Prediction and Analysis of Chinese Water Resource: A System Dynamics Approach

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Abstract. The data show that the shortage and deterioration of water resources have brought serious impact on China, and these problems need to be solved. In this paper, the four causal chains of China's water resources system are constructed by comprehensively considering the factors of population, society and economic development, and the system dynamics method for forecasting China's water resources demand from 2013 to 2025 is established. Based on the analysis of the proposed water system dynamics model, the total water demand, water conservancy investment and water recycling in China under different water resources strategies are predicted. Under the water resources strategy of high investment in water conservancy facilities, low wastewater discharge rate and high wastewater purification rate, the total water demand in China in 2025 will be about 722 billion M^3, the investment in water conservancy facilities will exceed 6815 billion yuan and the recycled water will exceed 43 billion M^3. In addition to population and economic factors, we also pay attention to environmental factors. In addition, we introduce water shortage coefficient and environmental pollution coefficient to evaluate the environmental benefits of different policies. From the perspective of our sustainability model and integrated numerical results, several interesting management insights were observed. For example, by reducing the discharge of domestic and production sewage, improving the sewage purification rate and investment in water infrastructure, the water shortage coefficient will be reduced by about 8.96%, and the environmental pollution coefficient will be reduced by about 14.8%, which is conducive to promoting the future development of China's water resources, as well as the environment and economy.

Keywords: System dynamics · Prediction · Water demand · Water resources development strategy

1 Introduction

Water is an indispensable substance in creature body. The basic necessities of human life are inseparable from water. According to authoritative data, China's share of water resources has reached 6% of the world's total water resources. However, 9.6 million square kilometers of land support 1.4 billion people, which makes China's per capita share of water resources being only 2710 m^2, less than 25% of the world's per capita water resources, ranking 88th in the world. The shortage of water resources cannot meet

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the needs of the population. The reasons for water shortage include water pollution 、the low recycling utilization rate of water resources and the publicity and management of water resources are not in place. Water shortage has brought many impacts on China: flood disaster, drought disaster and soil erosion.

Specifically, first flood disaster, the accumulated direct economic loss exceeds 1.1 trillion yuan, which is about 1/5 of the fiscal revenue in the same period. Then drought disaster, due to the lack of water supply, the annual output value of industry is directly affected by 230 billion yuan. In normal and dry years, grain production is reduced by 10–25 billion kg, but in severe drought years, grain output is nearly 50 billion kg. The third one is water environment; one is soil erosion. The average annual area of soil and water loss increased by development and construction activities in China reaches 10000 km^2, and the earthwork waste accumulated every year is about 3 billion tons, 20% of which flows into rivers, which directly affects flood protection. The another one is that the water pollution is serious. Because of the rapid increase of industrial wastewater discharge, it is discharged into the river without treatment, which leads to the deterioration of water environment represented by Huaihe River and Taihu Lake pollution.

One of the national policies adopted by China is to rationally control the total amount of development. Then, optimize the allocation of water resources.

The main contributions of this research include:

1. Research Object: We forecast chinese water demand, wastewater and recycled water from 2013 to 2025, analyze implications of implementing different water strategies and identify feasible measures to conserve water.
2. Model formulation: We consider population and economic development factors, construct four significant relations of chain effect in Chinese water resources system. Based on the relations of four chains, we establish a system dynamics (SD) approach to predict water demand, recycled water and wastewater of China from 2013 to 2025. Then we introduce two indicators: water shortage coefficient and environmental pollution coefficient to evaluate the environmental benefits. After that, we adjust relevant parameters according to authoritative documents and analyze the implications of different strategies.
3. Managerial implications: The final results of predicted water demand show that the total amount of water resources development in the national management policy is in urgent need of effective control. From the perspective of system dynamics model, we suggest that the optimal water resources development strategy suitable for China is to reduce the domestic sewage and production sewage discharge, increase the sewage purification rate, and improve the investment of Chinese water conservancy facilities, so that the environmental benefits and economic benefits can be maximized.

2 Literature Review

In the aspect of water resources prediction, there are various methods of water resources prediction, such as multi-objective analysis method, multi-objective decision TOPSIS method, least squares support vector machine method, water resources supply and demand balance method, etc. In the simulation and prediction of water supply and demand matching in water deficient cities such as Lanzhou [1], only linear and non-linear equations were used to simulate and predict the water demand of agriculture, industry, ecology and urban and rural life in Lanzhou, then the spatiotemporal matching water shortage of Lanzhou including its districts and counties in the future period was obtained under different water supply schemes; Wang et al. [2] combined with grey correlation analysis and multiple linear regression model, quantitatively predicted the supply and demand of water resources in different planning years; Meng et al. [3] established a fractional order cumulative grey prediction model to predict the per capita water consumption of China's provinces and cities from 2019 to 2024, and found that there are great differences in the per capita water consumption of different regions; Shuang et al. [4] determined the explanatory variables related to economy, community, water use and resource availability, established 11 statistical and machine learning models, conducted interpolation and extrapolation scenarios, and predicted the water consumption in Beijing Tianjin Hebei region.

To put forward appropriate water resources policies, the multi-objective optimization model is established in the allocation of water resources, which takes the unified allocation of water quantity and water quality into account. The theory of water demand hierarchy is put forward, which can forecast the domestic water demand in the future and fine tune the urban water resource management. Zheng Zang and Xinqing Zou [5] used panel model to study the intensity evolution trend of domestic water, agricultural water, industrial water and ecological water among provinces in China. It was found that the proportion of tertiary industry, the rate of industrial wastewater standard, annual precipitation and per capita GDP had significant influence on water demand. Gao et al. [6] comprehensively considered various factors affecting the water demand in China and established the water supply and demand forecasting model by regression prediction method. The analysis shows that the most important factor affecting Chinese water demand is the GDP, and the adjustment of industrial structure has a certain influence on water demand, especially, the influence of industrial development on water consumption is higher than that of agriculture. Because of the strong control of water price by government and low price of water, water price has little influence on demand [6].

At present, the application of SD model in water resources prediction is still in its infancy. In modern circumstance, most of the water resources prediction of SD model is based on the demand and supply of industrial, agricultural and ecological water. We not only forecast the water demand from 2013 to 2025, but also predicts the future recycled water according to the established water system. In addition to the population and economic factors, we also employ the environmental factors, introduces the water shortage coefficient and environmental pollution coefficient to evaluate the environmental benefits of different policies, and puts forward some policy suggestions suitable for the sustainable development of water resources in China.

3 Problem Statement and Solution Approach

3.1 Theory and Method of System Dynamics

System dynamics can be used to analyse information feedback system, system structure and function, which has the characteristics of systematization, integrity and dynamic.

The system dynamics model can be used in time dynamic analysis considering the best goal of the whole system and it has been successfully applied to strategic analysis and management decisions of social, economic and ecological complex systems universally. Moreover, SD model has been used to deal with the problems about water resources carrying capacity, water demand prediction and water supply and demand balance analysis in some researches.

We apply the System Dynamics method to construct the social-water resources system model. By changing the relevant parameters, the model can reflect the economic, social and ecological benefits obtained under different strategies. After that this paper can make scheme comparison and selection, so as to propose the optimal water resources strategy.

3.2 System Analysis Water Resources in China

The proposed SD model starts with the interaction and mutual constraints of resources, population, economy and environment, and form a feedback system structure. The following are the main chains in the system model (Fig. 1):

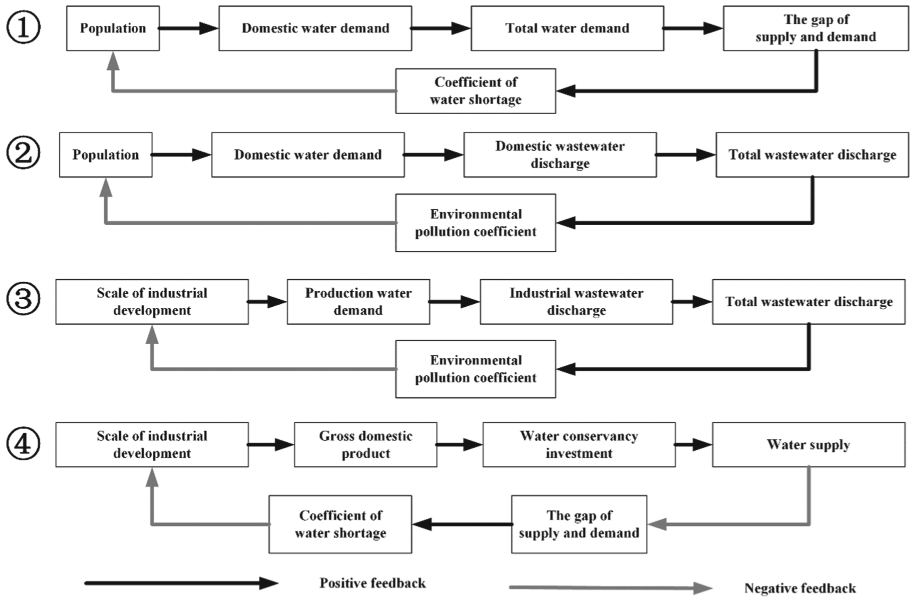

Fig. 1. Main chains in the system model

Chain ① reveals that population growth requires the consumption of water resources. With population growth, the more water resources are consumed, and when the water supply does not reach the consumption rate of water resources, it will restrict population growth and industrial development.

Chains ② and ③ indicate that water pollution restricts social and economic development. The more the population and industrial output value, the more wastewater discharge; the more serious the pollution of the water environment, the less the total population; the more economic losses will be caused, and further affect the expansion of the industrial scale.

Chain ④ indicates the positive feedback growth of economic development and water supply, the industrial development promotes the increase of regional GDP. With the increase of water conservancy investment, the water supply will increase and the industrial scale will expand.

In addition to building the main chain, this paper also adds the dynamic variables like population growth, and build casual graph of this system (Fig. 2):

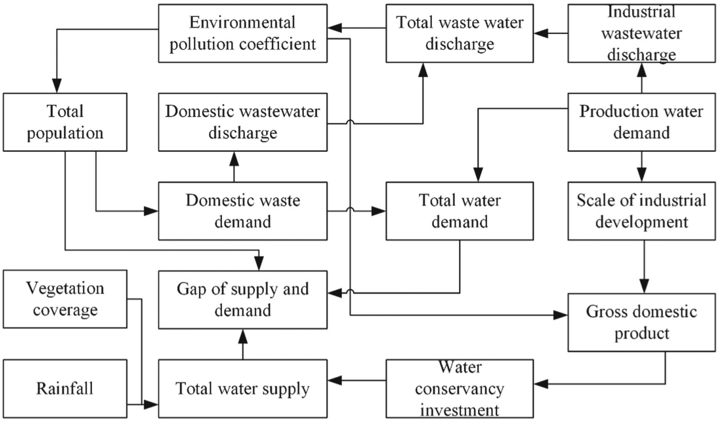

Fig. 2. Causality diagram of water SD model in China

3.3 Constructing System Dynamics Model

Based on the data of water resources supply and demand and social and economic development from 2003 to 2012, we establish a social-water resources system model by using ANYLOGIC simulation software.

Model Assumptions

1 Population growth rate is affected by water scarcity and environmental pollution;
2 The residents' water consumption per capita is a constant and it will not be affected by the change of time;
3 Through searching the literature, we suggest that the unit consumption cost of water resources has little effect on the limitation of water resources [4]. Therefore, when adjusting the parameters, the water price is fixed, so it is assumed that the cost required for the supply or production of water per cubic meter remains unchanged.
4 As the ecological water consumption only accounts for 2% of the total water consumption, the water demand is divided into domestic water and production water.

Notations

To construct a SD model, it is necessary to consider four factors: constant, stock, dynamic variable and flow equation.

In reference to the formulation of sewage discharge coefficient and recycled water coefficient in reference [5], we utilize water shortage coefficient and environmental pollution coefficient as the index of ecological benefit.

For the system, the physical quantities and meanings are as follow (Tables 1, 2, 3 and 4):

Table 1. Constant

Symbol	Definition
i	Population growth rate
P	Water consumption per capita
M	Cost of supply water per cubic metre
W_m	Water conservancy investment rate
W_r	Wastewater purification rate
Q	Domestic wastewater discharge rate
W_i	Industrial wastewater discharge rate

Table 2. Stock

Symbol	Definition
D_w	Domestic water demand
P_w	Production water demand
W_d	Domestic wastewater amount
W_p	Production wastewater amount
S	Water supply
W_t	Total wastewater discharge
D	Total water demand
R_w	Purified wastewater amount
W_c	Water conservancy investment

Table 3. Dynamic variables

Symbol	Definition
y	The year of y
N_y	Population in the year of y
G_{1y}	GDP of primary industries in the year of y
i_{1y}	GDP growth in primary industries in the year of y
G_{2y}	Secondary GDP in the year of y
i_{2y}	Growth GDP secondary industry in the year of y
G_{3y}	Tertiary GDP in the year of y
i_{3y}	Growth GDP tertiary industry in the year of y
G_y	Total GDP in the year of y
C_l	Coefficient of water shortage
C_p	Environmental pollution coefficient

Table 4. Equation

Definition	Equation
Coefficient of water shortage	$Cl = (D-S)/D$
Environmental pollution coefficient	$Cp = Wt \times (1-Rw)/S$
Domestic wastewater amount	$Wt = Wd + Wp$
Purified wastewater amount	$Rw = Wt \times Wr$
Domestic wastewater amount	$Wd = N \times Q$
Production wastewater amount	$Wp = Pw \times Wi$
The population in the year of y	$Ny = Ny-_1 \times (1 + i \times (1-C_l) \times (1-Cp))$
The GDP in the year of y	$G_y = G_{1(y-1)} \times (1 + i_{1(y-1)} \times (1-C_l) \times (1-C_p)) + G_{2(y-1)} \times (1 + i_{2(y-1)} \times (1-C_l) \times (1-C_p)) + G_{3(y-1)} \times (1 + i_{3(y-1)} \times (1-C_l) \times (1-C_p))$

3.4 Simulation Schemes

We collect relevant data from 2003 to 2012 and take 2012 as the current year to simulate the water resources system. The end of simulation time is 2025. The initial values of the main variables are fitted with historical data and initialized.

Main initial values in the proposed SD model (Table 5):

Table 5. Initial values of the system dynamics model

Parameter	Symbol	Value
Population growth rate	i	169‰
Water consumption per capita	P	453.9 m^3
Cost of supply water per cubic metre	M	4.78 CNY
Water conservancy investment rate	W_m	5.67%
Wastewater purification rate	W_r	77%
Domestic wastewater discharge rate	Q	7.60%
Industrial waste water discharge rate	W_i	8.10%

We use ANYLOGIC to establish and simulate the proposed SD model (Fig. 3).

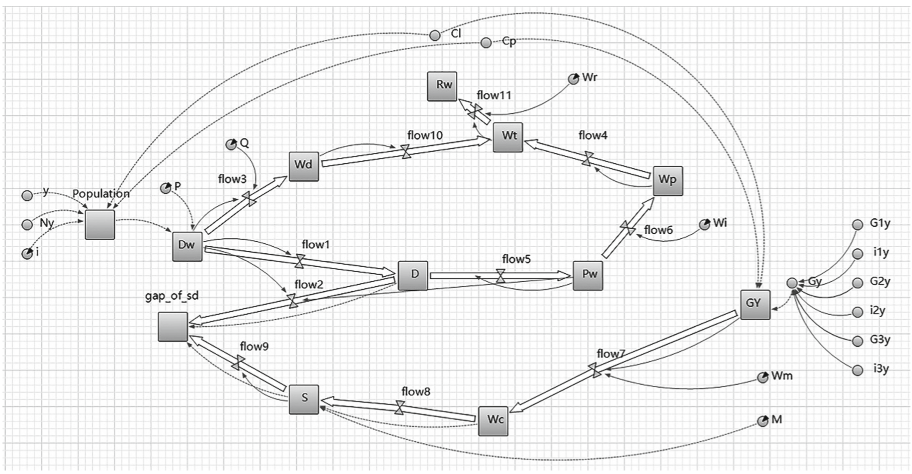

Fig. 3. System dynamics model

By adjusting the relevant parameters of the proposed SD model, we address four strategies:

First, the traditional development strategy, namely **low water investment rate, high wastewater discharge rate and low wastewater purification rate,** assumes that the model runs according to the existing initial value to analyse the supply and demand trend of water resources.

The second development strategy is **low water investment rate, low wastewater discharge rate and high wastewater purification rate.** The measures of reducing wastewater discharge rate in production process and improving wastewater utilization rate are adopted to modify the wastewater recycled rate, industrial wastewater discharge rate and domestic wastewater discharge rate in the model, so as to analyse the change trend of water resources.

The third development strategy is high water conservancy investment rate, which is **high wastewater discharge rate and low wastewater purification rate**. By increasing the investment in water conservancy facilities, the water supply can be increased, in order to reduce the supply and demand gap of water resources in the system, and then affect the social and economic development. This paper has modified the “investment rate of water conservancy facilities” in the model to analyse the supply and demand trend of water resources.

The fourth strategy is to combine strategy 2 and strategy 3, which is **high water conservancy investment rate, low wastewater discharge rate and high wastewater purification rate**, and modify the three initial values of the model, namely, wastewater recycled rate, industrial wastewater discharge rate and water conservancy facilities investment rate, to observe the trend of water resources supply and demand in the model.

Contents of the modification and basis for the modification:

The main targets this paper modified are investment rate of water conservancy facilities, wastewater discharge rate and wastewater recovery and utilization rate.

The investment rate of water conservancy facilities is based on *the in-depth Investigation and Investment Strategy Feasibility Report of China Water Conservancy Industry Market Development in 2020–2026* published by China gold enterprise information international consulting and statistics of Ministry of water resources show that: from 2010 to 2019, the total investment in water conservancy construction in China shows a fluctuating growth trend. According to this trend, the annual growth rate of water conservancy investment in China will maintain a high level, the investment and construction of water conservancy industry will continue to increase, so this paper set the value to 80%.

The wastewater discharge rate is based on the situation of reducing untreated wastewater discharge to the environment mentioned in *The National Comprehensive Water Resources Planning (2010–2030).* The average wastewater discharge rate from 2003 to 2012 is 7.6%. According to the contents of the comprehensive plan, this paper sets the wastewater discharge rate of 7% in 2025.

The wastewater recovery and utilization rate are based on the national wastewater discharge and reclaimed water volume target set in *The National Comprehensive Water Resources Planning (2010–2030)*, and the recycling coefficient of the reclaimed water in 2030 is estimated to be about 17%, so the recovery utilization rate in 2025 will be set at 15% (Table 6).

Table 6. Modifying table of control parameters of different strategies

Parameter	Unit	Strategy 1	Strategy 2	Strategy 3	Strategy 4
Population growth rate	‰	169	169	169	169
Water consumption per capita	m^3	453.9	453.9	453.9	453.9
Cost of supply water per cubic meter	%	5.67	5.67	5.67	5.67
Water conservancy investment rate	%	77	77	80	80
Domestic wastewater discharge rate	%	7.6	7	7.6	7
Wastewater purification rate	%	8.1	15	8.1	15

3.5 Output Results

After we input all initial data, ANYLOGIC simulate the operation of this system and output relevant index changes. The main index changes in the model simulation are shown in the Figs. 4, 5, 6, 7, 8 and 9 and the simulation results are shown in the Table 7.

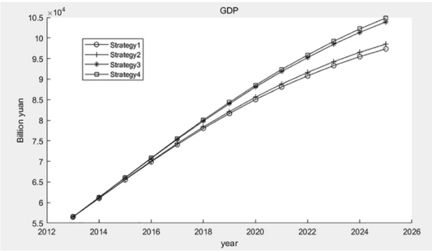

Fig. 4. GDP value from 2013 to 2025

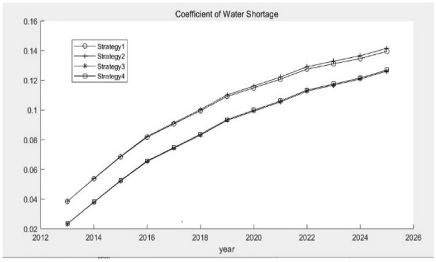

Fig. 5. Coefficient of water shortage from 2013 to 2025

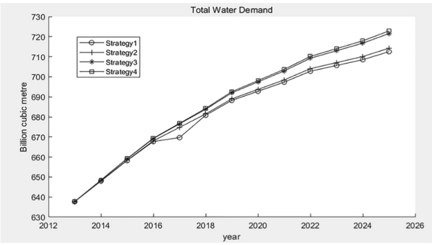

Fig. 6. Total water demand from 2013 to 2025

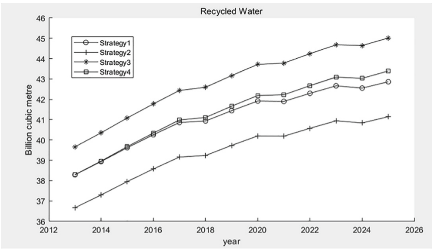

Fig. 7. The amount of recycled water from 2013 to 2025

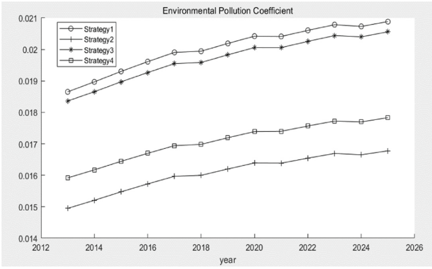

Fig. 8. Environmental pollution coefficient from 2013 to 2025

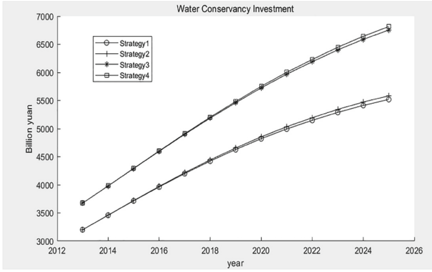

Fig. 9. Water conservancy investment from 2013 to 2025

Table 7. Comparison of China Water Resources Systems dynamics results 2025

Comparison of China Water Resources Systems dynamics results 2025				
Parameter (Unit)	Strategy1	Strategy2	Strategy3	Strategy4
The value of GDP (10^8¥)	973417.55	984978.36	1039143.00	1048594.50
Total water demand ($10^8 m^3$)	7125.14	7142.20	7215.49	7228.59
Water conservancy investment (10^8¥)	55192.78	55848.27	67544.29	68158.64
The amount of purified wastewater ($10^8 m^3$)	428.66	411.47	450.14	433.95
Coefficient of water shortage	0.1395	0.1416	0.1262	0.1270
Environmental pollution coefficient	0.0209	0.0168	0.0206	0.0178

3.6 Comparative Analysis

According to the research results of Cao et al. [9], the average relative error between the simulated value and the actual value of the main index can be less than 10%, so the simulation result can be considered to be effective. According to our SD model, after substituting the values, the relevant values of strategy 1 are compared with the total water demand values collected from 2013 to 2019 in China Water Resources Bulletin. We find that the prediction error of total water demand from 2013 to 2016 is less than 10%, and the result is effective. However, since 2017, the deviation of the predicted results has exceeded 10%. We think that this is related to the relevant water-saving policies implemented in China. Strategy 1 in our model is an original state, that is, the calculated value is the predicted value not regulated by policies. For strategy 2, 3 and 4, we only use the strategy to be executed in the future to adjust the parameters, but the actual situation is more complex. The actual value will be affected by many water-saving measures implemented by the Chinese government (Table 8).

For example, in 2016, in terms of domestic water saving, some areas implemented step-by-step water prices for households and raised water prices for non residents; In

Table 8. Comparison of actual water consumption and predicted total demand

Comparison of actual water consumption and predicted total demand					
Year	Actual water consumption	Total water demand of strategy 1 (10^8m^3)	Relative error	Total water demand of strategy 4 (10^8m^3)	Relative error
2013	6183.4	6376.383132	0.03120987	6378.120622	0.031490866
2014	6095	6479.235214	0.06304105	6484.468453	0.063899664
2015	6103.2	6581.843096	0.07842494	6592.234551	0.080127564
2016	6040.2	6677.180372	0.10545683	6694.190304	0.108272955
2017	6043.4	6742.851601	0.11573809	6768.276004	0.119945065
2018	6015.5	6808.522829	0.13182991	6842.361705	0.137455192
2019	6021.2	6881.944505	0.14295232	6925.366375	0.150163817

2017, the three departments issued the Water Saving Society Construction of "the 13th five year" Plan, vigorously promote water-saving policy; In 2018, China's national development and Reform Commission and the Ministry of water resources jointly issued the National Water Saving Action Plan, focusing on "double control of total amount and intensity", "agricultural water saving and efficiency", "industrial water saving and emission reduction", "urban water saving and loss reduction", "water saving and open source in key areas" and "scientific and technological innovation leading". After the implementation of these policies, the total amount of water use in China has been effectively controlled, the overall water use structure has been gradually adjusted, and the overall water use efficiency has reached the world average level. According to the statistics of China economic network, in 2019, the national water consumption of 10000 yuan GDP and 10000 yuan industrial added value decreased by 24% and 28% respectively compared with 2015, and the effective utilization coefficient of farmland irrigation water reached 0.559.

Among all the water-saving policies, advanced wastewater treatment process; speeding up the construction of water conservancy in grasslands and pastoral areas, and developing water-saving irrigation agriculture; continuing to promote water-saving water supply major water conservancy project construction and other important suggestions and measures are coincide with our management suggestions from SD model, which shows that our model, to a certain extent, can put forward management suggestions for the actual situation, which has reference value.

4 Numerical Results

Compared with strategy 1, the wastewater discharge rate of strategy 2 decreased from 7.6% to 7%, and the wastewater purification rate increased from 8.1% to 15%. As a result, the environmental pollution coefficient decreased by 19.6%, indicating that limiting the wastewater discharge rate and increasing the purification rate can reduce the environmental pollution coefficient and alleviate water pollution.

Compared with strategy 1, strategy 3 increased the investment rate of water conservancy facilities to 80%, increased the water supply, and reduced the water shortage coefficient by 9.5%, which can alleviate the shortage of water resources, but the environmental pollution coefficient is only reduced by 1.4%, which is still greater than 0.02, and the serious problem of environmental pollution still exists.

Strategy 4 combines the advantages of strategy 2 and strategy 3. Compared with strategy 1, under strategy 4, the water shortage coefficient decreased from 0.1395 to 0.1270, a decrease of 8.96%, and the environmental pollution coefficient decreased from 0.0209 to 0.0178, a decrease of 14.8%. It can not only alleviate the shortage of water resources, but also reduce environmental pollution, while maintaining the trend of economic growth. In addition, our results are similar to those predicted by Gao Jun et al.

From the results of the SD model, we conclude that adjusting the sewage discharge rate and sewage utilization rate can help solve the problem of environmental pollution. Raising the investment amount of water conservancy facilities can alleviate the shortage of water resources.

Moreover, we evaluate different strategies according to three aspects: economic benefit, ecological benefit and water utilization efficiency. From the perspective of economic benefit, strategy 4 can create the highest GDP, followed by strategy 3; from the perspective of ecological benefit, strategy 3 has the highest sewage treatment capacity, followed by strategy 4; in terms of water utilization efficiency, although the total water demand of strategy 3 and strategy 4 is higher than that of strategy 1 and strategy 2, the water shortage coefficient of strategy 3 and strategy 4 is lower than that of strategy 1 and strategy 2. This illustrates that strategy 3 and strategy 4 can alleviate the situation of water shortage.

After analysing the results of different strategies with this proposed SD model, we propose that: to maximize the environmental benefits, water utilization benefits and economic benefits, the suitable measures for Chinese government to take are reducing the discharge of domestic sewage and production sewage, improving the sewage purification rate and increasing the investment rate of Chinese water conservancy facilities.

5 Conclusion

Taking China as the research object, this paper constructs a sustainable development model of water resources based on China's population, economy and environment. We collected relevant data from 2003 to 2012, and changed the parameters of the proposed sustainable development model according to relevant policies, so as to predict China's total water demand, water conservancy investment and water recycling under different water resources strategies. Among them, under the water resources strategy of high investment in water conservancy facilities, low waste water discharge rate and high waste water purification rate, the total water demand of China in 2025 is about 722 billion M^3, the investment in water conservancy facilities will exceed 6815 billion yuan and the recycled water will exceed 43 billion M^3. From the perspective of maximizing social and environmental benefits, we put forward measures to ensure the sustainable development of water resources: although the contradiction between supply and demand of water resources will still exist in the next 13 years, the water shortage coefficient can be reduced to 0.1270 and the environmental pollution coefficient can be reduced to 0.0178 by increasing the investment rate of water conservancy, improving the recovery rate of wastewater and reducing the direct discharge rate of wastewater, so that the contradiction of water resources can be alleviated.

The interaction and restriction of each subject in the system can be taken into account in terms of the proposed SD model. By utilizing the model with ANYLOGIC, we dynamically analyse the complex social water resources system and intuitively compare various managerial implications.

However, the proposed SD model has some shortcomings. It does not take the impact of major accidents on the population growth rate into account, such as epidemics. Additionally, in terms of water demand, we simply divide it into domestic water and production water, without considering public and ecological water.

Although SD model has a certain degree of reference value, it is still only a simplified analysis of the complex system of water resources in China. In the future, more important factors need to be considered, such as overseas allocation of water resources, water demand of ecological environment, consumption of surface water and groundwater. Besides single factor analysis, it also needs to consider the comprehensive effects of various factors, and then, further explore the complex system of water resources in China. In the future, we will try to combine GIS technology with the proposed sustainable development model, and extend it to other geographical scales, such as urban agglomerations and basins with different levels of water resources development.

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