findings. Finally, Section 5 presents the primary conclusions.

2. MATERIALS AND METHODS

2.1. Study area

In this study, the Weihe River Basin (WRB) in northwest China was chosen as the study area. The WRB is 818 km long with a river basin area of 1.36×10^5 km^2, and it originates at Niaoshu Mountain, which is located in the western Qinlin Mountains and flows into the Yellow River. The research area includes nine prefectural level cities, Tianshui, Dingxi, Pingliang, Qingyang, Baoji, Tongchuan, Xi'an, Xianyang, and Weinan, among which the former four cities are located in the Gansu Province, while the remaining five cities are located in Shaanxi Province (Figure 1). The WRB is located in a transition zone between dry and humid areas, with an annual average precipitation of 572 mm/yr and an annual average surface evaporation in the basin ranging from 660 to 1,600 mm/yr. Since the Weihe River is treated as the 'Mother River' of the Guanzhong Region,[1] the WRB is the core area of the 'Guanzhong-Tianshui Economic Zone[2]' and plays an essential role in the socio-economic

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[1] The Guanzhong Region is located in the south of the Jin-Shaan basin belt. The northern portion of the Guanzhong Region is the loess plateau in Shaanxi, and the southern portion of Guanzhong is the Qinba Mountains.

[2] The 'Guanzhong-Tianshui Economic Zone' covers Xi 'an, Tongchuan, Baoji, Xianyang, Weinan, Yangling, and Shangluo City in the Shaanxi Province and Tianshui city in the Gansu Province. The economic zones are considered to be Xi 'an as the central city, Baoji as the sub-central city, and other cities as the sub-core cities. These areas form a developed city cluster and industrial agglomeration belt in Western China.

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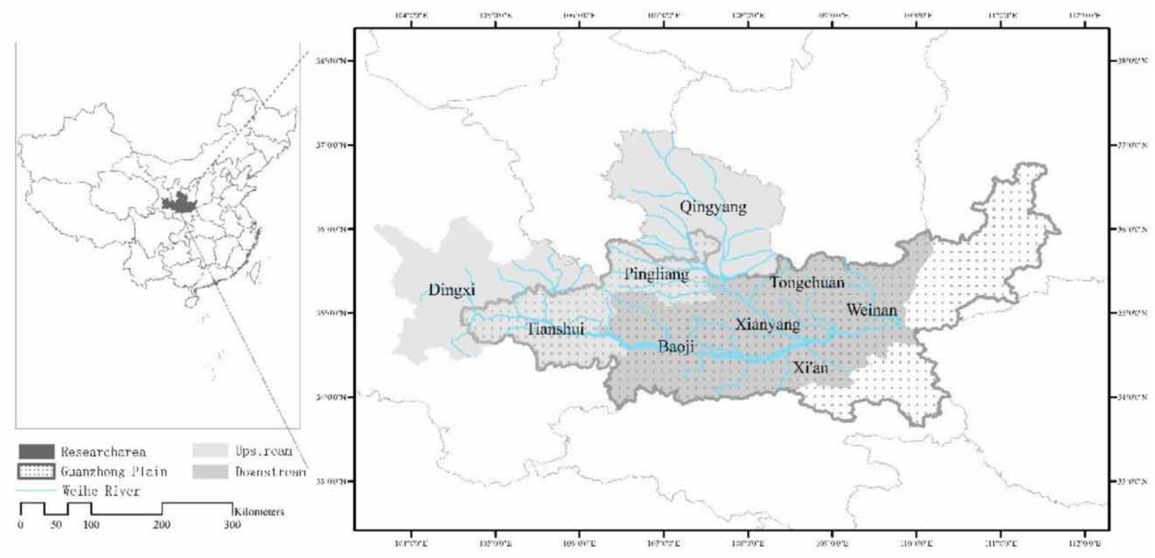

Fig. 1. | Map of the WRB.

development of northwest China, as well as the ecosystem health of the Yellow River. However, due to the continued decrease in the annual average rainfall and runoff of the mainstream of the Weihe River and the increases in water consumption due to economic development and population growth (Song *et al.*, 2018), there is a growing shortage of water resources in the WRB, which restricts sustainable development in the research area.

2.2. Data sources

Data regarding the population, economy, water resources, environmental pollution, and protection were obtained from the literature and field surveys. The indicators for the population and economic subsystem were primarily obtained from the statistical yearbooks of the Shaanxi and Gansu Provinces (Shaanxi Statistical Yearbooks, 2006–2017; Gansu Statistical Yearbooks, 2006–2017). The data regarding the water resource demand and supply were collected from the Shaanxi Water Resources Bulletin and the Gansu Water Resources Bulletin. Data related to the water environment subsystem and water pollution and management subsystem were obtained from Sun *et al.* (2017), Wang *et al.* (2018), and Yang *et al.* (2019).

2.3. Analytic methods

2.3.1. Analytic hierarchy process

Factors in the evaluation system are decomposed into several levels, which generally consist of an object, rule, and index hierarchy. Then, the relative importance degree of the indexes listed in each level is compared and judged by the experts according to their experience, and the results are obtained by weighting several levels and factors (Ishizaka & Labib, 2011; Kamaruzzaman *et al.*, 2018). During the process of calculating the hierarchical structure, it is necessary to test the rationality of the eigenvectors of the judgment matrix, that is, to test the consistency of the judgment matrix. The formula is as follows:

$$CR = CI/RI \tag{1}$$

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{2}$$

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where CR and CI represent the consistency ratio and consistency index of the judgment matrix, respectively; and RI represents the average random consistency index of the judgment matrix. When $CR < 0.1$, the judgment matrix is considered to pass the consistency test; otherwise, the judgment matrix needs to be modified.

2.3.2. SD model

The primary variables of the SD model include stock variables, rate variables, and auxiliary variables. Stock variables describe the current state of the system, which reflects the accumulation of information. Rate variables reflect the behavior of stocks and represent the speed of change in the values of stocks. Auxiliary variables are intermediate variables that reveal the internal mechanism of the system and quantify the relationship between variables. The relationships between the stock and rate variables present the dynamic change in the system, which can be described as below:

$$S(t) = S_0 + \int_0^t \left(\sum F_{in}(t) - \sum F_{out}(t)dt\right) \tag{3}$$

where $S(t)$ means the value of the stock variable S at time t; S_0 means the initial value of S; F_{in} and F_{out} mean the input and output flow rates into and out of S, respectively; and t represents time.

2.4. Evaluation model

2.4.1. SD model formulation

The SD model of the WECC combines the socio-economic and ecological environment, as well as the water resources of the WRB, which is naturally the system boundary of the SD model. Therefore, based on the WECC evaluation index system and the actual socio-economic development situation in the WRB, the WECC system was classified into six subsystems, including the population, economy, water demand, water supply, water environment, and water pollution and management subsystem. In this study, the research period extended from 2005 to 2040. Moreover, Vensim Software was employed to simulate the SD model of the WECC for the WRB, and the stock-flow chart of the SD model is shown in Figure 2. The primary variables and equations in the study are summarized in Supplementary Material, Appendix A.

2.4.1.1. Population subsystem. The population factor is one of the driving factors that have a crucial impact on socio-economic development and the ecological environment (Falkenmark & Widstrand, 1992; Immerzeel & Bierkens, 2012; Yang *et al.*, 2019). When constructing this subsystem, the connection between the population subsystem and other subsystems should be considered. Therefore, the total population (TP) was selected as the stock variable, which consisted of the urban population (UP) and the rural population (RP) and was determined by the net population change (NPC). The NPC was determined by the natural population growth rate (NPR). In addition, the urbanization rate (UR) determines the changes in the UP and RPs.

2.4.1.2. Economic subsystem. The economic subsystem is a core component of the entire system and has a significant influence on the ecological environment. Based on the method of industry classification, the economic subsystem should contain primary (PIP), secondary (SIP), and tertiary industry production (TIP). The different industrial structures of the economic subsystem have different water resource demands, which have an impact on the ecological environment (Feng *et al.*, 2017; Cheng *et al.*, 2019). Consequently, 10 indicators were selected to reflect the economic status and growth. These included the GDP, PIP, SIP, TIP,

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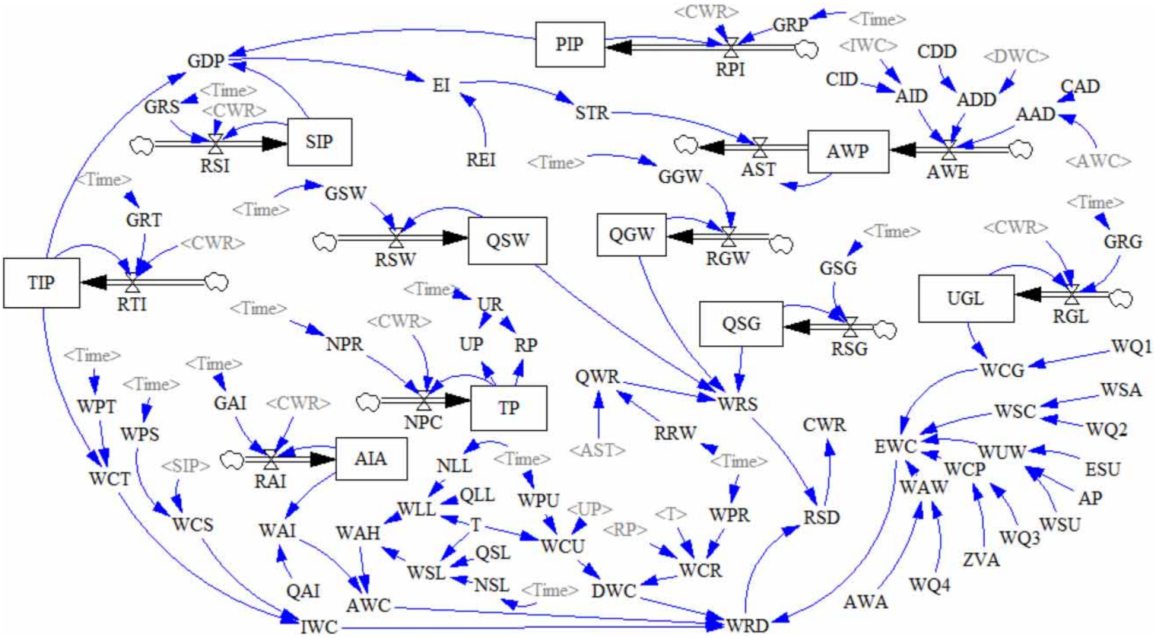

Fig. 2. | Stocks and flows of the simulated system.

rise in PIP (RPI), rise in SIP (RSI), rise in TIP (RTI), growth rate of PIP (GRP), growth rate of SIP (GRS), and growth rate of TIP (GRT). The PIP, SIP, and TIP are stock variables, while the RPI, PSI, and RIT are rate variables that cause the three stocks to vary.

2.4.1.3. Water resource demand subsystem. The water resource demand subsystem is a key element of the entire system (Sun *et al.,* 2017). It was divided into four classifications: agricultural water consumption (AWC), industrial water consumption (IWC), domestic water consumption (DWC), and ecological water consumption (EWC). The AWC is the water demand due to agricultural irrigation and animal husbandry, and the water demand of animal husbandry is composed of two parts: large livestock and small livestock. The IWC includes the water demand from secondary and tertiary industries, which is determined by the industry added value and water use per unit of industry added value. Furthermore, the DWC consists of the water demand of urban and rural households, which reflects the quantity of water consumption due to urban and rural daily life. In addition, EWC denotes the water resources consumed to maintain the ecological environment.

2.4.1.4. Water resource supply subsystem. The water resource supply subsystem reflects the water resource supply ability of the study area (Wang *et al.,* 2018). It was classified into four components: the quantity of surface water resources (QSW), the quantity of groundwater resources (QGW), the quantity of water recycled (QWR), and the quantity of overlap between the surface and groundwater (QSG). The amount of the surface and groundwater resources are, respectively, determined by the change in the QSW and the QGW, while the change in the QSW and the QGW is decided by the growth rate of the QSW and the QGW. Moreover, the reuse rate for recycled water determined the QWR. In addition, two crucial indicators are contained in this subsystem, namely the water resource balance (WRB) and the water resources factor.

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2.4.1.5. Water environment subsystem. The quality of the water environment affects regional sustainable development and water resource sustainable utilization (Kilkis, 2016). The rational allocation of ecological water resources is conducive to enhancing the carrying capacity of the water environment (Zhang *et al.*, 2019). Following Song *et al.* (2018), the indicator of water consumption of ecology (EWC) was selected to reflect the allocation of the ecological water resources. The EWC consists of five components: the water consumption of green area (WCG), water for water and soil conservation (WSC), water consumption of plants (WCP), water consumption of urban water surfaces (WUW), and water consumption of artificial water areas (WAW). The water consumption of a green area grows as the green area increases, and water use for soil and water conservation rises with the growth in the soil and water conservation areas. Additionally, the water consumption of the plant and artificial water areas is affected by the zonal vegetation areas and artificial water areas, respectively. Furthermore, the water consumption of the urban water surface depends on the urban water surface, the evaporation of the urban water surface, and the mean precipitation.

2.4.1.6. Water pollution and management subsystem. The water pollution and management subsystem directly affects the WECC, which is closely related to human health and ecological civilization (Zhang *et al.*, 2018). In this subsystem, the amount of water pollution (AWP) was the primary evaluation index, which is represented by the amount of wastewater effluent (AWE) and the amount of sewage treatment (AST). The AWE is the sum of the amount of industry wastewater discharge, the amount of domestic wastewater discharge, and the amount of agriculture wastewater discharge. Moreover, the AST is determined by the sewage treatment rate (STR), which is affected by the environmental investment (EI).

2.4.2. WECC index system

The WECC is a large and complex system affected by numerous factors, and a scientific and reasonable index system can accurately assess the WECC (Zhang *et al.*, 2014). The indicators in the index system should be selected to reveal the actual situation of ecological carrying capacity in the study area (Wang *et al.*, 2018). Compared with the single-factor assessment method, the application of a multi-factor evaluation method will obtain more precise results. As a multi-target and multi-criteria evaluation method, an AHP is widely used to assess index weights and to solve complex decision problems (Vidal *et al.*, 2011; Baumann *et al.*, 2019). Consequently, by considering the actual situation in the WRB and consulting with experts on the water environment, the index system for the WECC in the WRB was established. The WECC evaluation index was divided into three hierarchies, including the object hierarchy (the WECC of the river basin), the rule hierarchy (the subsystem index for the water resources, the water environment, the society, and the economy), and the indicator hierarchy (14 specific indicators). The weights of indicators in the index system were obtained by applying the AHP (Table 1), and the judgment matrices satisfied the consistency test, indicating that the weight coefficients were allocated reasonably.

2.4.3. WECC quantification

2.4.3.1. Data standardization. As the units and dimensions of the selected evaluation indices are different, the selected indexes should be standardized to eliminate dimensional effects before evaluating the WECC. In this study, the various WECC evaluation indicators were normalized to ascertain their scores. Some of the indices had a positive influence on the WECC, and these indices (e.g., the water resource supply and the reuse rate of recycled water) are referred to as development indices. In contrast, some of the indices had a negative influence, and these indices (e.g., the AWP and IWC) are referred to as restrict indices. The residual indicators

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Table 1. | Weighted values of the evaluation indices.

Object hierarchy	Rule hierarchy	Index hierarchy	Weight value
WECC in the WRB	Subsystem index for the water resources	Total available water resources	0.0473
		Reuse rate of recycled water	0.0219
		Ratio of water supply to water demand	0.1018
	Subsystem index for the water environment	Urban green area	0.0417
		Environmental protection investment	0.1343
		STR	0.0652
		AWP	0.1486
	Subsystem index for society	TP	0.0770
		Population UR	0.0312
		Agricultural irrigation area	0.0127
	Subsystem index for the economy	GDP	0.1297
		AWC	0.0586
		IWC	0.0985
		DWC	0.0315

(e.g., the TP and the agricultural irrigation area) are referred to as interval indices, which are more favorable for strengthening the WECC when the interval indices are closer to the mean value.

For the development indicator, Equation (4) was applied:

$$S_{ij} = \frac{g_{ij} - \min\limits_{j=1}^{m} g_{ij}}{\max\limits_{j=1}^{m} g_{ij} - \min\limits_{j=1}^{m} g_{ij}} \tag{4}$$

For the restrict index, Equation (5) was applied:

$$S_{ij} = \frac{\max\limits_{j=1}^{m} g_{ij} - g_{ij}}{\max\limits_{j=1}^{m} g_{ij} - \min\limits_{j=1}^{m} g_{ij}} \tag{5}$$

For the interval index, Equation (6) was applied:

$$S_{ij} = \frac{1 - |g_{\mathrm{ij}} - g_{ij}^{*}|}{\max\limits_{j=1}^{m} g_{ij} - \min\limits_{j=1}^{m} g_{ij}} \tag{6}$$

where S_{ij} represents the score of the *i*-index in the *j*-scenario; g_{ij} represents the value of the *i*-index in the *j*-scenario; and g_{ij}^{*} represents the mean value of g_{ij} in the study.

2.4.3.2. Calculation of the WECC index. The WECC was evaluated based on the weight determined by the AHP and the simulation values assessed by the SD model. According to the standardized data, the scores of all the indicators were weighted and summed to calculate the WECC in the WRB. The WECC index was evaluated

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using Equation (7):

$$U_j = \sum_{i=1}^{n} w_i S_{ij} \tag{7}$$

where U_j means the WECC index; and w_i represents the weight of the i-index decided by the AHP model.

The WECC value reflects the strength of the WECC. The larger the value, the better the WECC, which means that the ecological environment is capable of withstanding much larger ecological pressure. In contrast, the smaller the value, the weaker the WECC, which means that the ecological environment can barely support ecological pressure, and the water environment would become fragile, and possibly verge on collapse. According to the different statuses of the WECC, the carrying capacities were grouped into five types (Table 2).

2.5. Scenario design

To render the water ecological environment and the socio-economic development toward more sustainability, a variety of scenarios were designed to simulate the WECC. Using the SD model, various WECC evaluation indicators were then simulated to explore their changes between 2005 and 2040 under different scenarios.

Scenario 1 (S1: current situation): Maintain the current development pattern, keep all parameters in the system unchanged, and apply this scenario to compare with other scenarios.

Scenario 2 (S2: economic leading): Emphasize the importance of economic growth and give priority to economic development. Assume that the growth rate of PIP, SIP, and TIP accelerated by 5% each.

Scenario 3 (S3: water resource-saving): Focus on improving the water efficiency and water resource supply. Assume that the per capita urban and rural water use per day reduces by 10%, water use per unit of SIP and TIP declines by 10%, the water quota of agricultural irrigation drops by 10%, and the water quota of large and small livestock decreases by 10%.

Scenario 4 (S4: environment protection): Highlight the protection of the environment by controlling pollution and improving environmental quality. Assume that the reuse rate of recycled water rises by 10%, the EI ratio increases by 10%, and the coefficient of industry, domestic, and agriculture wastewater effluent declines by 10%.

Scenario 5 (S5: collaborative development): Represents an integrated scenario for the coordinative development of the socio-economy and the environment. A new parameter set is established by combining the previous scenarios. All parameters are raised or reduced by half as much in the above-mentioned measures.

3. RESULTS AND DISCUSSION

3.1. Test for the model

As the SD model abstracts the actual world into an information structure (Wang *et al.*, 2017b), to ensure the quality of model simulation results, the validation and sensitivity of the model should be tested prior to running a simulation (Yang *et al.*, 2019).

Table 2. | Carrying status of the WECC.

WECC index	0.8–1.0	0.6–0.8	0.4–0.6	0.2–0.4	0–0.2
Carrying status	Excellent	Good	General	Poor	Weak

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3.1.1. Validation test

To guarantee the applicability and accuracy of the SD model, error tests should be applied to examine whether the model accurately interprets the actual system. The data from 2005 to 2016 were substituted into the SD model, and only four representative variables among other variables were chosen for the test, including the TP, GDP, the urban green area, and the agricultural irrigation area. Table 3 shows that the error rate of most of the parameters was less than 10%, and the average error rate of all parameters was within 10%, which falls within the acceptable range (Sun *et al.*, 2017). The maximum and minimum values of the average error rate were 1.42 and 6.57%, respectively. Consequently, the model validation results coincided well with the actual system, showing that the model can reflect reality accurately.

Table 3. | Error rates between the true and simulated values.

	TP (10^4 persons)				**GDP (10^8 yuan)**			
Year	**Actual value**	**Simulation value**	**Error rate (%)**	**Average error rate (%)**	**Actual value**	**Simulation value**	**Error rate (%)**	**Average error rate (%)**
2005	3,416.17	3,416.17	0	2.31	3,034.41	3,034.41	0	4.53
2006	3,427.72	3,504.99	2.25		3,521.34	3,593.87	2.06	
2007	3,436.21	3,515.51	2.31		4,228.60	4,122.27	2.51	
2008	3,449.3	3,522.54	2.12		5,245.49	5,006.46	4.56	
2009	3,425.01	3,536.63	3.26		6,085.80	6,208.35	2.01	
2010	3,345.71	3,511.87	4.97		7,352.52	7,205.72	2.00	
2011	3,356.73	3,431.1	2.22		8,943.54	8,700.81	2.71	
2012	3,373.17	3,441.39	2.02		10,263.13	10,574.4	3.03	
2013	3,382.25	3,458.6	2.26		11,629.35	12,136	4.36	
2014	3,391.67	3,468.97	2.28		12,802.20	13,757.6	7.46	
2015	3,406.59	3,479.38	2.14		13,354.18	15,153	13.47	
2016	3,427.03	3,493.3	1.93		14,292.71	15,753	10.22	
	Urban green area (10^4 ha)				**Agricultural irrigation area (10^4 ha)**			
2005	1.62	1.62	0	6.57	112.29	112.36	0	1.42
2006	2.13	1.71	19.49		113.88	112.25	1.43	
2007	2.34	2.25	3.80		111.14	113.82	2.41	
2008	2.40	2.48	3.49		109.03	111.09	1.89	
2009	2.46	2.54	3.27		112.96	108.98	3.53	
2010	2.71	2.60	3.84		109.36	112.90	3.24	
2011	2.87	2.87	0.14		108.03	109.29	1.16	
2012	3.20	3.04	5.11		108.56	107.98	0.54	
2013	3.43	3.39	1.12		108.03	108.52	0.45	
2014	3.60	3.64	1.03		108.75	107.97	0.71	
2015	5.93	3.81	35.67		109.48	108.73	0.69	
2016	6.17	6.29	1.89		110.57	109.49	0.98	

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3.1.2. Sensitivity test

A sensitivity test was conducted to ascertain the influence caused by the change in parameters and to evaluate the reliability of the model. The sensitivity was examined by altering the value of one parameter at a time, while the others remained unchanged. To test the model's sensitivity, 14 parameters were selected to confirm their influence on the stock variables, and each parameter was increased or decreased by 10% annually. The sensitivity index was defined as follows (Zhang *et al.*, 2008):

$$R_Y = \left| \frac{\Delta Y_t}{Y_t} \cdot \frac{X_t}{\Delta X_t} \right| \tag{8}$$

$$R = \frac{1}{n} \sum_{i=1}^{n} R_{Y_i} \tag{9}$$

where R_Y represents the sensitivity index of the stock variable Y to the parameter X; Y_t and X_t mean the value of Y and X at time t, respectively; ΔY_t and ΔX_t are the increments of the stock variable Y and the parameter X at time t, respectively; t means time; R represents the average sensitivity degree; R_Y means the sensitivity degree of the stock variable Y; and n means the number of stock variables. If $R \leq 0.1$, the variable was not sensitive; if $R \geq 0.1$, the variable was sensitive.

Table 4 shows that the sensitivity values for the growth rate of SIP, water consumption per unit of SIP, and the coefficient of industry wastewater discharge were higher than 10%, while the other parameters were no more than 10%. Therefore, the model was insensitive to change for most of the parameters, indicating that the model was robust.

According to the model validation and sensitivity analysis results, the SD model was perceived not only valid, but also robust. Therefore, it suggested that the SD model can reflect actual situations well and thus provide a good basis for subsequent predictions.

3.2. Scenario analysis

3.2.1. Comparison of different scenarios

Based on the test results, the SD model was simulated, and the results under the different scenarios were obtained using the Vensim software, as shown in Figure 3.

Table 4. | Sensitivity analysis results.

Variable	Average sensitivity by increasing 10% (%)	Average sensitivity by decreasing 10% (%)	Variable	Average sensitivity by increasing 10% (%)	Average sensitivity by decreasing 10% (%)
NPR	3.15	2.32	GRS	43.70	39.23
GRP	2.84	6.76	GAI	0.69	0.75
NLL	3.37	3.52	NSL	8.98	9.21
WPS	18.08	18.10	WPT	4.17	4.17
WPU	5.91	5.91	GGW	8.60	7.83
RRW	0.99	0.98	WSU	7.14	7.14
AWA	0.55	0.55	CID	10.44	10.44

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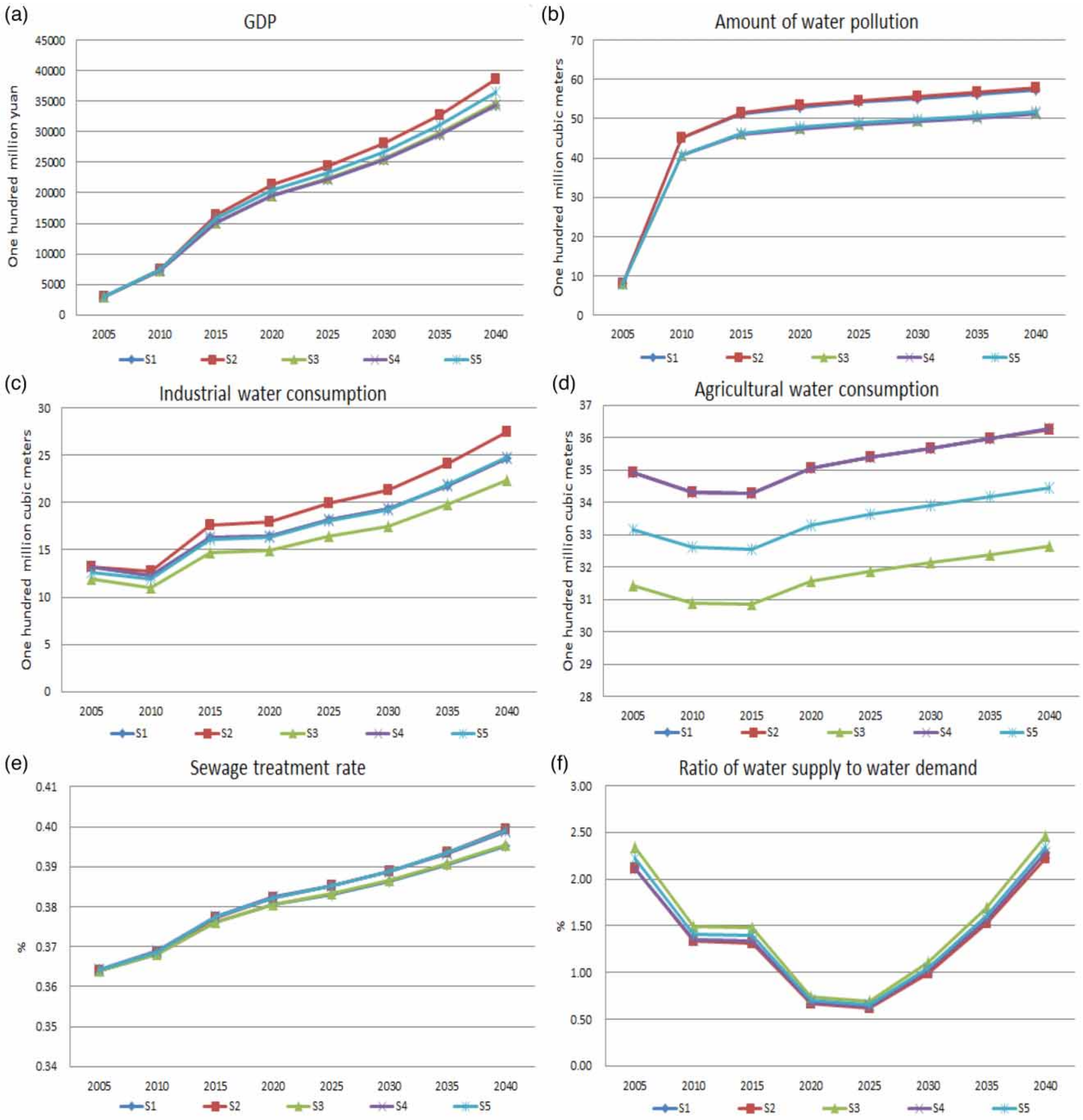

Fig. 3. | The simulation results of the five scenarios: (a) GDP, (b) amount of pollution, (c) IWC, (d) AWC, (e) STR, and (f) the ratio of water supply to water demand.

In the current situation scenario (S1), the GDP would reach 34,394 × 10^8 yuan in 2040, 11.33 times higher than that in 2005. The amount of pollution predicted to be 57.32 × 10^8 m^3, which was 6.97 times higher than that in 2005. The IWC and AWC would reach 24.67 × 10^8 and 36.26 × 10^8 m^3, which corresponded to an increase by 86.44 and 3.85%, compared with 2005, respectively. Moreover, the STR and the ratio of water supply to water demand were projected to be 0.4 and 2.28, with increments of 8.58 and 7.79%, compared with 2005, respectively.

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In the economic leading scenario (S2), economic growth exhibited the fastest growth rate compared with the other scenarios. The GDP value in 2040 was 12.03% higher than in S1, and the IWC was also the highest among the other scenarios. However, such a rapid growth rate in the economic sector would inevitably exert excessive pressure on the environment, since the amount of pollution would reach the highest value among all the scenarios, 57.88×10^8 m^3 in 2040. However, the minimum ratio of water supply to water demand appeared in this scenario. Therefore, S2 had little effect on the improvement of the WECC in the WRB.

In the water resource-saving scenario (S3), the IWC and AWC would reach minimum values of 22.38×10^8 and 32.66×10^8 m^3 in 2040, respectively. In addition, as the water efficiency improved in this scenario, the ratio of water supply to water demand was predicted to be 2.4608 in 2040, with an increase of 7.75% compared with S1. By comparing with S1 and S2, saving the water resources would be beneficial to enhance the WECC in the WRB.

In the environmental protection scenario (S4), the amount of pollution would decline by 10.71%, and the STR would improve by 0.87% in 2040 compared with S1. The drawback in this scenario, however, was the poor performance in economic growth, and the GDP would reach 34394×10^8 yuan in 2040, which was the lowest among all the scenarios. Therefore, to balance economic growth and environmental protection, a more comprehensive program should be proposed.

In the comprehensive solution (S5), economic growth, water-saving, and pollution abatement were comprehensively considered. The GDP was higher than most of the other scenarios, except for the economic leading scenario. The STR was higher than the values in scenarios 1, 3, and 4, which indicated that it had more effective sewage management. Furthermore, except for the water resource-saving scenario, the ratio of water supply to water demand in S5 was higher than the other scenarios. Consequently, scenario 5 was more moderate compared with the other scenarios.

3.2.2. WECC of the different scenarios

As shown in Figure 4, the WECC demonstrated a pattern that first dropped from 2005 to 2010, and then slowly grew from 2025 to 2040 for all the scenarios. Under the current situation scenario, as the Chinese government constantly emphasizes the importance of ecological and environmental protection, the WECC in the WRB increases from 0.51 in 2005 to 0.54 in 2040, denoting a 'general' status of the WECC. In the economic leading

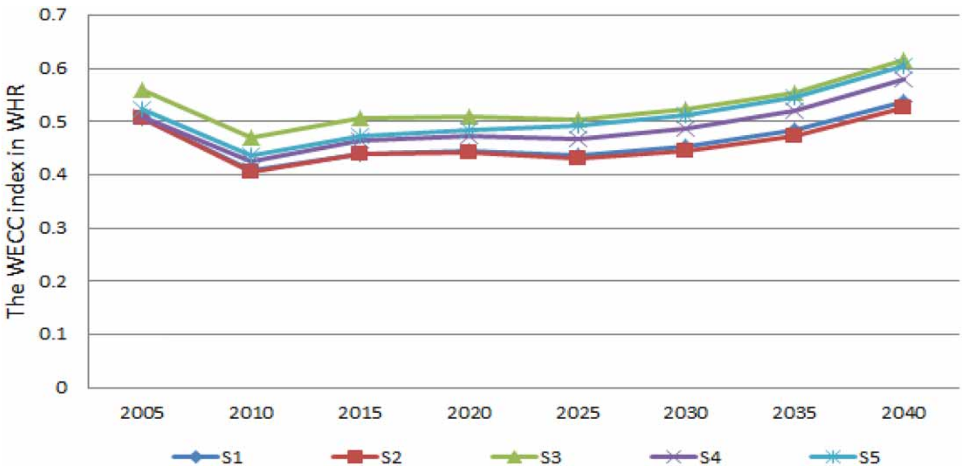

Fig. 4. | Simulated WECC values in the different scenarios.

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scenario, although the rapid economic growth exerted excessive pressure on the environment, the WECC still would be 'general' in 2040. In the water resource-saving scenario, the imbalance between the water supply and demand by decreasing water consumption is alleviated, and the WECC upgraded to a 'good' status. In the environmental protection scenario, although the WECC was better than that of scenario 1, the WECC would still have a 'general' status in 2040. However, in the comprehensive solution scenario, the WECC would achieve a 'good' status in 2040, and the value of the WECC in S5 was slightly lower than that of scenario 3. Since S5 took socio-economic development and river basin environment protection into consideration, it was more appropriate than the other scenarios.

3.3. Discussion

This study aimed to evaluate the WECC of the WRB and attempted to pursue the optimal development scenario through the adoption of the AHP and the SD models. The model test results showed that the SD model was not only valid but also robust. Moreover, the results of the scenario analysis revealed the trends of the WECC changes and the effects of various policy combinations so as to offer guidance for regional development.

Along with the economic prosperity and population growth, the demand for water resources and the production of sewage will accelerate. In scenario 2, rapid economic growth will induce a rise in water consumption, exert excessive pressure on the environment, and aggravate the contradiction between socio-economic development and the ecological environment. In this case, reducing water consumption and strengthening water resource management are effective measures to protect the ecological environment of the river basin. According to the simulations of the five scenarios, water-saving was not only an essential way to reduce pollution, but also an effective way to improve the WECC. Therefore, the Chinese government can achieve the water-saving goal by adopting measures such as raising water-saving standards, strengthening water-saving measures, developing agricultural and industrial water-saving systems, and creating a water-saving atmosphere. In addition, sewage treatment has been proved to be beneficial for water resource protection and ecological environment improvements, and the reuse of recycled water is an ideal solution for covering water resource shortages and increasing the water supply. Therefore, the Chinese government can improve the STR and reuse the rate of recycled water by accelerating technology research and development.

Furthermore, traditional industries, such as the textile industry and chemical industry, have become the primary drivers of economic growth in the WRB. However, most of these industries are energy-intensive and environmentally destructive, and they consume large amounts of water and produce a large amount of pollution. Once economic development exceeds the carrying capacity of the water environment, society will be trapped in a vicious circle of economic development at the expense of destroying wild nature. Therefore, the blind pursuit of rapid economic growth is inadvisable, and it will compromise the sustainability of the river basin area. Therefore, the Chinese government can accelerate the transformation of industrial structure by improving technological transformation and innovation, which can improve the utilization efficiency of water resources and optimize the demand structure of water resources. Meanwhile, the economic and environmental benefits need to be comprehensively considered in the process of pursuing green development and revitalizing emerging industries.

Currently, the Chinese government is paying more attention to ecological environment protection in the WRB. To protect the ecological environment and improve the WECC of the WRB, local governments at the upstream and downstream of the river basin have demonstrated mutual cooperation and have signed an ecological compensation agreement for the WRB. However, the amount of compensation is far from sufficient to compensate the upstream for the cost of protecting the ecological environment and improving the WECC. Currently, ecological compensation primarily consists of vertical transfer payments from the central government and horizontal transfer payments from the local government, which is not conducive to the realization of social equity and

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the improvement of water resource utilization efficiency. Therefore, broadening the sources of compensation funds, improving methods of market compensation, and promoting the enthusiasm of residents for compensation participation are effective ways for the Chinese government to protect the ecological environment and improve the WECC in the WRB. The research area should divert local development modes toward increased sustainability, that is to say, to emphasize the coordinated development of society, the economy, and the environment. Since no single step, such as merely the control of population growth, the management of economic development, or the preservation of natural resources, would be a sufficient condition for achieving the double win of improving the WECC without affecting the socio-economic development level.

4. CONCLUSIONS

In this study, a SD model combined with the AHP method was applied to assess the WECC in the WRB. Based on the characteristics of the WECC in the WRB, the index system was classified into four major components, with 14 indicators according to the AHP. Then, a SD model was constructed that was composed of the population, economy, water resource demand and supply, and water pollution and the management subsystems. After conducting validation and sensitivity tests, the test results verified the applicability, accuracy, and robustness of the model. Thereafter, five scenarios, including the current situation, economic growth, water-saving, environmental protection, and a comprehensive solution, were designed to simulate the WECC in the WRB. The primary conclusions were as follows:

(1) The simulation results for the WECC indicated that the comprehensive solution scenario was the optimal scenario. This scenario combined the advantages of other scenarios and considered socio-economic development and river basin environmental protection. The WECC would upgrade from a ‘general’ status to a ‘good’ status, which effectively improved the WECC of the research area.
(2) Since the Chinese government constantly emphasizes the importance of ecological and environmental protection of the river basin in recent years, and the reuse rate of recycled water has continued to grow, the water resources would reach a balance between supply and demand by 2030 under most of the scenarios (except for the economic leading scenario), which was the premise of emphasizing the ecological and environmental protection.
(3) Although the STR grew continuously, the amount of pollution also kept increasing. Pollution issues cannot be solved merely by increasing EIs or adopting the traditional economic development path of ‘pollution first and protection afterward’. Strengthening the WECC in the research area requires the coordinated development of the socio-economy and the environment.

Compared with the existing models, this model clearly expresses the stock-flow among socio-economic development factors, water resource demand and supply, and environmental pollution and protection in the river basin. It also pays sufficient attention to identifying the optimal and practical strategy to achieve a higher WECC. Therefore, this SD model combined with the AHP method could help researchers understand the features and behaviors of a river basin and hence provides a powerful tool for assisting decision-making regarding issues of improving the WECC in a river basin area. Moreover, this model can provides reference for government departments to conduct an evaluation of the WECC of a river basin.

However, there are limitations of this study. First, the WECC is a complex and multi-factor system, and the model presented in this paper is simplified. It does not contain relevant factors such as water price and quality due to the limited data. Second, the number of variables in the model is rather small, and some possible scenarios are not evaluated in this paper. Third, considering that most planners need a more simplified approach, we should

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apply more advanced methods and technologies to obtain more accurate and reasonable results, and apply these results in a simpler method. These inadequacies indicate directions for future research.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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