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System dynamics simulation for the coordinative development of socio-economy and environment in the Weihe River Basin, China

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Abstract

A reliable system simulation combining socio-economic development with water environment and comprehensively reflect a watershed's dynamic features is crucial. In this study, a complex system dynamics model is constructed to evaluate dynamic changes of socio-economic development and ecological environment of Weihe River Basin (WHR). Development trends of the population, economy, land resources, water demand and supply, water environment and water pollution and management are obtained from 2005 to 2030 through scenarios analysis representing different regional development orientations, namely, population growth (S1), economic leading (S2), resources saving (S3), environment leading (S4), collaborative development (S5). Compared with other scenarios, the total population and GDP will, respectively, reach $3,716.55 \times 10^4$ person and $40,077.30 \times 10^8$ yuan, and the gap between demand and supply and the amount of water pollution will, respectively, narrow to 0.56×10^8 and 12.26×10^8 cubic meters in collaborative development scenario (S5). The results reveal the collaborative development scenario (S5) can achieve not only steady population and economy growth, as well as narrow down the gap between water supply and demand, but also optimize watershed environment management of the WHR. Thus, the system dynamics model used in our research provides a powerful tool for assisting decision-making on issues of coordinative socio-economic development, environmental health protection, water resources conservation, etc., in a river basin area.

Keywords: Coordinated development; Scenario analysis; Sustainable development; System dynamics; Weihe River Basin

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Highlights

- Discussing interrelations among socio-economy, resources and environment in watershed.
- Evaluating the joint effects of socio-economic development and watershed environment management.
- Water resource demand causes the water resource imbalance in the Weihe River Basin.
- Strengthening environmental protection requires coordinative development.
- Identifying optimal and practical strategy for coordinative development mode.

1. Introduction

Water resources play a vital role in all aspects of human life (Zomorodian *et al.*, 2018) and its scarcity is among the major global challenges today. Water resources, which constitute an indispensable foundation of social development, are not only an irreplaceable natural resource, but also an indispensable economic resource (Walter *et al.*, 2012). In accordance with the rapid development of contemporary society, the contradiction between increasing water demand and severe water resources scarcity have become more severe (Cai *et al.*, 2011; Valipour, 2017; Seo *et al.*, 2018), which would cause a series of problems that may endanger the qualities of socio-economic development, environmental health, and population welfare (Kreuter *et al.*, 2004; Zhu & van Ierland, 2012; Valipour, 2016).

Regions near the upper and lower reaches of rivers are often crowded with high-density population and have undergone various production activities that may endanger the quality of water resources. For this reason, the protection of watersheds in the upper and lower reaches and their adjacent environment has attracted much academic attention (Heinz *et al.*, 2007; Madani & Mariño, 2009; Liu *et al.*, 2015; Feng *et al.*, 2017). In order to improve the ecological environmental quality of the watersheds and achieve effective and sustainable utilization of environmental resources, the use of comprehensive watershed management has been widely recognized in recent years (Imperial, 2005; Qi & Chang, 2011; Sušnik *et al.*, 2012; Dai *et al.*, 2013; Kotir *et al.*, 2017; Ding *et al.*, 2019).

Watersheds contain a stable, identifiable, and functional natural boundary and can serve as the basic unit for natural resources management (Misganaw & Keefer, 1998; Bohn & Kershner, 2002). From a ‘system’ perspective, the watershed can be regarded as a system that integrates socio-economic and environmental aspects (Heathcote, 1998; Nakamura, 2003; Liu *et al.*, 2015) and shows dynamic, nonlinear, complex, and diverse characteristics, which cannot only comprehend the various features of the watershed but also remain simple to apply. Compared to the traditional methods, system dynamics (SD) can assess and analyze the complex dynamic feedbacks in socio-economic and ecological environments (Kotir *et al.*, 2016; Allington *et al.*, 2017; Dong *et al.*, 2019) and, thereby, can be taken as a test model for real-world systems.

As a powerful contextual tool for determining the adaptive development patterns for decision-makers (Yim *et al.*, 2004; Goh, 2012; Sivapalan, 2015; Pluchinotta *et al.*, 2018), SD provides a tool for examining the impacts of various strategies and policies and simulating socio-economic systems (Vidal-Legaz *et al.*, 2013). In water resources and ecological environment management, SD has been applied to the following major fields: sustainable utilization of water resources (Sun *et al.*, 2017) carrying capacity of water resources (Wang *et al*., 2018), smart groundwater governance (Barati *et al*., 2019), agricultural water footprint (Feng *et al*., 2017), global modeling of water resources (Davies & Simonovic, 2011), water resources planning (Wang *et al*., 2011), water quality management (Tangirala *et al*., 2003) and environmental flow allocation (Wei *et al*., 2012), and water resources management (Hassanzadeh *et al*., 2014).

However, much less attention has been paid to the application of SD to simulate interrelations among socio-economy, water and land resources and their adjacent ecological environment in watersheds, and the joint effects of socio-economic development and watershed environment management. In order to fill this gap, this study uses a SD model to build a comprehensive assessment and management system to evaluate socio-economic impacts of different levels of natural resources saving and ecological environment protection in the watershed, and identifying optimal and practical strategy to permit the establishment of a coordinative development mode.

2. Materials and methods

2.1. Site description

In this study, we take the Weihe River Basin (WHR) in Northwest China as our research area. The WHR is 818 km long with a river basin area of 1.36×10^5 km^2, and it originates in the Niaoshu Mountain, which is ocated in the Western Qinlin Mountain, 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 first four cities are located in Gansu Province while the remainiing five cities are located in Shaanxi Province (Figure 1). The WHR is located in the transition zone between dry and humid areas, with annual average precipitation of 572 mm/yr, and the average annual surface evaporation in the basin ranges from 660 mm/yr to 1,600 mm/yr. As the WHR is treated as the 'Mother River' of the Guanzhong Region[1], it is the core area of the 'Guanzhong-Tianshui Economic Zone[2]', playing an important role in the socio-economic development of Northwest China and the ecosystem health of the Yellow River. However, there is a growing shortage of water resources as the annual average rainfall and runoff of the main stream of the WHR has decreased year by year and water consumption has increased substantially due to the economic development and population growth, which restricts the sustainable development in the research area.

2.2. Data sources

The data for population, economy, land and water resources, environmental pollution and protection were obtained from the literature and field surveys. The indicators for the population, economy and land

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

[2] 'Guanzhong-Tianshui Economic Zone' covers Xi'an, Tongchuan, Baoji, Xianyang, Weinan, Yangling, and Shangluo cities in Shaanxi Province and Tianshui city in Gansu Province. The Economic Zone, taking Xi'an as the central city, Baoji as the sub-central city, and the other cities as the sub-core cities, forms a developed city cluster and industrial agglomeration belt in Western China.

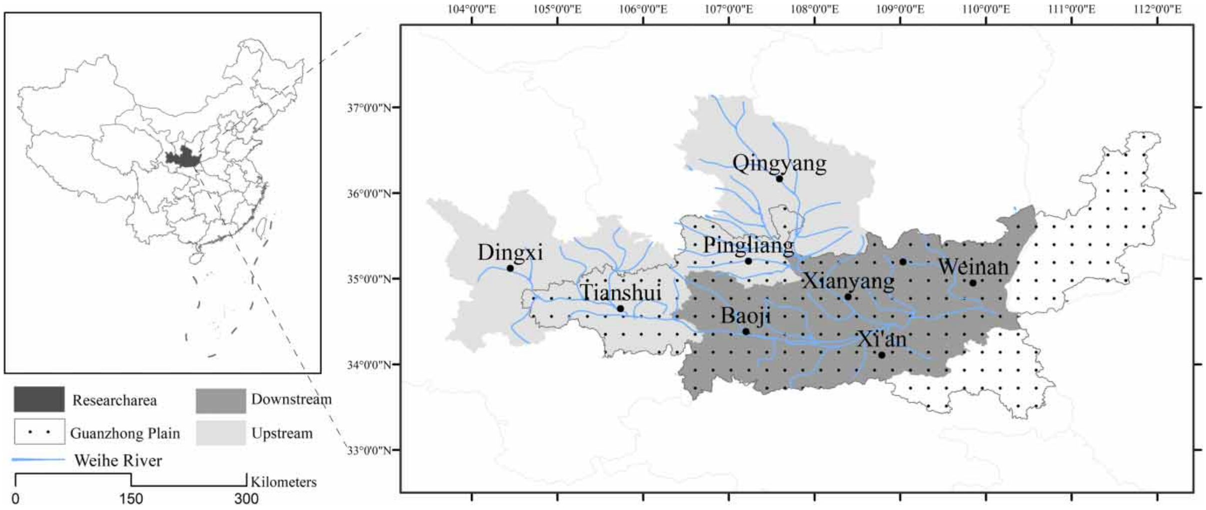

Fig. 1. Map of Weihe River Basin.

resources subsystem were mainly obtained from the statistical yearbooks of Shaanxi and Gansu Province (Shaanxi Statistical Yearbooks, 2006–2017; Gansu Statistical Yearbooks, 2006–2017). The data of water resource demand and supply were selected from Shaanxi Water Resources Bulletin and Gansu Water Resources Bulletin. The data related to the water environment subsystem were obtained from Wei *et al.* (2012), Sun *et al.* (2017), and Song *et al.* (2018).

2.3. System dynamics model

System dynamics model is a method to describe complex systems and analyze its dynamic behavior (Forrester, 1961, 1969), 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 simulation. Compared with other frequently used approaches, the SD model can be applied to simulate the microscale and macroscale systems to solve dynamic problems (Leal Neto *et al.*, 2006). The SD method has attested to be efficient not only for operational and strategic issues (Senge & Sterman, 1992; Sterman, 2000), but also for the simulation of environmental and socio-economic development issues (Davies & Simonovic, 2011; Han *et al.*, 2017; Song *et al.*, 2018), which makes it suitable for examining the effect of the coordinative development of socio-economic and environmental aspects.

The main variables of the SD model include stock variables, rate variables, and auxiliary variables. Stock variables describe the current state of the system, which reflect 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 of the system, which can be described as below:

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

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; t represents time.

3. Model setting and description

3.1. Stock-flow figure

To quantify and simulate the SD model, Figure 2 shows the stock-flow chart, which is on the basis of the relationship among the indicators and the main equations. There are nine stock variables, 53 auxiliary variables, and 15 constant parameters. The symbols for the main variables, parameters, and equations in the paper are in Vensim language, as shown in Supplementary Material, Appendix A.

3.2. Model validation and sensitivity analysis

As the SD model abstracts the actual world into an information structure (Wang *et al.*, 2017), to ensure the quality of model simulation results, an appropriate quantitative method should be selected to examine the model validation and sensitivity analysis before running a simulation (Yang *et al.*, 2019).

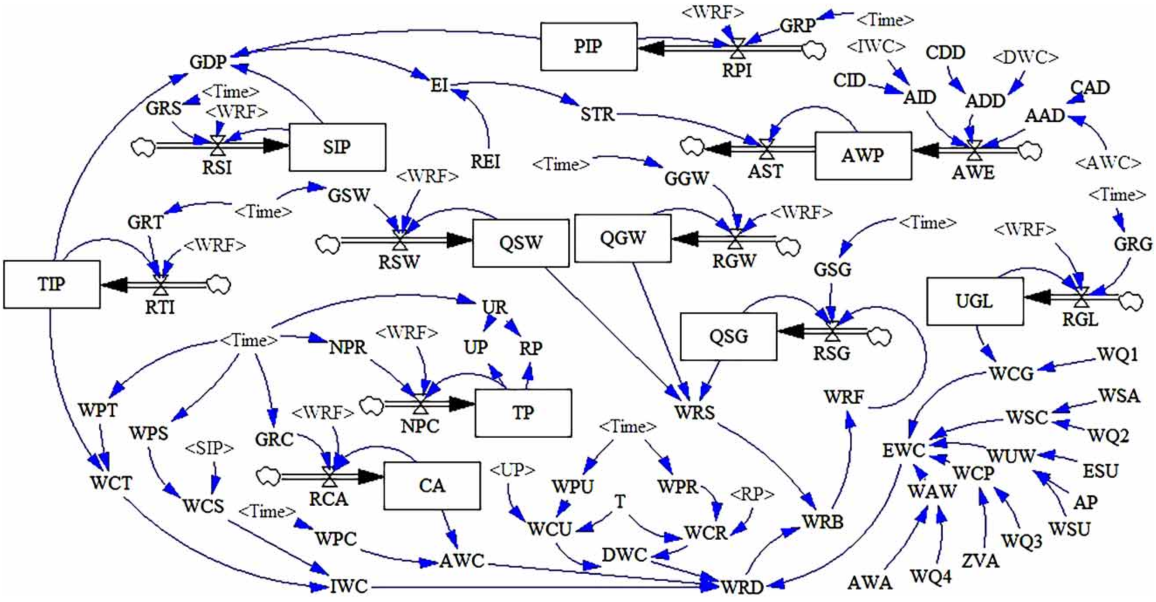

Fig. 2. Stocks and flows of the simulated system.

3.2.1. Model validation. To validate the applicability and accuracy of the SD model, the actual values are compared with simulation results. According to the validation results, the model can be examined to verify if it accurately interprets the actual system. The validation index can be calculated as follows (Xiong *et al.*, 2015):

$$ERR = \left|\frac{\hat{Y}_t - Y_t}{Y_t}\right|$$

where $\hat{Y}_t$ and Y_t represent actual and simulated values, respectively; t is time. If $ERR \leq 0.1$, the variable is accurate; if $ERR \geq 0.1$, the variable is not accurate.

3.2.2. Sensitivity analysis. Sensitivity test is carried out to ascertain the influence caused by the change of parameters, which is the basis for optimization of the model. The sensitivity can be examined by altering the value of one parameter at a time while the others remain unchanged. The sensitivity index can be defined as follows (Zhang *et al.*, 2008):

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

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

where R_Y represents the sensitivity index of stock variable Y to 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 stock variable Y and parameter X at time t, respectively; t means time; R represents the average sensitivity degree; R_Y means sensitivity degree of stock variable Y; i means parameter for stock variables; n means the number of parameter for stock variables. If $R \leq 0.1$, the variable is not sensitive; if $R \geq 0.1$, the variable is sensitive.

3.3. Selection of variables

This study builds an integrative model which combines socio-economic, ecological environment, and water resources of WHR, which is naturally the system boundary of the SD model in the paper. The research period extends from 2005 to 2030, and the time step is one year. Following Wei *et al.* (2012), Sun *et al.* (2017), and Song *et al.* (2018) and considering the accessibility of data, this study selects five subsystems as the model subsystems, including the population, economy, land resources, water demand and supply, and water environment subsystem.

3.3.1. Population subsystem. The population factor is one of the driving factors that has a vital impact on the socio-economic development and the ecological environment (Falkenmark & Widstrand, 1992; Sinding, 2009; Immerzeel & Bierkens, 2012; Yang *et al.*, 2019). In this subsystem, we choose six indicators to show the scale and growth rate of the population, including total population (TP), net population change (NPC), urban population (UP), rural population (RP), urbanization rate (UR), and natural population growth rate (NPR). The total population is the stock variable, which is decided by the net population change, while the net population change is decided by the natural population growth rate. The urbanization rate determines the change of the urban and rural population.

3.3.2. Economy subsystem. The main elements of the economic subsystem should contain general production, for instance, agricultural and industrial production, which are supported by water resources. Economic development not only affects the ecological environment, but also influences the consumption of water resources (Feng *et al*., 2008). Consequently, ten indicators are selected to reflect the economic status and its growth, including GDP, primary industry production (PIP), secondary industry production (SIP), tertiary industry production (TIP), rise in primary industry production (RPI), rise in secondary industry production (RSI), rise in tertiary industry production (RTI), growth rate of primary industry production (GRP), growth rate of secondary industry production (GRS), and growth rate of tertiary industry production (GRT). PIP, SIP, and TIP are stock variables, while RPI, PSI, and RIT are rate variables that cause the three stocks to vary.

3.3.3. Land resources subsystem. The relationship between land and water resources is reflected by the interaction in terms of their utilization (Gilmour *et al*., 2005; Keeley & Faulkner, 2008). The change in cultivated area affects agricultural water demand, while the ecological water consumption will grow as the urban green land increases. Therefore, six indicators are selected as follows: cultivated area (CA), urban green land (UGL), rise in cultivated area (RCA), rise in urban green land (RGL), growth rate of cultivated area (GRC), and growth rate of urban green land (GRG).

3.3.4. Water demand and supply subsystem. Water demand and supply in the total amount of water resources are reflected in this subsystem (Wei *et al*., 2012; Sun *et al*., 2017). In this study, the water resources demand (WRD) is measured from the actual consumption of water resources, including agricultural water consumption (AWC), industrial water consumption (IWC), domestic water consumption (DWC), and ecological water consumption (EWC). In addition, the structure of the water resources supply (WRS) is classified into three types: the quantity of surface water resources (QSW), the quantity of ground water resources (QGW), and the quantity of overlap between surface and ground water (QSG). Moreover, two crucial indicators are contained in this subsystem, named water resource balance (WRB) and water resources factor (WRF).

3.3.5. Water environment subsystem. The quality of the water environment affects the regional sustainable development and water resource sustainable utilization (Kılkış, 2016; Song *et al*., 2018). The rational allocation of ecological water resource and the effective control of water pollution are beneficial to the sustainable development of the region (Song *et al*., 2018). Following Sun *et al*. (2017) and Song *et al*. (2018), we select the indicator of water consumption of ecology (EWC) and the amount of water pollution (AWP) to reflect the allocation of ecological water resource and the control of water pollution, respectively. Furthermore, the EWC is divided into five components, including water consumption of green area (WCG), water for water and soil conservation (WSC), water consumption of plant (WCP), water consumption of urban water surface (WUW), and water consumption of artificial water area (WAW). The AWP is influenced by amount of wastewater effluent (AWE) and amount of sewage treatment (AST) (Qin *et al*., 2011; Sun *et al*., 2017). Moreover, the amount of sewage treatment is determined by the sewage treatment rate (STR), which is affected by the environmental investment (EI).

3.4. Scenario design

To compare with other scenarios, we use Scenario 0 to evaluate the future trend under the current development pattern. In Scenario 0, all features of the basin remain unchanged. Moreover, five alternative scenarios are proposed to facilitate the coordinative development of socio-economy and environment.

Scenario 1 (S1: Population growth) addresses basin water resources under rapid population increases. Rapid population growth can affect water demand (Sophocleous, 2004) and thereby exert new pressures on the carrying capacity of water resources in the research area.

Scenario 2 (S2: Economic leading) gives priority to economic development, which emphasizes the importance of economic growth. Jointly considering the current development status and future potential of regional economic development of Shannxi and Gansu Province, a high economic growth is employed. To simulate this situation, the parameters related to economic development are appropriately amplified (Liu *et al.*, 2015).

Scenario 3 (S3: Resource saving) focuses on improving the water efficiency and water resource supply, which are crucial for the coordinated development of ecology and socio-economy (Xue *et al.*, 2017). Considering this situation, we assume that the WPU, WPR, WPS, WPT, and WPC all decline by 25%.

Scenario 4 (S4: Environment leading) emphasizes the protection of the environment with controlling pollution and improving environmental quality. For years, basin environmental issues have dramatically influenced the socio-economy development, therefore, effective strategies for improving the ecological and environmental quality of the river basin are urgently needed (Yang *et al.*, 2019). Increasing environmental investment and reducing wastewater discharge are effective measures to protect the environment of the river basin, so we assume that the CID, CDD, and CAD all decline by 25%, while the REI rises by 25%.

Scenario 5 (S5: Collaborative development) represents an integrated scenario for the coordinative development of socio-economy and environment. A new parameter set is established by combining the above-mentioned scenarios (S1, 2, 3, and 4). The scenarios and parameters used in the model are shown in Table 1.

4. Results

4.1. Test for model

4.1.1. Validation test. The data from 2005 to 2016 are substituted into the SD model, and considering a mass of variables in the model, only four representative variables are chosen for the test. Table 2 demonstrates the error rate and average error rate of each parameter in the model are less than 10%, which falls within the acceptable range. The optimal and least optimal values of average error rate are 0.15% and 3.5%, respectively. The model validation results match well with the actual system, indicating that the model can reflect the reality accurately.

4.1.2. Sensitivity test. To test the model's sensitivity, we select 12 parameters to confirm their influence towards the stock variables. Each parameter increases or decreases by 10% annually during the

Table 1. Comparison of the model.

Parameter	S0 Natural growth	S1 Population growth	S2 Economic leading	S3 Resource saving	S4 Environment leading	S5 Collaborative development
Natural population growth rate (NPR)	Normal	Increase by 25%	Normal	Normal	Normal	Increase by 12.5%
Growth rate of primary industry production (GRP)	Normal	Normal	Increase by 25%	Normal	Normal	Increase by 12.5%
Growth rate of secondary industry production (GRS)	Normal	Normal	Increase by 25%	Normal	Normal	Increase by 12.5%
Growth rate of tertiary industry production (GRT)	Normal	Normal	Increase by 25%	Normal	Normal	Increase by 12.5%
Water consumption per day by per urban resident (WPU)	Normal	Normal	Normal	Decrease by 25%	Normal	Decrease by 12.5%
Water consumption per day by per urban resident (WPR)	Normal	Normal	Normal	Decrease by 25%	Normal	Decrease by 12.5%
Water consumption per unit of secondary industry production (WPS)	Normal	Normal	Normal	Decrease by 25%	Normal	Decrease by 12.5%
Water consumption per unit of tertiary industry production (WPT)	Normal	Normal	Normal	Decrease by 25%	Normal	Decrease by 12.5%
Water consumption per cultivated area (WPC)	Normal	Normal	Normal	Decrease by 25%	Normal	Decrease by 12.5%
Coefficient of industry wastewater discharge (CID)	Normal	Normal	Normal	Normal	Decrease by 25%	Decrease by 12.5%
Coefficient of domestic wastewater discharge (CDD)	Normal	Normal	Normal	Normal	Decrease by 25%	Decrease by 12.5%
Coefficient of agriculture wastewater discharge (CAD)	Normal	Normal	Normal	Normal	Decrease by 25%	Decrease by 12.5%
Environmental investment ratio (REI)	Normal	Normal	Normal	Normal	Increase by 25%	Increase by 12.5%

Table 2. Error rate between the actual and simulation values.

Year	Actual value	Simulation value	Error rate (%)	Average error rate (%)	Actual value	Simulation value	Error rate (%)	Average error rate (%)
	Total population (104 persons)				GDP (108 yuan)			
2005	3,416.17	3,416.17	0	2.31	3,034.41	3,034.41	0	3.50
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	3,981.48	−5.84	
2008	3,449.3	3,522.54	2.12		5,245.49	4,832.3	−7.88	
2009	3,425.01	3,536.63	3.26		6,085.80	5,936.35	−2.46	
2010	3,345.71	3,511.87	4.97		7,352.52	6,890.47	−6.28	
2011	3,356.73	3,431.1	2.22		8,943.54	8,311.47	−7.07	
2012	3,373.17	3,441.39	2.02		10,263.13	10,091.6	−1.67	
2013	3,382.25	3,458.6	2.26		11,629.35	11,579.8	−0.43	
2014	3,391.67	3,468.97	2.28		12,802.20	12,969.5	1.31	
2015	3,406.59	3,479.38	2.14		13,354.18	14,128.1	5.80	
2016	3,427.03	3,493.3	1.93		14,292.71	14,469.3	1.24	
	Cultivated area (104 ha)				Water resources demand (108 m^3)			
2005	322.79	322.79	0.00	0.15	68.14	68.14	0.00	1.74
2006	321.90	322.14	0.08		64.18	67.83	5.70	
2007	322.62	321.18	−0.45		60.80	62.84	3.35	
2008	322.30	321.82	−0.15		63.78	63.95	0.27	
2009	322.42	321.50	−0.29		64.16	65.65	2.33	
2010	321.91	321.82	−0.03		63.77	64.69	1.44	
2011	321.35	321.18	−0.05		65.24	65.31	0.12	
2012	320.75	320.53	−0.07		66.18	67.14	1.45	
2013	320.09	319.89	−0.06		64.72	65.39	1.03	
2014	318.49	319.25	0.24		66.82	67.81	1.48	
2015	317.34	317.66	0.10		66.84	68.29	2.16	
2016	315.40	316.39	0.31		66.86	67.87	1.51	

simulation period. The results shown in Table 3 reveal that only three of the 12 parameters have a higher sensitivity than 10%, including GRS, WPS, and WPC. Other parameters, however, are insensitive to target system state, indicating that the model is robust.

According to the results from model validation and sensitivity analysis, the SD model is perceived to be not only valid, but also robust. Therefore, it suggests that the SD model can reflect the actual situation well and thus provides a good basis for the subsequent prediction.

Table 3. The results of sensitivity analysis.

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	36.91	33.45
GRC	0.71	0.71	WPU	5.39	5.39
WPR	9.55	9.55	WPS	14.96	14.98
WPT	3.80	3.80	WPC	57.79	65.18
GGW	9.29	8.86	WSU	7.02	7.02
AWA	0.55	0.55	CID	8.74	8.74

4.2. Scenario analysis

4.2.1. Natural growth (S0). Based on the test results, we simulate the SD model under Scenario 0, and the results are summarized in Table 4.

In the population subsystem, the total population will reach 3,644.33 × 10^4 person in 2030, and the growth rate is 6.68%. The urban population will change from 881.37 × 10^4 in 2005 to 2,004.38 × 10^4 in 2030 with a relative increase of 127.42%, indicating that the speed of urbanization in the research area will accelerate.

In the economy subsystem, the GDP will reach 29,499.9 × 10^8 yuan in 2030, 9.72 times than that in 2005. The primary industry production with the slowest growth rate is predicted to be 2,235.79 × 10^8 yuan, while the secondary industry production with the fastest growth rate is predicted to be 15,050.00 × 10^8 yuan, which is 5.99 and 11.15 times higher than that in 2005, respectively.

In the land resources subsystem, the cultivated area will reach 305.36 × 10^4 ha in 2030, and the value is reduced by 5.4% compared to 2005. Urban green land is predicted to increase from 1.62 × 10^4 ha in 2005 to 16.42 × 10^4 ha in 2030, which corresponds to an increase by 10.14 times.

In the water demand and supply subsystem, the water resource demand will reach 82.24 × 10^8 cubic meters, which is increased by 20.69% compared to 2005. Meanwhile, the water resources supply is projected to decrease from 123.72 × 10^8 cubic meters in 2005 to 73.73 × 10^8 cubic meters in 2030, which corresponds to a decrease by 40.41%. Moreover, the gap between demand and supply will reach 8.52 × 10^8 cubic meters by 2030, suggesting that we should explore other effective ways to balance water demand and supply.

In the water environment subsystem, the ecological water consumption and amount of water pollution will reach 6.37 × 10^8 and 14.85 × 10^8 cubic meters, which are 2.53 and 1.81 times than that in 2005, indicating that more and more attention has been paid to environmental protection and the growth rate of pollution emissions has been slowed.

Table 4. Simulated values of the critical variables in Scenario 0.

Subsystem/Unit	Variable	2005	2020	2030	Growth rate (%)
Population/10^4 person	TP	3,416.17	3,571.19	3,644.33	6.68
	UP	881.37	1,767.74	2,004.38	127.42
	RP	2,534.80	1,803.45	1,639.95	−35.30
Economy/10^8 yuan	GDP	3,034.41	18,284.7	29,499.9	872.18
	PIP	373.02	1,770.59	2,235.79	499.38
	SIP	1,349.78	8,450.78	15,050.00	1,015.00
	TIP	1,311.61	8,063.33	12,214.10	831.23
Land resources/10^4 ha	CA	322.79	310.35	305.36	−5.40
	UGL	1.62	9.32	16.42	913.58
Water demand and supply/10^8 m^3	WRD	68.14	70.75	82.24	20.69
	WRS	123.72	65.25	73.73	−40.41
	WRB	55.58	−5.50	−8.52	−115.33
Water environment/10^8 m^3	EWC	2.52	4.52	6.37	152.78
	AWP	8.22	13.80	14.85	80.66

4.2.2. Different scenarios analysis. On the basis of the descriptions provided above, the simulation results under different scenarios can be obtained by using Vensim software (see Tables 5–9).

Table 5 shows that compared with the natural growth scenario (S0), the growth rate of total population in Scenario 1 is the highest (about 10.42%), and will be $3,772.05 \times 10^4$ person, while the value in Scenario 2 is the lowest (about 6.11%), and will reach $3,624.89 \times 10^4$ person. The population growth rate should be kept at a reasonable level to maintain regional development. Considering that too fast a growth rate may exert excessive pressure on the environment and resources, Scenario 5 is more appropriate in this regard. In Scenario 5, the total population will be $3,716.55 \times 10^4$ person, and the growth rate is predicted to be 8.79%.

Table 5. Simulation results of the population subsystem in all scenarios (unit: 10^4 person).

Variable	Year	S0	S1	S2	S3	S4	S5
TP	2005	3,416.17	3,416.17	3,416.17	3,416.17	3,416.17	3,416.17
	2020	3,571.19	3,677.15	3,568.61	3,572.56	3,571.19	3,629.96
	2030	3,644.33	3,772.05	3,624.89	3,670.22	3,644.33	3,716.55
	Growth rate (%)	6.68	10.42	6.11	7.44	6.68	8.79
UP	2005	881.37	881.37	881.37	881.37	881.37	881.37
	2020	1,767.74	1,820.19	1,766.46	1,768.42	1,767.74	1,796.83
	2030	2,004.38	2,074.63	1,993.69	2,018.62	2,004.38	2,044.10
	Growth rate (%)	127.42	135.39	126.20	129.03	127.42	131.92
RP	2005	2,534.80	2,534.80	2,534.80	2,534.80	2,534.80	2,534.80
	2020	1,803.45	1,856.96	1,802.15	1,804.14	1,803.45	1,833.13
	2030	1,639.95	1,697.42	1,631.20	1,651.60	1,639.95	1,672.45
	Growth rate (%)	−35.30	−33.04	−35.65	−34.84	−35.30	−34.02

Table 6. Simulation results of the economy subsystem in all scenarios (unit: 10^8 yuan).

Variable	Year	S0	S1	S2	S3	S4	S5
GDP	2005	3,034.41	3,034.41	3,034.41	3,034.41	3,034.41	3,034.41
	2020	18,284.7	18,279.70	27,729.10	18,361.30	18,284.7	22,789.60
	2030	29,499.9	29,391.10	43,433.10	35,190.80	29,499.9	40,077.30
	Growth rate (%)	872.18	868.59	1,331.35	1,059.72	872.18	1,220.76
PIP	2005	373.02	373.02	373.02	373.02	373.02	373.02
	2020	1,770.59	1,770.18	2,507.66	1,776.80	1,770.59	2,127.24
	2030	2,235.79	2,231.66	3,135.91	2,427.47	2,235.79	2,800.51
	Growth rate (%)	499.38	498.27	740.68	550.76	499.38	650.77
SIP	2005	1,349.78	1,349.78	1,349.78	1,349.78	1,349.78	1,349.78
	2020	8,450.78	8,446.25	13,030.80	8,520.59	8,450.78	10,729.10
	2030	15,050.00	14,982.20	22,486.00	18,461.40	15,050.00	21,151.00
	Growth rate (%)	1,015.00	1,009.97	1,565.90	1,267.73	1,015.00	1,467.00
TIP	2005	1,311.61	1,311.61	1,311.61	1,311.61	1,311.61	1,311.61
	2020	8,063.33	8,063.29	12,190.70	8,063.92	8,063.33	9,933.24
	2030	12,214.10	12,177.20	17,811.20	14,302.00	12,214.10	16,125.80
	Growth rate (%)	831.23	828.42	1,257.96	990.42	831.23	1,129.47

Table 7. Simulation results of the land resources subsystem in all scenarios (unit: 10^4 ha).

Variable	Year	S0	S1	S2	S3	S4	S5
CA	2005	322.79	322.79	322.79	322.79	322.79	322.79
	2020	310.35	310.27	310.26	310.51	310.39	310.41
	2030	305.36	305.02	303.54	306.72	305.46	306.03
	Growth rate (%)	−5.40	−5.51	−5.96	−4.98	−5.37	−5.19
UGL	2005	1.62	1.62	1.62	1.62	1.62	1.62
	2020	9.32	9.31	9.22	9.37	9.34	9.37
	2030	16.42	16.35	14.19	20.05	16.53	16.96
	Growth rate (%)	913.58	909.26	775.93	1,137.65	920.37	946.91

Table 6 shows that the indicators of GDP, primary, secondary and tertiary industry production have a similar growing trend. Compared with Scenario 0, Scenario 2 has the most significant influence on the economy, Scenario 1, however, has the lowest economic level. In Scenario 2, the GDP will be 43,433.10 × 10^8 yuan, and the growth rate will reach 1,331.35%. The secondary industry production and tertiary industry production will, respectively, reach 22,486.00 × 10^8 and 17,811.20 ×10^8 yuan, which will be predicted to improve by 16.66 and 13.58 times. Considering that rapid economic development may cause environmental contamination, Scenario 5 is more moderate. In Scenario 5, the GDP will reach 40,077.30 × 10^8 yuan, 13.21 times higher than that in 2005.

Table 7 shows that the maximum and minimum values of urban green land, respectively, appear in Scenario 3 and Scenario 2. In Scenario 3, urban green area will reach 20.05 × 10^4 ha, which is improved by 1,137.65%. However, the value will be 14.19 × 10^4 ha, which corresponds to an increase by 775.93% in Scenario 2. Meanwhile, the different scenarios have few significant differences in the values of the total cultivated area. Compared with the other models, Scenario 5 is more suitable. In Scenario 5, the cultivated area will reach 306.03 × 10^4 ha, and the urban green land will be 16.96 × 10^4 ha.

Table 8 shows that the gap between water resource supply and demand exhibits a growing trend. The lowest and highest water resource imbalance values, respectively, appear in Scenario 3 (about −87.56%)

Table 8. Simulation results of the water demand and supply subsystem in all scenarios (unit: 10^8 m^3).

Variable	Year	S0	S1	S2	S3	S4	S5
WRD	2005	68.14	68.14	68.14	57.74	68.14	62.64
	2020	70.75	71.08	79.46	54.28	70.37	67.83
	2030	82.24	82.53	94.53	68.35	81.86	74.75
	Growth rate (%)	20.69	21.12	38.73	18.38	20.14	19.33
WRS	2005	123.72	123.72	123.72	123.72	123.72	123.72
	2020	65.25	65.25	65.14	65.27	65.25	65.27
	2030	73.73	73.70	71.27	76.56	73.95	74.19
	Growth rate (%)	−40.41	−40.43	−42.39	−38.12	−40.23	−40.03
WRB	2005	55.58	55.58	55.58	65.98	55.58	61.08
	2020	−5.50	−5.83	−14.12	10.99	−5.12	−2.56
	2030	−8.52	−8.83	−23.26	8.21	−7.91	−0.56
	Growth rate (%)	−115.33	−115.89	−141.85	−87.56	−114.23	−100.92

and Scenario 2 (about −141.85%), and the gap between demand and supply will reach 23.26 × 10^8 cubic meters in Scenario 2. Meanwhile, different scenarios have few significant differences in water supply, indicating that the imbalance is mainly influenced by water consumption, which shows an increasing trend in all scenarios. Moreover, the results imply that although Scenario 2 guarantees the economic development, it enlarges this imbalance between water resource supply and demand. Compared with the other models, Scenario 5 is more appropriate. In Scenario 5, the gap between demand and supply will reach 0.56 × 10^8 cubic meters.

Table 9 shows that the growth rate of ecological water consumption in Scenario 2 and Scenario 3 will, respectively, be the lowest and highest (about 129.83% and 190.16%), and the values will reach 5.79 × 10^8 and 7.31 × 10^8 cubic meters, respectively. Moreover, the growth rate of amount of water pollution is greatest in Scenario 2 (about 97.76%) and lowest in Scenario 4 (about 35.49%), and will, respectively, reach 16.26 × 10^8 and 11.14 × 10^8 cubic meters. In Scenario 2, the economy displays rapid development, resulting in an increase in amount of water pollution. Considering that the economy cannot be developed at the cost of destroying the environment, Scenario 5 is more suitable as before. In Scenario 5, the ecological water consumption and amount of water pollution will reach 6.72 × 10^8 and 12.26 × 10^8 cubic meters, respectively.

5. Discussion

This study aims to construct a comprehensive evaluation and management system for the joint effects of socio-economic development and watershed environment management, which could be obtained through model tests and scenario analysis. The model test results show that the SD model is considered not only valid, but also robust. Moreover, the results of the scenario analysis can reveal the trends of system changes and effects of various policy combinations, so as to offer guidance to policy makers. The population growth and economic leading scenarios (S1 and S2) reveal the single pursuit of rapid population and economic growth will enhance the imbalance between water resource supply and demand, and aggravate the contradiction between the socio-economic development and ecological environment, which development is still at the expense of good ecological environment. Without effective watershed management, rapid socio-economic development most likely causes serious environmental problems. This suggests that a comprehensive strategy with the socio-economic and eco-environment should be taken into account in watershed management.

Table 9. Simulation results of the water environment subsystem in all scenarios (unit: 10^8 m^3).

Variable	Year	S0	S1	S2	S3	S4	S5
EWC	2005	2.52	2.52	2.52	2.52	2.52	2.52
	2020	4.52	4.52	4.50	4.53	4.53	4.53
	2030	6.37	6.35	5.79	7.31	6.51	6.72
	Growth rate (%)	152.78	152.06	129.83	190.16	158.41	166.74
AWP	2005	8.22	8.22	8.22	8.22	8.22	8.22
	2020	13.80	13.90	14.75	10.36	10.35	10.96
	2030	14.85	14.96	16.26	12.58	11.14	12.26
	Growth rate (%)	80.66	82.02	97.76	53.03	35.49	49.20

In addition, Scenario 3 presents that water resource saving can narrow the gap between water resource supply and demand; however, the sustainable utilization of water resources and socio-economic development cannot be met in the future. Meanwhile, although the amount of water pollution increases in all scenarios, the growth rate in Scenario 3 is the lowest, demonstrating that water resource conservation is an effective measure to protect the ecological environment of the river basin. Compared with other scenarios, Scenario 4 is intended to assess the protection of environment with controlling pollution and improving the environmental investment. The result shows that the socio-economic development will be constrained and the ecological environment quality of the river basin can be improved. To achieve more sustainable development, we integrated the first four scenarios into the fifth scenario and provide an optimal choice for river basin development, which comprehensively considers population, economy, land and water resources, environmental pollution and protection.

Furthermore, based on the status quo in Weihe River Basin, there is a prominent contradiction between economic development and environmental protection, and the government should schedule a series of measures for coordinated development of socio-economic and environmental aspects.

First, the socio-economic development should not exceed the carrying capacity of the environment and avoid falling into the vicious cycle of economic development at the expense of wild nature, as exhibited in Scenarios 1 and 2. We should adjust the industrial structure, optimize the industrial layout, and promote the transformation and upgrading of traditional industries through strengthening technological transformation and innovation. Moreover, vigorous development of the tertiary industry, including high and new technology industry, cultural industry and service industry, should be encouraged to reduce the large consumption of resources and environment. As for the secondary industry, we should appropriately increase investment in research and development, raise the proportion of technology-intensive industries, and promote the development of high-end technology industries and products in the secondary industry.

Second, local governments in the WHR should format policies and countermeasures to prevent urban sprawl at the expense of cultivated land, and advocated intensive use of urban land as well as increasing the green areas, to facilitate the protection of the ecological environment. We should strengthen the management of planning implementation to promote the rational and intensive use of land for all kinds of construction, especially for urban construction. Through strict examination of the applications for urban construction land, a land expropriation system should be rigorously implemented to control the scale of the land use. Furthermore, a red line for the permanent protection of the basic cultivated area should be drawn, and land development, consolidation, and reclamation should be promoted, which can increase the effective cultivated area.

Third, tailored policies on water resources management in the research area should also be directed by the local government, in order to extend the sources of water supply, increase the efficiency of water usage, and optimize the existing structure of water supply in the research area. In terms of agriculture, we should improve irrigation measures and adopt new irrigation methods, such as sprinkler irrigation and drip irrigation, and improve the construction of water-saving supporting projects in irrigated areas. In terms of industry and household life, technical measures should be taken to improve sewage treatment, and the recycling rate of industrial wastewater and domestic sewage should be raised. In addition, the rational design of rainwater systems can realize the collection, treatment, and reuse of rainwater.

Last but not least, the research area should divert the local development mode towards a more sustainable fashion, that is to say, to emphasize the coordinated development of society, economy, and environment. Since no single step, no matter population increase, economic development, nor nature resources preservation, will be the solution for achieving the double win of alleviation of the environmental pressures without affecting the socio-economic development level.

6. Conclusions

In this study, a watershed-scale SD model is applied to assess the coordinative development of the socio-economy and environment in the WHR. The model is calibrated based on the data collected from the 2005 to 2016 period, and the test results of validation and sensitivity confirm the applicability, accuracy, and robustness of the model. Based on the test results, different scenarios are established to predict the overall performance of the model. The main conclusions can be derived as follows: (1) The collaborative development scenario (S5) is the optimal scheme that takes both the socio-economic development and the environment protection into consideration. Therefore, development strategies based on S5 can accelerate population and economic development, assure a moderate growth rate, reduce the imbalance between water resource supply and demand, and improve the ecological environment of the river basin. (2) The imbalance between water resource supply and demand is mainly influenced by water resource demand. Since the water resource consumption will increase with production growth and population explosion, the imbalance will expand in the near future, which will lead to accumulated unsustainable trends in the research area. (3) Pollution issues cannot be solved through merely environmental investment, or traditional economic development path under the notion of ‘pollute first and then protect’. Strengthening environmental protection in the research area requires coordinative development of the socio-economy and environment.

Compared with the existing models, our SD modeling framework clearly expresses the stock-flow among socio-economic development, land and water resources, environmental pollution and protection in a river basin. It also pays sufficient attention to identifying an optimal and practical strategy to allow the establishment of a coordinative development mode. Therefore, this model can help to understand the features and behaviors of a river basin, and hence provide a powerful tool for assisting decision-making on issues of coordinative socio-economic development, environmental health protection, water resources conservation, etc., in the river basin area. By using the SD model, the study found that without effective watershed management, rapid socio-economic development most likely causes serious environmental problems. This suggests that integrated socio-economic and eco-environmental strategies should be considered in watershed management. Factors such as population, economy, water and soil resources, environmental pollution and protection should be considered comprehensively, and the coordinated development of society, economy, and environment should be emphasized.

However, this study has the following inadequacies: First, the model presented in the paper is simplified, and it does not contain relevant factors such as water price and quality due to the limited data. Second, the amount of variables in the model is rather small, and some possible scenarios are not evaluated in the paper. Third, the model results may have certain errors, and the application of big data in the river basin may make the dynamic simulation results more precise and rational in the future. These inadequacies indicate directions for future research. In future studies, we will introduce water price, water quality, and other related factors into the study, and add more variables and scenarios for evaluation. In addition, we will make comprehensive use of big data to conduct dynamic simulation, which can make future dynamic simulation results more accurate and reasonable.

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Data availability statement

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

References

Allington, G. R. H., Li, W. & Brown, D. G. (2017). Urbanization and environmental policy effects on the future availability of grazing resources on the Mongolian Plateau: modeling socio-environmental system dynamics. *Environ. Sci. Policy 68*, 35–46.

Barati, A. A., Azadi, H. & Scheffran, J. (2019). A system dynamics model of smart groundwater governance. *Agric. Water Manag. 221*, 502–518.

Bohn, B. A. & Kershner, J. L. (2002). Establishing aquatic restoration priorities using a watershed approach. *J. Environ. Manage. 64*, 355–363.

Cai, Y. P., Huang, G. H., Tan, Q. & Yang, Z. F. (2011). An integrated approach for climate-change impact analysis and adaptation planning under multi-level uncertainties. Part I: methodology. *Renew. Sustain. Energy Rev. 15*, 2779–2790.

Dai, S., Li, L., Xu, H., Pan, X. & Li, X. (2013). A system dynamics approach for water resources policy analysis in arid land: a model for Manas River Basin. *J. Arid Land 5*, 118–131.

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.

Ding, X., Zhou, C., Mauerhofer, V., Zhong, W. & Li, G. (2019). From environmental soundness to sustainable development : improving applicability of payment for ecosystem services scheme for diverting regional sustainability transition in developing countries. *Sustainability 11*, 361.

Dong, Q., Zhang, X., Chen, Y. & Fang, D. (2019). Dynamic management of a water resources-socioeconomic-environmental system based on feedbacks using system dynamics. *Water Resour. Manag. 33*, 2093–2108.

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. Simul. 79*, 269–278.

Feng, L., Chen, B., Hayat, T., Alsaedi, A. & Ahmad, B. (2017). Dynamic forecasting of agricultural water footprint based on Markov Chain-a case study of the Heihe River Basin. *Ecol. Modell. 353*, 150–157.

Forrester, J. W. (1958). Industrial dynamics a major breakthrough for decision makers. *Harv. Bus. Rev. 36*, 37–66.

Forrester, J. W. (1961). *Industrial Dynamics*. MIT Press, Cambridge, MA, USA.

Forrester, J. W. (1969). *Urban Dynamics*. MIT Press, Cambridge, MA, USA.

Gilmour, J. K., Letcher, R. A. & Jakeman, A. J. (2005). Analysis of an integrated model for assessing land and water policy options. *Math. Comput. Simul. 69*, 57–77.

Goh, Y. M. (2012). Methodological application of system dynamics for evaluating traffic safety policy. *Saf. Sci. 50*, 1594–1605.

Han, T., Zhang, C., Sun, Y. & Hu, X. (2017). Study on environment-economy-society relationship model of Liaohe River Basin based on multi-agent simulation. *Ecol. Modell. 359*, 135–145.

Hassanzadeh, E., Elshorbagy, A., Wheater, H. & Gober, P. (2014). Managing water in complex systems: an integrated water resources model for Saskatchewan, Canada. *Environ. Model. Softw. 58*, 12–26.

Heathcote, I. W. (1998). *Integrated Watershed Management*. John Wiley & Sons, New York, USA.

Heinz, I., Pulido-Velazquez, M., Lund, J. R. & Andreu, J. (2007). Hydro-economic modeling in river basin management: implications and applications for the European Water Framework Directive. *Water Resour. Manag. 21*, 1103–1125.

Immerzeel, W. W. & Bierkens, M. F. P. (2012). Asia's water balance. *Nat. Geosci. 5*, 841–842.

Imperial, M. (2005). Using collaboration as a governance strategy: lessons from six watershed management programs. *Adm. Soc. 37*, 281–320.

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.

Kılkış, Ş. (2016). Sustainable development of energy, water and environment systems index for Southeast European cities. *J. Clean. Prod. 130*, 222–234.

Kotir, J. H., Smith, C., Brown, G., Marshall, N. & Johnstone, R. (2016). A system dynamics simulation model for sustainable water resources management and agricultural development in the Volta River Basin, Ghana. *Sci. Total Environ. 573*, 444–457.

Kotir, J. H., Brown, G., Marshall, N. & Johnstone, R. (2017). Systemic feedback modelling for sustainable water resources management and agricultural development: an application of participatory modelling approach in the Volta River Basin. *Environ. Model. Softw. 88*, 106–118.

Kreuter, M. W., De Rosa, C., Howze, E. H. & Baldwin, G. T. (2004). Understanding wicked problems: a key to advancing environmental health promotion. *Heal. Educ. Behav. 31*, 441–454.

Leal Neto, A. d. C., Legey, L. F. L., González-Araya, M. C. & Jablonski, S. (2006). A system dynamics model for the environmental management of the Sepetiba Bay Watershed, Brazil. *Environ. Manage. 38*, 879–888.

Liu, H., Benoit, G., Liu, T., Liu, Y. & Guo, H. (2015). An integrated system dynamics model developed for managing lake water quality at the watershed scale. *J. Environ. Manage. 155*, 11–23.

Madani, K. & Mariño, M. A. (2009). System dynamics analysis for managing Iran's Zayandeh-Rud River Basin. *Water Resour. Manag. 23*, 2163–2187.

Misganaw, D. & Keefer, L. (1998). Watershed approach for the protection of drinking water supplies in central Illinois. *Water Int. 23*, 272–277.

Nakamura, T. (2003). Ecosystem-based river basin management: its approach and policy-level application. *Hydrol. Process. 17*, 2711–2725.

Pluchinotta, I., Pagano, A., Giordano, R. & Tsoukiàs, A. (2018). A system dynamics model for supporting decision-makers in irrigation water management. *J. Environ. Manage. 223*, 815–824.

Qi, C. & Chang, N. -B. (2011). System dynamics modeling for municipal water demand estimation in an urban region under uncertain economic impacts. *J. Environ. Manage. 92*, 1628–1641.

Qin, H. -P., Su, Q. & Khu, S. -T. (2011). An integrated model for water management in a rapidly urbanizing catchment. *Environ. Model. Softw. 26*, 1502–1514.

Senge, P. M. & Sterman, J. D. (1992). Systems thinking and organizational learning: acting locally and thinking globally in the organization of the future. *Eur. J. Oper. Res. 59*, 137–150.

Seo, S. B., Mahinthakumar, G., Sankarasubramanian, A. & Kumar, M. (2018). Conjunctive management of surface water and groundwater resources under drought conditions using a fully coupled hydrological model. *J. Water Resour. Plan. Manag. 144*, 4018060.

Sinding, S. (2009). Population, poverty and economic development. *Philos. Trans. R. Soc. Lond. B. Biol. Sci. 364*, 3023–3030.

Sivapalan, M. (2015). Debates–Perspectives on socio-hydrology: changing water systems and the 'tyranny of small problems'–Socio-hydrology. *Water Resour. Res. 51*, 4795–4805.

Song, J., Tang, B., Zhang, J., Dou, X., Liu, Q. & Shen, W. (2018). System dynamics simulation for optimal stream flow regulations under consideration of coordinated development of ecology and socio-economy in the Weihe River Basin, China. *Ecol. Eng. 124*, 51–68.

Sophocleous, M. (2004). Global and regional water availability and demand: prospects for the future. *Nat. Resour. Res. 13*, 61–75.

Sterman, J. D. (2000). *Business Dynamics: Systems Thinking and Modeling for A Complex World*. Irwin/McGraw-Hill, Boston, MA, USA.

Sun, Y., Liu, N., Shang, J. & Zhang, J. (2017). Sustainable utilization of water resources in China: a system dynamics model. *J. Clean. Prod. 142*, 316–325.

Sušnik, J., Vamvakeridou-Lyroudia, L. S., Savić, D. A. & Kapelan, Z. (2012). Integrated system dynamics modelling for water scarcity assessment: case study of the Kairouan region. *Sci. Total Environ. 440*, 290–306.

Tangirala, A. K., Teegavarapu, R. & Ormsbee, L. (2003). Modeling adaptive water quality management strategies using system dynamics simulation. *Environ. Informatics Arch. 1*, 245–253.

Valipour, M. (2016). How do different factors impact agricultural water management? *Open Agric. 1*, 89–111.

Valipour, M. (2017). Global experience on irrigation management under different scenarios. *J. Water Land Devel. 32*, 95–102.

Vidal-Legaz, B., Martínez-Fernández, J., Picón, A. S. & Pugnaire, F. I. (2013). Trade-offs between maintenance of ecosystem services and socio-economic development in rural mountainous communities in southern Spain: a dynamic simulation approach. *J. Environ. Manage. 131*, 280–297.

Walter, A., Cadenhead, N., Sze Weii Lee, V., 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.

Wang, X., Zhang, J., Liu, J., Wang, G., He, R., Elmahdi, A. & Elsawah, S. (2011). Water resources planning and management based on system dynamics: a case study of Yulin city. *Environ. Dev. Sustain. 13*, 331–351.

Wang, D., Ma, G., Song, X. & Liu, Y. (2017). Energy price slump and policy response in the coal-chemical industry district: a case study of ordos with a system dynamics model. *Energy Policy 104*, 325–339.

Wang, Y., Zhou, X. & Engel, B. (2018). Water environment carrying capacity in Bosten Lake basin. *J. Clean. Prod. 199*, 574–583.

Wei, S., Yang, H., Song, J., Abbaspour, K. C. & Xu, Z. (2012). 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.

Xiong, Y., Li, J. & Jiang, D. (2015). Optimization research on supply and demand system for water resources in the Chang-Zhu-Tan urban agglomeration. *J. Geogr. Sci. 25*, 1357–1376.

Xue, J., Guan, H., Huo, Z., Wang, F., Huang, G. & Boll, J. (2017). Water saving practices enhance regional efficiency of water consumption and water productivity in an arid agricultural area with shallow groundwater. *Agric. Water Manag. 194*, 78–89.

Yang, Z., Song, J., Cheng, D., Xia, J., Li, Q. & Ahamad, M. I. (2019). Comprehensive evaluation and scenario simulation for the water resources carrying capacity in Xi'an city, China. *J. Environ. Manage. 230*, 221–233.

Yim, N.-H., Kim, S.-H., Kim, H.-W. & Kwahk, K.-Y. (2004). Knowledge based decision making on higher level strategic concerns: system dynamics approach. *Expert Syst. Appl. 27*, 143–158.

Zhang, X. H., Zhang, H. W., Chen, B., Chen, G. Q. & Zhao, X. H. (2008). Water resources planning based on complex system dynamics: a case study of Tianjin city. *Commun. Nonlinear Sci. Numer. Simul. 13*, 2328–2336.

Zhu, X. & van Ierland, E. C. (2012). Economic modelling for water quantity and quality management: a welfare program approach. *Water Resour.. Manag. 26*, 2491–2511.

Zomorodian, M., Lai, S. H., Homayounfar, M., Ibrahim, S., Fatemi, S. E. & El-Shafie, A. (2018). The state-of-the-art system dynamics application in integrated water resources modeling. *J. Environ. Manage. 227*, 294–304.

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