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Sustainable utilization of water resources in China: A system dynamics model

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A B S T R A C T

Water resources play an important role in demographic, social, and economic development. The present study divides the macroeconomic factors that affect the sustainable use of water resources into five major subsystems: economy, population, water supply and demand, land resources, and water pollution and management. It then constructs a feedback loop and stock-flow chart of the systems with the system dynamics model to simulate water supply and demand conditions and future changes in the gap between supply and demand from 2005 to 2020. Further, this study designs different development programs to simulate the changes to the key variables by changing the value of important model parameters. It is found that a balanced development program can achieve not only steady economic growth, provide a demographic dividend, and protect arable land resources, but also maximize the sewage treatment rate and improve the reutilization efficiency of water. Moreover, we find that the fundamental way in which to bridge the gap between the supply and demand of water resources is to improve water supply rather than control demand.

1. Introduction

Water resources play a vital role in people's daily lives as well as in agricultural irrigation, fish farming, and manufacturing. Water is not only an indispensable natural resource, but also an irreplaceable economic resource. However, the water shortage problem has become more serious in China over the past five decades. According to the *China Water Resources* website, China is desperately short of freshwater, with the volume of per capita freshwater being only one quarter of the world's average. Among all 669 cities in China, 440 cities have a lack of water, while 110 have severe water shortages. Not only is daily water demand increasing, water pollution and waste are also serious issues. Hoekstra (2013) noted that water pollution affects the health of residents seriously, while Bian et al. (2014), using a DEA model, confirmed that water use efficiency in China is lower than that in many other countries (see also Che and Han, 2014). Meanwhile, An et al. (2016) used a two-stage DEA model, finding that a decentralized production system leads to more water waste than centralized production, even though the former system is the most popular industrial mode. Wu et al. (2016) also used a two-stage DEA model to analyze the efficiency of reusing water resources. Moreover, Dalin et al. (2015) stated that the uneven distribution of water resources has led to their unsustainable utilization. Only by balancing the supply and demand of water resources, reducing water pollution, and building a warning system to encourage the sustainable utilization of water resources nationally can sustainability improve.

Previous research on water resources can be categorized into four types: surface and ground hydrology, water resources carrying capacity, sustainable utilization of water resources, and water pollution and management. First, surface and groundwater hydrology studies are typically associated with modeling climate change theoretically. Liang et al. (1994) proposed the variable infiltration capacity model and used hydrologic and meteorological data to obtain good simulation results. Christensen et al. (2004) predicted the impact of climate change on the Colorado River Basin in the 21st century, finding that water demand is expected to exceed water inflow volume, which would result in reservoir degradation. Similarly, Hagemann et al. (2013) used a multiple global climate-hydrological model to research the Colorado River Basin and found that climate change was not the only factor that had lead to the uncertainties in the changes of the hydrological cycle.

Second, studies of water resources carrying capacity mainly use assessment methods such as the EPI (Wang et al., 2013), CCRR (Song

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et al., 2011), information diffusion theory (Feng and Huang, 2008), cluster analysis (Wang et al., 2014), the fuzzy synthetic evaluation method (Hou and Tang, 2014; Meng and Chen, 2013), and system dynamics theory (Feng et al., 2008, 2009; Yang et al., 2015a). The system dynamics model helps clarify the relationships between the impact factors and water resources carrying capacity, whereas other methods focus on choosing indicators to measure water resources carrying capacity. However, both types of studies focus on the city or regional scale instead of the national scale.

Third, research on the sustainable utilization of water resources has drawn inconclusive findings. Hannouche et al. (2016) concluded that it is now time to apply concepts of integrated and sustainable management of water resources because of the growing agricultural practice and population needs. Lambooy (2011) introduced several tools to reduce water consumption by enterprises, such as the global water tool and water footprint tool. Pahl-Wostl et al. (2013) found that policymaking based on scientific findings should play an important role in the sustainable utilization of water resources at the global scale. Liu et al. (2010) introduced an effective water resources sustainable utilization project in the Hai Hua Ecological Industry Pilot Zone that operated at the individual firm, inter-firm, and regional levels. Chinese scholars have also used evaluation systems and methods to analyze the sustainable utilization of water resources. For example, Jin et al. (2012) examined sustainable utilization in Yunnan Province and Ling et al. (2012) built a series of comprehensive assessment indicators covering fields from ecological security to supply and demand conditions.

Finally, research on water pollution and management evaluates different water pollution control techniques, and control from source is considered to be a better approach, particularly compared with the “treatment after pollution” method (Gani and Scrimgeour, 2014; Zhang et al., 2014). Innovative approaches to sharing water use data have been encouraged to evaluate water pollution and management (Laituri and Sternlieb, 2014). For example, Ai and Yue (2014) discussed the application of big data to water resources and proposed a framework for this purpose. However, a lack of data means that the application of big data is still in the theoretical stage.

Recent research on water resources across these four domains has adopted diverse methods and models. However, it mostly focuses on the district or county levels, and seldom examines the national scale, preventing us from understanding the overall utilization of water resources at the macro level. To bridge this gap in the body of knowledge on this topic, this study uses a system dynamics model to build a comprehensive assessment and management system for understanding water resources use at the national scale in China. We examine the following five subsystems that influence the sustainable utilization of water resources: economy, population, water supply and demand, land resources, and water pollution and management. Then, we build a system dynamics model to analyze the influence of the variables of each subsystem on the supply and demand of water. Finally, suggestions from the perspectives of the economy, demographics, resources, and the environment are put forward to promote the sustainable utilization of water resources in the long-term.

2. Basic theory of system dynamics

System dynamics, a discipline based on systems science and computer simulation techniques to study systems with dynamic complexity, was first put forward by Forrester (1958) as both a tool to solve problems and a kind of a system mindset. This scientific method is a combination of theory and computer science, which allows for the research of systematic feedback structure and behavior. For instance, Meadows (1972) established a global model for analyzing industries, pollution, population, and other important factors by using the system dynamics model. From its birth in the 1950s, the system dynamics model become widely applied globally and gained more comprehensive development as a consequence in the fields of policy development, project management, learning organization, logistics and supply chains, and a company's strategic areas at both the macro and the micro levels. The standard system dynamics approach runs as follows: first, specify the problems and clarify the boundaries of the system; second, put forward a dynamic hypothesis, write the formulation, and conduct the simulation test; and finally, finish the policy design and evaluate. Every causal loop in system dynamics models should have at least one stock, otherwise no cumulant will appear. Only the flow can change the stock value, as all variables change over time.

As system dynamics theory has developed, the application range has enlarged as well to include industry, finance, medical science, education, resources and the environment, real estate, and many other fields. Among these fields, resources and the environment is the field to which system dynamics applies most (Yang et al., 2015b). For instance, Movilla et al. (2013) used system dynamics to analyze the photoelectric energy market in Spain. Based on a system dynamics model, Tan et al. (2012) formulated a cultivated land pressure index as the object variable and then built population, cultivated land, and grain subsystems to analyze their impact on cultivated land pressure in Hubei province. Xie et al. (2014) set up a system dynamics model to analyze the water resources carrying capacity of the Luanhe River Basin. The authors found a decreasing trend for the water resources carrying capacity in the basin and showed that current economic growth was not sustainable. Zhou et al. (2013) used a system dynamics model to analyze the characteristics and balance of water and land resources when planting three kinds of crops: winter wheat, summer corn, and cotton.

Compared with other common methods for analyzing water resources (e.g., principal component analysis, analytic hierarchy process, fuzzy evaluation), which are typically single equation econometric models that have strict conditions and are more adaptable to short-term quantitative research and forecasting, system dynamics is suitable for the qualitative and quantitative analysis of complex systems. The subjective qualitative analysis of the decision maker is the first step, and this is followed by the quantitative analysis (Forrester, 1958). With the help of modern computer technology, economic or societal problems, especially the sustainable utilization of water resources, can be studied in depth by using simulation techniques. Indeed, researchers can formulate feasible policy based on the estimation and simulation results provided by the system dynamics model. Indeed, system dynamics can reflect the complex relationship between large numbers of variables in huge systems and thus it is widely applied to complex nonlinear systems, and it can make better mid- or long-term predictions. Therefore, this study uses a system dynamics model to analyze the sustainable utilization of water resources in China.

3. Development of system dynamics

3.1. Selection of variables in the model

This study chooses water resources in China as the research object and the period 2005–2020 as the research period. Following Feng et al. (2008, 2009), Wu et al. (2013), and Yang et al. (2015a, 2015b) and considering the availability of data, this study selects as the model variables five major variables, including those related to the economy, population, land, and pollution and management. Factors that have an indirect influence are excluded from the model (e.g., water quality, health care, labor force). Five subsystems are then used to analyze the impact on the sustainable utilization of water resources, namely economy, population, land resources, water supply and demand, and water pollution and management, as described more in detail below.

3.1.1. *Economy subsystem*

The content of economic development should include general industries such as agricultural production and construction, which are supported by water resources. Economic development not only determines demand for water resources, but also affects the supply capacity of water resources (Feng et al., 2008). Therefore, the variables in the economy subsystem should reflect the status, growth rate, and industry structure of the economy. In this study, we select 11 indicators that best reflect the economy subsystem. Altogether, 11 indicators are selected as follows: GDP, primary industry added value (AV), secondary industry AV, tertiary industry AV, rise in tertiary industry AV, the growth rate of tertiary industry AV, industry AV, rise in industry AV, the growth rate of industry AV, gross agricultural output value, and environmental investment. Tertiary industry AV and industry AV are both stock variables, while the growth rate of tertiary industry AV and growth rate of industry AV are rate variables that lead these two stocks to change.

3.1.2. *Population subsystem*

The population factor is one direct factor that affects the supply of and demand for water resources (e.g., the discharge of sewage) (Yang et al., 2015a, 2015b). Following Yang et al. (2015a, 2015b), we firstly select three major indicators to reflect the scale and growth rate of the population: total population, urban population, and rural population. In addition, we add two major indicators (natural population growth rate and rise in population) to further show the scale and growth rate of the population. The natural population growth rate is a rate variable that leads total population to change. Immigration and emigration are not considered because the flow between different regions does not affect total population.

3.1.3. *Land resources subsystem*

There exists a close relationship between land and water resources, which interact in terms of the utilization of water and land resources (Gilmour et al., 2005). One of the major innovations of our study is that land resources are considered to be an important element of the sustainable use of water resources. Therefore, the indicators in the land resources subsystem include the area distribution of different types of land. There are 12 indicators as follows: cultivated land quantity, agricultural land area, added cultivated area, shrinking cultivated area, effective irrigation area, cultivated area for construction, other agricultural area for construction, construction land area, cultivated land destroyed by disaster, reforestation area, shrinking cultivated area for agricultural structure adjustment, and the change rate of added farmland. Cultivated land quantity is the stock variable in this subsystem, whereas the change rate of added farmland is its rate variable.

3.1.4. *Water supply and demand subsystem*

This subsystem reflects the variations in total water resources (TWR), namely total water supply and demand (Wu et al., 2013). Here, total water demand is calculated from the actual use of water resources. The following variables are related to demand for water resources: ecology water consumption, industry water consumption, domestic water consumption, and urban domestic water consumption (Hoekstra, 2009; Wu et al., 2013). Total water supply is represented by the TWR provided to consumers through all kinds of water supply projects, including water conveyance loss, which is estimated based on TWR and the utilization rate of water resources. TWR is the stock variable.

3.1.5. *Water pollution and management subsystem*

In this subsystem, total sewage is the stock variable, while the quantity of wastewater effluent (including the quantity of industry wastewater effluent and of domestic wastewater effluent) and sewage treatment capacity are the rate variables (Qin et al., 2011). The stock variable is simulated by both the quantity of wastewater effluent and sewage treatment capacity. Besides these variables, investment in wastewater management projects, sewage treatment rate, sewage recycling amount and pollution factors are in this subsystem. The water pollution and management subsystem is thus a core subsystem in this study.

3.1.6. *Miscellaneous variables*

Besides the stock and rate variables, the system dynamics model also takes into account auxiliary variables and constants. The former are those variables that connect the five subsystems. There are six auxiliary variables: water consumption per 10 K GDP, water consumption per 10 K industry AV, per capita GDP, per capita water supply, per capita water demand, and per capita cultivated land (18 constants in total). The constants and their initial values are listed in Table 1.

In Table 1, coefficient 1 is the coefficient between the secondary industry AV and the industry AV in question, which is regressed based on data from 2003 to 2012. Coefficient 2 is the coefficient between gross agricultural output value and primary industry AV. To avoid the influence of prices, constant prices are used as the initial values of the growth rates of the tertiary industry AV and of industry AV.

3.2. *Data sources*

The data selected from 2005 to 2012 mainly come from the China Statistics Yearbook, notably the indicators for the economy subsystem and some of the variables of the water supply and demand subsystem such as total water supply, total water consumption, and per capita water consumption. Water consumption per 10 K GDP, water consumption per 10 K industry AV, and other indicators related to water consumption are taken from China's Water Resources. Data related to the land resources subsystem come from the Land Resources Communiqué and survey data about land utilization. Data on the water pollution and management subsystem mainly come from the National Environment Statistic Communiqué and Statistics Yearbook of China's City Construction. The data derived from the above data source are issued by the Chinese government, meaning that they are the most comprehensive and fair raw data available at present.

4. Analysis of the sustainable utilization of water resources

4.1. *Main feedback loops in the model*

The feedback loops in the system dynamics model show the direct causality between the variables. This structure shows the micro composition of the factors in each system, which is suitable for analyzing the relationships between the variables. After addressing the aim of the study and overcoming any problems, it can carry out the overall analysis, select the important and nonimportant factors, retain the key parameters of each subsystem,

Table 1
The initial values of the constants in the system dynamics model.

Variable type	Variable name	Initial value	Unit
Constant	Coefficient of industry wastewater effluent	17.2330	%
	Coefficient of domestic wastewater effluent	46.7452	%
	The ratio of environmental invest in GDP	1.4060	%
	The growth rate of tertiary industry AV	10.9200	%
	The growth rate of industry AV	11.2500	%
	Industry water consumption	13559040	10 K m^3
	Ecology water consumption	1016470	10 K m^3
	Change rate of TWR	−4.1900	%
	Utilization rate of water resources	22.0800	%
	Change rate of added farmland	−12.0708	%
	Natural population growth rate	0.5270	%
	Urbanization rate	46.4633	%
	Rural domestic water resource consumption per capita	26.7545	m^3/year
	Urban domestic water resource consumption per capita	76.2485	m^3/year
	Water consumption of a unit effective irrigation area	431.70	m^3/mu
	Agricultural output of a unit cultivated area	1487.8948	yuan/mu
	Proportion of cultivated land transferred into construction land	0.1751	%
	Proportion of cultivated land destroyed by disaster	0.0342	%
	Reforestation proportion	0.3141	%
	Proportion of agriculture structure adjustment	0.0587	%
	Ratio of farmland irrigation	45.9306	%
	Coefficient 1	1.1613	–
	Coefficient 2	1.1343	–
Stock variable	Industry AV	77230.78	100 M yuan
	The tertiary industry AV	74919.28	100 M yuan
	Total population	130756	10 K
	Total water resources	28053.1	100 Mm^3
	Cultivated land quantity	183100.00	10 K mu
	Total sewage	2313490.72	10 K m^3

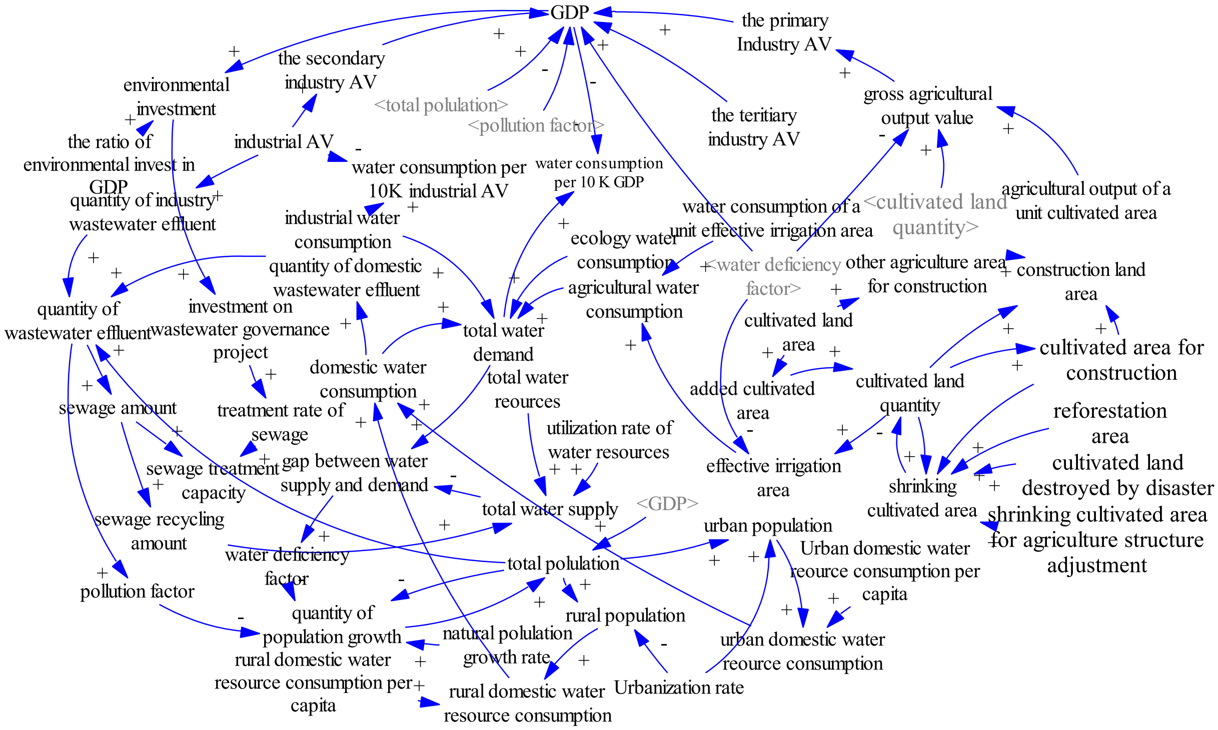

Fig. 1. General feedback loops of the sustainable utilization of water resources.

and link subsystems together based on the contact of the parameters. Fig. 1 illustrates the causal loop diagram. As Fig. 1 shows, each arrow points from the independent variables to the dependent variables. As none of the subsystems exists alone, this leads to loops in the system, which intuitively shows the model development process.

4.2. *Stock-flow figure and main equations*

4.2.1. *Analysis of the stock-flow figure of water resources*

To quantify the system model and simulate feedback loops over time, Fig. 2 presents the cause/effect diagram, which is based on the relationships among the variables and the established equation.

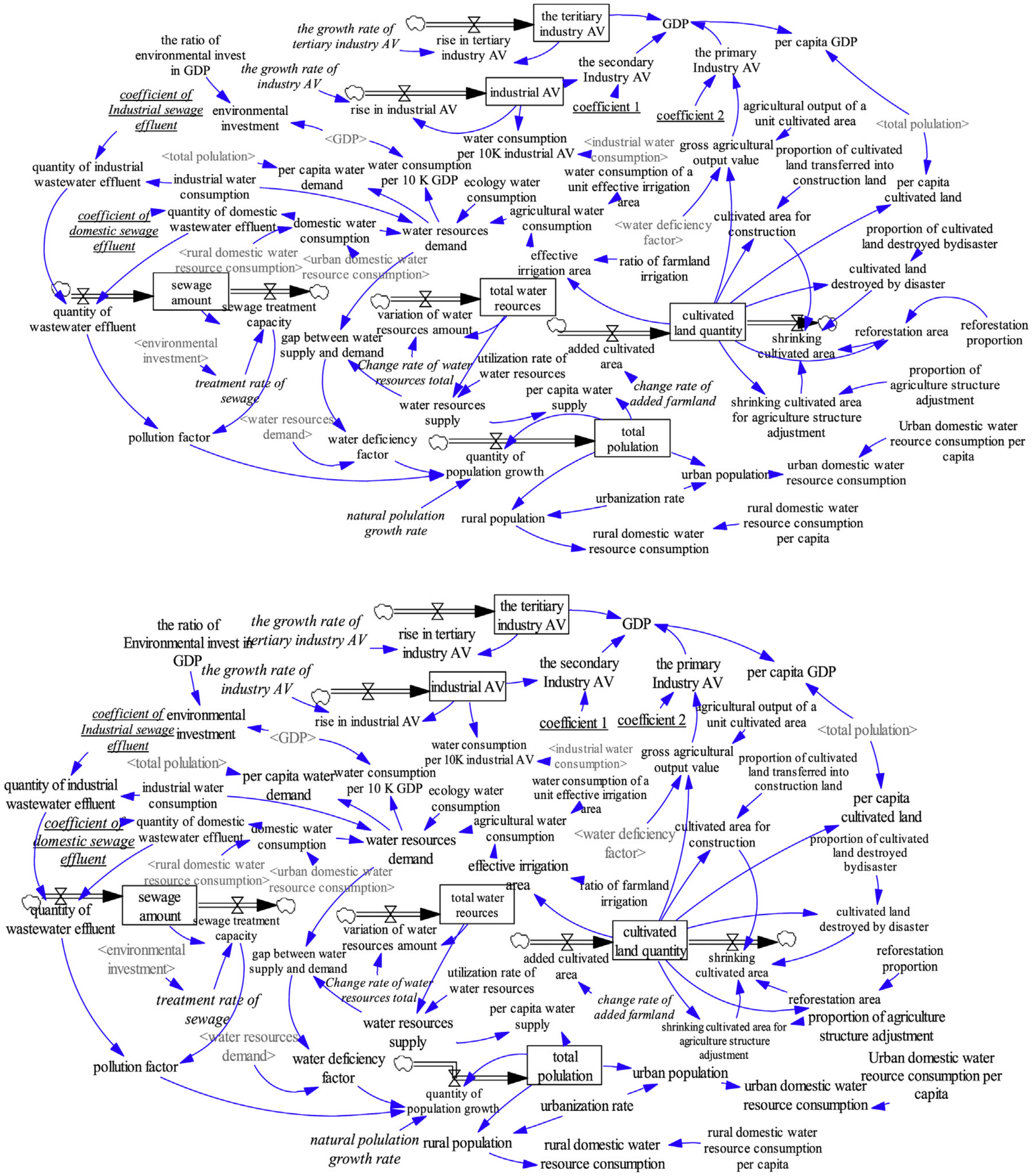

Fig. 2. Stocks and flows of the sustainable utilization of water resources.

There are six stock variables: industry AV, tertiary industry AV, total population, TWR, cultivated land quantity, and sewage amount.

4.2.2. *Main equations*

A positive equation in the system dynamics model plays an important role in promoting accuracy. Of the 72 effect variables (43 variables, 23 constants, six auxiliary variables), there are 44 equations. The relationship between these equations is shown in the Appendix.

4.3. *Test for model*

Before running the simulation, a suitable quantitative method should be chosen to test the applicability, sensitivity, and robustness of the model.

4.3.1. *Test for goodness for fit*

The fitting degree of the model can be tested by comparing the coefficients between the simulation and true values in 2005–2012 (Table 2).

Table 2 demonstrates that the coefficients between the simulation and true values are mostly very high, especially the variables of the economy and population subsystems (above 93.7%) compared with above 80% for the other subsystems. However, the coefficients of cultivated land quantity and per capita cultivated land in the land resources subsystem are 60.71% and 44.47%, respectively. This may be because per capita cultivated land is calculated from the simulation values of cultivated land quantity

Table 2
Correlations between the true and simulation values.

Subsystem	Key variable	Correlation between the true and simulation values
Economy	GDP	0.9932
	Added value of the primary industry	0.9374
	Added value of the secondary industry	0.9943
	Added value of the tertiary industry	0.9947
	Industrial added value	0.9951
	Gross agriculture output value	0.9433
	Environmental invest.	0.9692
	Per capita GDP	0.9925
Population	Total population	0.9904
	Rural population	0.9929
	Urban population	0.9923
Water supply and demand	Total amount of water resources	0.1367
	Total water supply	0.9898
	Total water demand	0.9892
	Agricultural water consumption	0.8759
	Domestic water consumption	0.7767
	Per capita water supply	0.9646
	Per capita water demand	0.9470
	Water consumption/10 K yuan GDP	0.9961
	Water consumption per 10 K industrial added value [1]	0.9906
	Per capita amount of water resources	0.0141
Land resources	Cultivated land quantity	0.6071
	Effective irrigation area	0.9951
	Per capita cultivated land	0.4447
Water pollution and management	Quantity of wastewater effluent	0.9918
	Sewage treatment capacity	0.8229
	Treatment rate of sewage	0.9737

Table 3
Error rate between the true and simulation values.

Year	Variable					
	Total water resources (100 M m^3)			Cultivated land quantity (10 K mu)		
	True value	Simulation value	Error rate	True value	Simulation value	Error rate
2005	28053.10	28053.10	0.00	183100.00	183100.00	0.00
2006	25330.14	26877.70	6.11	182700.00	181972.00	−0.40
2007	25255.16	25751.50	1.97	182600.00	180850.00	−0.96
2008	27434.30	24672.50	−10.07	182574.00	179734.00	−1.56
2009	24180.20	23638.70	−2.24	203077.00	178625.00	−12.04
2010	30906.41	22648.30	−26.72	202902.00	177523.00	−12.51
2011	23256.70	21699.30	−6.70	182476.00	176427.00	−3.31
2012	29526.88	20790.10	−29.59	202738.00	175337.00	−13.52

and total population. Further, the coefficients for TWR and per capita water resources are 13.67% and 1.41%, respectively. Table 3 lists the error rate between the true and simulation values of cultivated land quantity and TWR.

When using system dynamics models to simulate economic data, if the error rate between the true and simulation values is in the interval −10% to 10%, the results should be strong. As shown in Table 3, the error rate in 2010 and 2012 is beyond the 10% significance level, as the recent trend and changes in the real values of TWR have been beyond expectations. Similarly, the true values of cultivated land quantity in 2009, 2010, and 2012 are not in accordance with the previous years' trend, which leads to a high error rate.

The variance between the simulation results and real-world system is mainly caused by the following three reasons. First, the changing rules of the stock variables lead to poor accuracy. In system dynamics models, only the flow variable can change the stock variable. For example, tertiary industry AV can only be influenced by the growth rate of tertiary industry AV. However as this is a constant, irrespective of which method is chosen to determine the value of the constant, it cannot reflect the real situation exactly, which leads to poor model accuracy. Second, the limited parameters determination method also leads to poor model accuracy. Indeed, this study only uses regression equations and averages to simulate the parameters and constants. Third, the imprecise variable relationships in the equations can lead to poor levels of accuracy as well. Despite these drawbacks, most simulation results reflect reality well and thus provide a good foundation for the following forecasting.

4.3.2. Robustness test

To test the model's robustness, we shortened the time steps to three and six months, as shown in Fig. 3.

Fig. 3 shows that the core variables deviate little after shortening the time steps. To investigate this trend, we calculate the average change rates in the three- and six-month time steps (see Table 4). We find that the average rates of the core variables are very small (below 6%). In particular, for total population and cultivated land quantity, shortening the time steps has little influence, suggesting that the model is robust.

4.4. Simulating and forecasting

4.4.1. Forecasting results of supply and demand until 2020

Based on these test results, we simulated the system dynamics

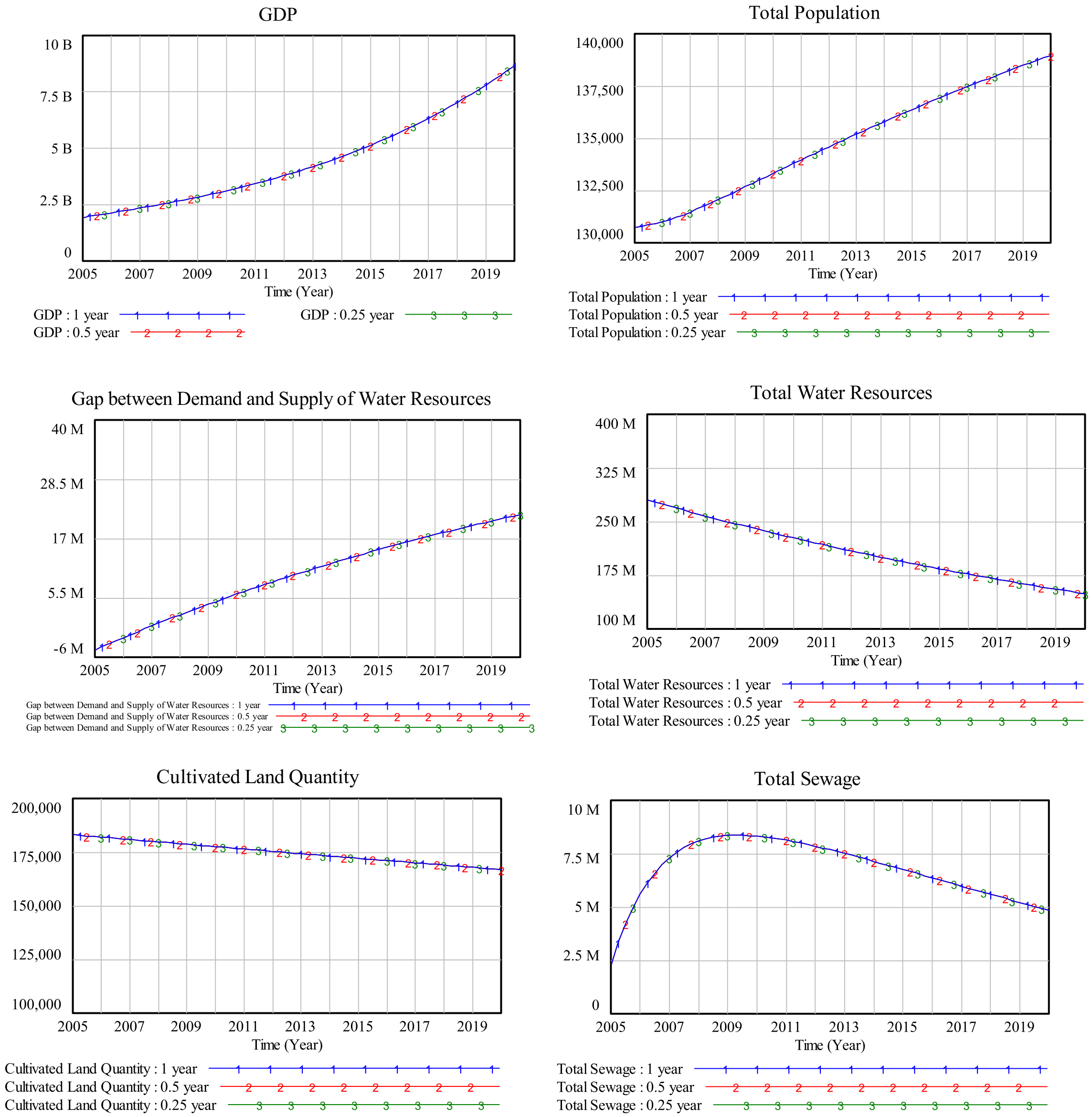

Fig. 3. Trend of the main variables after shortening the time steps.

Table 4
Test results of model robustness.

Key variable	Average change rate of interval 0.5 year (%)	Average change rate of interval 0.25 year (%)
GDP	2.02	3.11
The primary Industry AV	0.35	0.52
The secondary Industry AV	2.16	3.33
Industrial AV	2.16	3.33
The tertiary industry AV	2.04	3.14
Total population	0.02	0.02
Total water resources	0.34	0.51
Gap between water supply and demand	3.95	5.90
Cultivated land quantity	0.01	0.01
Sewage amount	−2.70	−3.97

model (i.e., a natural growth model) of the sustainable utilization of water resources (see Table 5).[2]

In the economy subsystem, except for primary industry AV, the other variables increased by 3–4 times, suggesting that GDP at constant prices will reach 81,527 billion yuan by 2020, 4.22 times that in 2005. The rate of increase of the variables in the population subsystem is lower: by 2020, population will increase by 4.22 times compared with 2005, with urban and rural population growth in accordance with that of the total population. In the water supply and demand subsystem, except the gap between water supply and demand, the other variables decreased. Indeed, water consumption

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[1] Because these data are published from 2007, the correlation is calculated from 2007 to 2015.

[2] As of the publication date, the data for 2015 had not been issued fully. Hence, here 2015 is considered to be one of the prediction years.

[3] Except for per capita GDP, the other variables' units are transferred into “100 M” from “10 K” for clarity.

[4] For clarity, the units of “Water consumption per 10 K GDP” and “Water consumption per 10 K industry added value” are changed to “10 K m^3/10 K yuan” from “m^3/10 K yuan”.

Table 5
Predicted values of the key variables in the natural growth model.

Subsystem	Variable	2005	2015	2020	Growth rate (%) 2005–2020
Economy[3]	GDP	193056	492790	815269	322.30
	The primary industry AV	28448.7	21134.3	16817.9	−40.88
	The secondary industry AV	89688.1	260456	443849	394.88
	The tertiary industry AV	74919.3	211199	354602	373.31
	Industrial AV	77230.8	224280	382200	394.88
	Environmental invest	2714.37	6928.63	11462.7	322.30
	Per capita GDP	14764.6	36131.6	58656.5	297.28
Population	Total population	130756	136388	138990	6.30
	Urban population	60753.6	63370.2	64579.5	6.30
	Rural population	70002.4	73017.5	74410.8	6.30
Water supply and demand	Water resources supply	61941200	40372700	32594400	−47.38
	Water resources demand	57386200	55486600	54573000	−4.90
	Gap between water supply and demand	−4555020	15113800	21978600	582.51
	Per capita water supply	473.72	296.02	234.52	−50.50
	Per capita water demand	438.88	406.83	392.639	−10.54
	Water consumption per 10 K GDP[4]	297	113	67	−77.48
	Water consumption per 10 K industrial added value	175.6	60.5	35.5	−79.79
Land resources	Cultivated land quantity	183100	172107	166846	−8.88
	Effective irrigation area	84098.9	79049.6	76633.3	−8.88
	Per capita cultivated land	1.400	1.262	1.200	−14.28
Water pollution and management	Sewage treatment capacity	1280040	5884660	5920820	362.55
	Quantity of wastewater effluent	5377510	5508490	5569010	3.56

Note: the growth rate is calculated from the predicted values in 2005 and 2020.

Table 6
Contrast between the planned and simulation values in 2015.

Indicator	Planning value	Simulation value	Gap (%)
Total water consumption (100 M m^3)	6350	5549	−12.62
Water consumption per 10 K GDP (m^3)	105	112.6	7.24
Water consumption per 10 K industrial added value (m^3)	63	60.5	−3.97
Water consumption for agriculture irrigation (100 M m^3)	3320	3071	−7.50
Treatment rate of sewage (%)	85.00	85.18	0.21
Cultivated land quantity (100 M mu)	18.00	17.21	−4.39

Note: Data on total water consumption, water consumption per 10 K GDP, water consumption per 10 K industry AV, and water consumption for agricultural irrigation come from the "Water-saving Society Make 12th five-year plan" report released by MWR; the planned values for the sewage treatment rate come from the China Urban Water Supply Communiqué by MOHURD; the planned values of cultivated land quantity come from the 1.8 billion arable land minimum set up by the Ministry of Land and Resources; the simulation values for total water consumption and water consumption for agricultural irrigation are estimated from total water demand and agricultural water consumption.

per 10 K GDP and water consumption per 10 K industry AV reduced by 77.48% and 79.79%, respectively, suggesting that water use efficiency will improve significantly compared with 2005. However, this finding is not positive as expected, as the gap between water supply and demand will reach 220 billion m^3 by 2020, 4.8 times that in 2005, with water supply reducing by 47.38% compared with only 4.9% for water demand. Because simply improving water use efficiency cannot solve water shortage, we must explore other effective ways in which to grow water supply by balancing supply and demand.

In the land subsystem, cultivated land quantity and effective irrigation area both reduced by 8.88%, while a booming population can reduce cultivated land per capita by 14.28%. Nonetheless, this may not lower demand for agricultural water, as it can lead to poor drought resistance. Cultivated land protection in China will thus face serious challenges.

In the water pollution and management subsystem, sewage treatment capacity increased by 362.55% in 2020 compared with 2005. Although the quantity of wastewater effluent increased by 3.56%, total sewage decreased overall. In other words, sewage management is effective.

4.4.2. Gap between the predictions and China's 12th five-year plan

The short-term predictions above allow us to assess whether the goals in the 12th five-year plan can be achieved (see Table 6). Table 6 shows that by 2015, except water consumption per 10 K GDP and the sewage treatment rate, the planned values of the other variables are below the simulation values.

4.5. Early warning mechanism of water resources: different models

In this section, given that different subsystems influence the sustainable utilization of water resources differently, we introduce several models that have alternative parameters to the natural growth model (see Table 7).

China is suffering from a number of water-related issues. The gap between supply and demand is enlarging every year, meaning that water use efficiency must be improved. Cultivated land loss is becoming more and more serious, while the gap of per capita cultivated land area between China and the global average is becoming bigger and bigger and shrinking cultivated land area has a severe influence on gross agricultural output value, which may lead to food crises. The simulation values and growth rates for all these models are listed in Tables 8–12.

Table 8 shows that compared with the natural growth model (model A), models B and C have the most significant influence on the economy. For model B, industry AV and secondary industry AV both improved by 475.50%, while tertiary industry AV improved by 448.24% in model C. In other words, when the growth rate of industry AV and tertiary industry AV both improve by 10%, the rise in industry AV is bigger than that in tertiary industry AV. Meanwhile, this table shows that the input-output ratio of resources in China is greater than that in the tertiary industry, suggesting that this industry still needs vigorous expansion. In model G, all the variables range between the values for models B and C, and are larger than those in the other models.

Table 9 shows that total population, urban population, and rural population are in accordance with each other. Compared with the other models, the growth rate of population in model D is the greatest (about 6.94%), whereas it is the lowest in model E (about 6.28%). Because of the aging population in China, the population

Table 7
Comparison of the models.

Parameter	A	B	C	D	E	F	G
	Natural growth	Industry leading	Tertiary industry leading	Population growth	Resource saving	Environment leading	Balanced development
Growth rate of industry AV	Constant	Raise by 10%	Constant	Constant	Constant	Constant	Raise by 5%
Growth rate of tertiary industry AV	Constant	Constant	Raise by 10%	Constant	Constant	Constant	Raise by 5%
Growth rate of population	Constant	Constant	Constant	Raise by 10%	Constant	Constant	Raise by 5%
Ratio of cultivated area for construction	Constant	Constant	Constant	Constant	Drop by 10%	Constant	Drop by 5%
Reforestation proportion	Constant	Constant	Constant	Constant	Drop by 10%	Constant	Drop by 5%
Proportion of cultivated land destroyed by disaster	Constant	Constant	Constant	Constant	Drop by 10%	Constant	Drop by 5%
Proportion of agriculture structure adjustment	Constant	Constant	Constant	Constant	Drop by 10%	Constant	Drop by 5%
Environmental investment ratio	Constant	Constant	Constant	Constant	Constant	Raise by 10%	Raise by 5%

Table 8
Simulation values and the growth rate of the economy subsystem in all models (unit: 100 B yuan).

Variable	Year	Model A	Model B	Model C	Model D	Model E	Model F	Model G
GDP	2005	193056	193056	193056	193056	193056	193056	193056
	2015	492790	520359	514528	492779	492838	492789	516910
	2020	815269	887575	871402	815256	815328	815269	877276
	Growth rate (%)	322.30	359.75	351.37	322.29	322.33	322.30	354.42
The primary industry AV	2005	28448.7	28448.7	28448.7	28448.7	28448.7	28448.7	28448.7
	2015	21134.3	21133.9	21134	21123.5	21182.2	21133.4	21152.0
	2020	16817.9	16817.4	16817.5	16805	16876.5	16817.2	16840.0
	Growth rate (%)	−40.88	−40.89	−40.88	−40.93	−40.68	−40.89	−40.81
The secondary industry AV	2005	89688.1	89688.1	89688.1	89688.1	89688.1	89688.1	89688.1
	2015	260456	288026	260456	260456	260456	260456	273929
	2020	443849	516155	443849	443849	443849	443849	478730
	Growth rate (%)	394.88	475.50	394.88	394.88	394.88	394.88	433.77
Industrial AV	2005	77230.8	77230.8	77230.8	77230.8	77230.8	77230.8	77230.8
	2015	224280	248020	224280	224280	224280	224280	235882
	2020	382200	444463	382200	382200	382200	382200	412236
	Growth rate (%)	394.88	475.50	394.88	394.88	394.88	394.88	433.77
The tertiary industry AV	2005	74919.3	74919.3	74919.3	74919.3	74919.3	74919.3	74919.3
	2015	211199	211199	232937	211199	211199	211199	221829
	2020	354602	354602	410735	354602	354602	354602	381707
	Growth rate (%)	373.31	373.31	448.24	373.31	373.31	373.31	409.49
Environmental investment	2005	2714.37	2714.37	2714.37	2714.37	2714.37	2985.81	2850.09
	2015	6928.63	7316.25	7234.26	6928.48	6929.3	7621.48	7631.14
	2020	11462.7	12479.3	12251.9	11462.5	11463.5	12608.9	12951.2
	Growth rate (%)	322.30	359.75	351.37	322.29	322.33	322.29	354.41
Per capita GDP	2005	14764.6	14764.6	14764.6	14764.6	14764.6	14764.6	14764.6
	2015	36131.6	38147	37720.7	35980	36137.7	36118.8	37809.7
	2020	58656.5	63844.9	62684.4	58301.9	58669.7	58637.5	62908.8
	Growth rate (%)	297.28	332.42	324.56	294.88	297.37	297.15	326.08

Table 9
Simulation values and the growth rate of the population subsystem in all models (unit: 10 K).

Variable	Year	Model A	Model B	Model C	Model D	Model E	Model F	Model G
Total population	2005	130756	130756	130756	130756	130756	130756	130756
	2015	136388	136409	136405	136959	136378	136436	136714
	2020	138990	139021	139014	139834	138969	139035	139452
	Growth rate (%)	6.30	6.32	6.32	6.94	6.28	6.33	6.65
Urban population	2005	60753.6	60753.6	60753.6	60753.6	60753.6	60753.6	60753.6
	2015	63370.2	63380.2	63378.2	63635.7	63365.7	63392.5	63521.7
	2020	64579.5	64593.5	64590.6	64971.3	64569.7	64600.4	64794.0
	Growth rate (%)	6.30	6.32	6.32	6.94	6.28	6.33	6.65
Rural population	2005	70002.4	70002.4	70002.4	70002.4	70002.4	70002.4	70002.4
	2015	73017.5	73028.9	73026.6	73323.4	73012.3	73043.1	73192.0
	2020	74410.8	74427.0	74423.6	74862.3	74399.5	74434.9	74658.0
	Growth rate (%)	6.30	6.32	6.32	6.94	6.28	6.33	6.65

growth rate should stay at a suitable level to provide a demographic dividend. However, too great a growth rate may place pressure on the environment and resources, suggesting that model G is the most suitable in this regard.

Table 10 shows that the different models have few significant differences in the growth rate of TWR and water supply, meaning that the gap between water supply and demand is mainly affected by water demand. Water demand, the gap between supply and demand, and per capita water demand mostly change in models D and E. This finding implies that although model D guarantees the

Table 10
Simulation values and the growth rate of the water supply and demand subsystem in all models.

Variable	Year	Unit	Model A	Model B	Model C	Model D	Model E	Model F	Model G
Total water resources	2005	100 M m^3	28053.1	28053.1	28053.1	28053.1	28053.1	28053.1	28053.1
	2015		18284.8	18284.8	18284.8	18284.8	18284.8	18284.8	18284.8
	2020		14761.9	14761.9	14761.9	14761.9	14761.9	14761.9	14761.9
	Growth rate	%	−47.38	−47.38	−47.38	−47.38	−47.38	−47.38	−47.38
Water demand	2005	100 M m^3	5738.62	5738.62	5738.62	5738.62	5738.62	5738.62	5738.62
	2015		5548.66	5548.77	5548.74	5551.50	5568.68	5548.90	5560.30
	2020		5457.30	5457.45	5457.42	5461.49	5486.45	5457.52	5474.20
	Growth rate	%	−4.90	−4.90	−4.90	−4.83	−4.39	−4.90	−4.61
Water supply	2005	100 M m^3	6194.12	6194.12	6194.12	6194.12	6194.12	6194.12	6194.12
	2015		4037.27	4037.27	4037.27	4037.27	4037.27	4037.27	4037.27
	2020		3259.44	3259.44	3259.44	3259.44	3259.44	3259.44	3259.44
	Growth rate	%	−47.38	−47.38	−47.38	−47.38	−47.38	−47.38	−47.38
Gap between water supply and demand	2005	100 M m^3	−455.50	−455.50	−455.50	−455.50	−455.50	−455.50	−455.50
	2015		1511.38	1511.49	1511.47	1514.23	1531.41	1511.62	1523.03
	2020		2197.86	2198.01	2197.98	2202.06	2227.02	2198.08	2214.76
	Growth rate	%	582.51	582.55	582.54	583.44	588.92	582.56	586.22
Water consumption per 10 K GDP	2005	M^3	297.251	297.251	297.251	297.251	297.251	297.251	297.251
	2015		112.597	106.633	107.841	112.657	112.992	112.602	107.568
	2020		66.9386	61.4872	62.628	66.9911	67.2914	66.9414	62.3999
	Growth rate	%	−77.48	−79.31	−78.93	−77.46	−77.36	−77.48	−79.01
Water consumption per 10 K industrial AV	2005	M^3	175.565	175.565	175.565	175.565	175.565	175.565	175.565
	2015		60.4557	54.6689	60.4557	60.4557	60.4557	60.4557	57.4822
	2020		35.4762	30.5064	35.4762	35.4762	35.4762	35.4762	32.8914
	Growth rate	%	−79.79	−82.62	−79.79	−79.79	−79.79	−79.79	−81.27
Per capita water demand	2005	M^3	438.88	438.88	438.88	438.88	438.88	438.88	438.88
	2015		406.83	406.774	406.785	405.34	408.327	406.705	406.712
	2020		392.639	392.564	392.58	390.571	394.796	392.528	392.551
	Growth rate	%	−10.54	−10.55	−10.55	−11.01	−10.04	−10.56	−10.56
Per capita water supply	2005	M^3	473.716	473.716	473.716	473.716	473.716	473.716	473.716
	2015		296.015	295.968	295.978	294.78	296.036	295.911	295.309
	2020		234.508	234.457	234.468	233.094	234.544	234.432	233.732
	Growth rate	%	−50.50	−50.51	−50.50	−50.79	−50.49	−50.51	−50.66

Table 11
Simulation values and the growth rate of the land resources subsystem in all Models.

Variable	Year	Unit	Model A	Model B	Model C	Model D	Model E	Model F	Model G
Cultivated land quantity	2005	10 K mu	183100	183100	183100	183100	183100	183100	183100
	2015	10 K mu	172107	172107	172107	172107	173119	172107	172612
	2020	10 K mu	166846	166846	166846	166846	168322	166846	167582
	Growth rate	%	−8.88	−8.88	−8.88	−8.88	−8.07	−8.88	−8.48
Effective irrigation area	2005	10 K mu	84098.9	84098.9	84098.9	84098.9	84098.9	84098.9	84098.9
	2015	10 K mu	79049.6	79049.6	79049.6	79049.6	79514.6	79049.6	79281.8
	2020	10 K mu	76633.3	76633.3	76633.3	76633.3	77311.1	76633.3	76971.5
	Growth rate	%	−8.88	−8.88	−8.88	−8.88	−8.07	−8.88	−8.48
Per capita cultivated land	2005	mu	1.40032	1.40032	1.40032	1.40032	1.40032	1.40032	1.40032
	2015	Mu	1.26189	1.26169	1.26173	1.25663	1.26941	1.26145	1.26258
	2020	mu	1.20041	1.20015	1.20021	1.19317	1.21121	1.20003	1.20172
	Growth rate	%	−14.28	−14.29	−14.29	−14.79	−13.50	−14.30	−14.18

Table 12
Simulation values and the growth rate of the water pollution and management subsystem in all models (unit: 10 K m^3).

Variable	Year	Model A	Model B	Model C	Model D	Model E	Model F	Model G
Sewage amount	2005	2313490	2313490	2313490	2313490	2313490	2313490	2313490
	2015	6908150	6719470	6758150	6922710	6907530	6528320	6553970
	2020	5047380	4764480	4824670	5064290	5046700	4710350	4639990
	Growth rate (%)	118.17	105.94	108.55	118.90	118.14	103.60	100.56
Quantity of wastewater effluent	2005	5377510	5377510	5377510	5377510	5377510	5377510	5377510
	2015	5508490	5508980	5508880	5521770	5508260	5509600	5516070
	2020	5569010	5569720	5569570	5588620	5568520	5570060	5579750
	Growth rate (%)	3.56	3.57	3.57	3.93	3.55	3.58	3.76
Sewage treatment capacity	2005	1280040	1280040	1280040	1280040	1280040	1324530	1302280
	2015	5884660	5908450	5903200	5896980	5884460	5881530	5909130
	2020	5920820	5932100	5929320	5940580	5920320	5907960	5932230
	Growth rate (%)	362.55	363.43	363.21	364.09	362.51	346.04	355.53

growth rate of population, it enlarges the gap between water supply and demand (supply cannot meet demand). Further, model E can control the loss of cultivated land to some extent, but it causes higher demand for agriculture, which can enlarge this gap.

Compared with the other models, model G is more moderate.

Table 11 shows that cultivated land quantity and effective irrigation area are mainly affected by model E and have similar ranges, while model G is moderate as before.

In Table 12, total sewage, quantity of wastewater effluent, and the sewage treatment rate differ by model. Models B, C, E, and G all affect the growth rate of total sewage. Of these, the growth rate in model G is the smallest, followed by that in model E, which means the former has the most efficient sewage management. Further, the rise in wastewater effluent in model D is the greatest, implying the urgent need to control domestic wastewater effluent to release the pressure of a crowded population on water resources.

5. Conclusion

5.1. Concluding remarks

The presented analysis allows us to derive five main conclusions. Firstly, the balanced development model can accelerate economic development, guarantee a suitable growth rate, and reduce the gap between water supply and demand as well as maintain cultivated land quantity and effective irrigation areas and reduce total sewage.

Secondly, economic development can contribute to the sustainable utilization of water resources by improving environmental investment and reducing total sewage. Today in China, the input-output ratio of industry resources is greater than that in the tertiary industry. Hence, to stimulate the economy, the Chinese government should enhance the input-output ratio of the tertiary industry.

Thirdly, water demand will increase as the population booms and the economy continues to develop. Under such conditions, the gap between water supply and demand cannot be shortened by controlling water demand. The exploitation rate of water resources should thus be enhanced gradually to increase water supply.

Fourthly, the 1.8 billion arable land minimum will soon be surpassed, which may negatively affect crop output (especially grain) and exacerbate the food crisis. Meanwhile, land degradation weakens the drought resistance of soil, suggesting that protecting and saving land resources demand urgent policymaking.

Finally, sewage problems cannot be solved only through environmental investment; the thought "pollute first and then protect" must be discarded. Strengthening environmental protection will contribute to the sustainable utilization of water resources greatly.

5.2. Policy suggestions

5.2.1. Adjust industry structure

There is little space for the secondary industry to grow in China. Therefore, to ensure steady economic growth, the Chinese government should increase the relative proportion of the tertiary industry's output values.

5.2.2. Balance population and natural resources policies

There is a close relation between population and natural resources: as one grows, the other will shrink. Hence, maintaining a balance between them is crucial. This could occur in three main ways.

(1) *Population policy should emphasize steady growth*: In general, population policy should not only ensure a demographic dividend, but also consider the carrying capacity of water and land resources. The government could gradually relax the restrictions of its one-child policy, but it must prevent too much pressure being placed on the environment by population growth.

(2) *Water resources policy should broaden the supply of water resources*: Controlling demand can only relieve pressure on water resources temporarily. Although none of the models studied herein considers changes in water supply, TWR has declined in the real world over the past 50 years. As the supply of water resources may reduce in the future, amending the policy of water supply, seeking more ways to expand water supply, and balancing and narrowing the gap between water supply and demand is urgent.

To expand the supply of water resources, techniques to improve the utilization of water resources could be explored or the existing water supply structure could be expanded to supply water resources indirectly. For example, domestic water in most cities is supplied as drinking water; however, this may lead to a waste of high quality water. Further, the limitations of water supply lines and implementation cost suggest that new techniques be implemented to construct feed pipes to improve potential water supply.

(3) *Protection of cultivated land is crucial*: The protection of land resources, especially cultivated land, remains crucial to land resources policy in China. To prevent breaking the 1.8 billion arable land minimum, the government should control cultivated land reduction and intensify the development of unused land. It could also increase the availability of cultivated land to balance requisition with compensation and thus ensure the sustainable utilization of cultivated land in the long-term. Further, supervision should be strengthened through farmland occupation.

5.2.3. Combine environmental policy with other policies

The water pollution and management subsystem has a close relationship with the population and water supply and demand subsystems, suggesting that environmental policy cannot be carried out in isolation. In addition to exploring more advanced environmental management techniques, seeking ways to prevent environment pollution is important. This study showed that domestic sewage is a major source of sewage effluent, implying that environmental protection needs to come from the power of mass society. Environmental education, supervision, and publicity should be carried out to improve environmental protection by the public.

5.2.4. Improve data

The lack of detailed data relationships is the one of the largest problems in this area. For example, the Water Resources Bulletin by MWR in China only provides the definition and calculation method of each module; the logic and mathematic relationships between the macro-indexes are not listed, leading to some ambiguity. The procedure to build system dynamics models should be based on statistical indicators and econometrics theory as well as focus on the construction of cause/effect loops. These loops can adopt Granger causality tests to enhance model logic and accuracy. In the literature, equation building needs to be improved as well, as does the accuracy of simulations and predictions. The integrated application of interdisciplinary fields may thus become a popular trend in system dynamics development. Because these policy suggestions are related, policymakers from different fields should aim to discuss the alternatives to ensure the effective sustainable utilization of water resources.

5.2.5. *Use modern techniques to collect and analyze big data on water resources*

Although this study uses a large amount of data to analyze the sustainable utilization of water resources, most of which come from the National Statistics and are published annually or over a longer time period, many modern techniques make it possible to collect and analyze big data. Further, the popularity of sensors makes it possible to deliver data in real time as well. Researchers and experts from different fields, including ecology, environtology, and computer science, need to work together to explore new techniques for the collection of water resources information. This would allow people to monitor the status of water resources in real time and react accordingly.

5.3. *Limitations and future directions of the study*

Firstly, the system dynamics model presented in the study is simplified and it adopts only basic approaches to determine the relationships between the variables and parameter values. Secondly, the number of variables and equations in the model is rather small; thus, the scale of the system seems too small to be considered to be a national model. Further, the application of big data on water resources could lead to more accurate and reasonable data to populate and run the system dynamics model in the future (Rosenberg and Madani, 2014). Thirdly, the supply of water resources is assumed to be constant, implying that the gap between water supply and demand cannot be measured precisely. These three points serve to suggest directions for future research.

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Appendix

1. *Main equations in the economy subsystem*

GDP = Primary industry AV + Secondary industry AV + Tertiary industry AV (1)

Gross agricultural output value = Agricultural output of a unit cultivated area × Cultivated land quantity × (1 − water shortage factor) (2)

Primary industry AV = Coefficient of gross agricultural output value × Coefficient 2 (3)

Secondary industry AV = Coefficient of industry AV × Coefficient 1 (4)

Environmental investment = GDP × Ratio of environmental investment to GDP (5)

2. *Main equations in the population subsystem*

Total population = INTEG (population growth, 130756) (6)

Population growth = Total population × Natural population growth rate × (1 − Pollution factor) × (1 − water shortage factor) (7)

In equation (7), the natural population growth rate is the difference between the birth rate and mortality rate. This means that besides the birth rate, mortality rate, and population growth, total population can also be affected by pollution and water shortages. Obviously, pollution and water shortages have a negative influence on total pollution. Therefore, in equation (7), we suppose a simple relationship between these variables.

3. *Main equations in the water supply and demand subsystem*

TWR = INTEG (variation in TWR, 2.80531e+008) (8)

Water resources demand = Agricultural water consumption + Industry water consumption + Ecology water consumption + Domestic water consumption (9)

Water resources supply = TWR × Utilization rate of water resources (10)

Gap between water supply and demand = Water resources demand − Water resources supply (11)

Domestic water consumption = Rural domestic water consumption + Urban domestic water consumption (12)

Water shortage factor = ABS (Gap between water supply and demand/Water resources demand) (13)

Equation (13) shows that the water shortage factor is calculated as the gap between water supply and demand and water resources demand, which reflects the shortage of water resources.

4. *Main equations in the land resources subsystem*

Cultivated land quantity = INTEG (Added cultivated area − Shrinking cultivated area 183,100) (14)

Shrinking cultivated area = Cultivated area for construction + Reforestation area + Cultivated land destroyed by disaster + Shrinking cultivated area for agricultural structure adjustment (15)

Shrinking cultivated area is the flow variable, whereas cultivated land quantity is the stock variable and cultivated area for construction and reforestation area are the main factors that lead to the shrinking of cultivated land.

5. *Main equations in the water pollution and management subsystem*

Sewage amount = INTEG (Quantity of wastewater effluent − Sewage treatment capacity, 2.31349e+006) (16)

Quantity of wastewater effluent = Quantity of industry wastewater effluent + Quantity of domestic wastewater (17)

Sewage treatment rate = Environmental investment × 7.08427 × 10ˆ(−9)+0.361 (18)

Pollution factor = (Quantity of wastewater effluent − Sewage treatment capacity)/Quantity of wastewater effluent (19)

Equation (18) is a regression equation based on data from 2003 to 2012 that explain the regression relationship between the sewage treatment rate and environmental investment.

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