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Optimal allocation of system dynamics models for urban water management

Chenxi Zhu

Management School, Ecole Supérieure de Management en Alternance, Paris 77437, France, email: 505708440@qq.com

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ABSTRACT

Water resources management possesses an essential influence on the socio-economic advancement of cities in the region. In order to ensure that the urban economy develops on the basis of healthy and sustainable water environment and ecology, this research constructs a system dynamics model of urban water environment carrying capacity, and constructs a water environment carrying capacity evaluation index system. The level and trend of water environment carrying capacity of a city in southwest China from 2005 to 2019 were analysed through the model study, and the future trend of water environment carrying capacity of the city was also predicted and analysed. In the experiment, the prediction performance of the system dynamics model is analysed through historical tests, and the results show that in the four indexes of population, water supply, wastewater discharge, and chemical oxygen demand discharge, the prediction of the model has an error of less than 1.12%, 0.5%, 0.33%, and 0.1% from the actual value, respectively. Meanwhile, in the estimation of water resources carrying capacity, it is found that the city has the worst management effect in 2009, with a score of –2.58, and the best water environment carrying capacity evaluation in 2019, with a score of 2.88. In the control of drainage and pollution prevention programme, water conservation and environmental protection programme and the integrated programme, it is found that the integrated programme is better able to avoid the water environment crisis in the future, and improves the future carrying capacity of the city's water environment.

Keywords: Water resources; System dynamics modelling; Carrying capacity; management; Principal components

1. Introduction

Water is a precious natural resource essential to the survival of life and human development, an indispensable and irreplaceable element of the ecosystem, and an extremely important strategic economic resource and environmental element for human society. The health and safety of the water environment (WE) is a prerequisite for the continuous enhancement of people's living standards, a guarantee for the sound advancement of the national economy, and a fundamental basis for the sustainable progress of human civilisation. Therefore, this study combines system dynamics (SD) and principal component analysis methods to evaluate and predict urban water resources (WR) management with resource and environmental carrying capacity (CC) as the entry point. In this study, the hierarchical analysis method and DPSIR evaluation index model were used to establish the evaluation index system of WE CC, and the MATLAB program was used to calculate the comprehensive score of WE CC according to the principal component analysis method, so as to provide a reference for the future evaluation and prediction of the CC of the WE and the formulation of WE management programmes. The innovation of this study is to propose the optimal allocation of WR management programmes on the ground of the prediction of the future CC of the urban WE. This study analyses the current status of urban WR management and SD methods in the current stage in chapter 1. In chapter 2, the SD and principal component analysis methods are investigated in the estimation of English in the environmental CC of WR. Empirical

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analyses are carried out in chapter 3 to verify the application performance of the model and predict the evaluation of WR CC in cities. In chapter 4, the experimental analysis results were integrated and presented.

2. Related work

Voogd et al. [1] conducted a survey on the Netherlands and concluded that in order for the government to play a good macro-control function, the public's feelings and trust must be the first consideration in setting water prices, so the government should pay attention to the public trust as a prerequisite to give full play to the regulation mechanism of the market price, and to promote the efficient use of WR. Karl et al. [2] used digital solutions to propose optimisation of the water distribution pipes and water losses, which in turn improves the effectiveness of WR utilisation. Digital regulation and public participation help managers to better manage WR, fulfil their functions in accordance with the law, and protect the allocation, delivery and use of WR. For the assessment aspect of agricultural structure and WE resource CC, Rong et al. [3] proposed a fuzzy credibility constrained mixed integer planning model based on imprecise simulation. The study conducted a model analysis of water resource management using the Xinfengjiang Reservoir watershed as a sample, and the experimental results showed that the model was suitable for planning the agricultural production structure and population size under a variety of uncertainty conditions for the watershed. Ma'Mun et al. [4], using Ostrom's eight design principles, took a province in India as an example of a water resource utilisation system robustness, studied and made a series of recommendations, which, among others, focused on the need to decentralise local policy making managers to encourage and increase water supply and rationalise the use of water for community prosperity. Barkey and Nursaputra [5] analysed the health of WEs in forests through Landsat imagery, and used SWAT modelling in the context of changes in forest condition to determine the effect of forest conditions on WR. In the case of Maros forest watershed, the experimental results showed that the increase in forest area increases the value of WR, but the increase in forest area was optimal at 33.44% of the Maro watershed area.

Wang et al. combined SD and fuzzy analysis methods for analysing the complexity of WE and socio-economic systems in Northeast China. Both Monte Carlo and scenario analysis methods were also used in the simulating, and the experiment showed that neither the purely Yu economic development model nor the environmental protection model can improve the local WR and regional development, and that both must be combined [6]. Keesstra et al. [7] introduced a new concept of connectivity to study water and sediment transfer and their related substances. This approach increases the ability to analyse water and sediment changes at long time scales, while the parameters are simple for modelling. The SD model used by Wu et al. to analyse the urban climatic environment and reveal dynamic trends, academic collaborations, and research hotspots in the literature of Web of Science for the period 1997–2017 [8]. Zarghami et al. [9] conducted a review of the water sector (WS) by providing a comprehensive literature review of academic papers on SD model development and then discussing the various steps of the modelling. The study also discussed the advantages and merits of using SD in the WS and provided directions for future research in this area. Pluchinotta et al. [10] developed an information dynamics evolution system on WR management using SD modelling while the study explored how different actions affect the decision making process of various stakeholders in IS. Li et al. [11] constructed a SD model for analyzing the relationship between the urban water cycle and the socio-economic ecosystem, the experiment was based on the example of Shenzhen, and the results showed that the city's water supply and demand will increase from 0.89 in the baseline scenario to 1.04 in the optimisation scenario in 2020, and from 0.64 to 1.05 in 2030.

In summary, although the research on urban WR management has achieved some stage-by-stage results, its content mainly focuses on the basic concept of WE CC, the construction of WE model and the evaluation method of WE CC, which is yet to be extended to the quantification of the results of the comprehensive estimation of the CC of the WE, the scientific planning and management of the WE, and the harmonious development of the socio-economics and the WE, and other aspects of the research. Based on this, this study adopts a SD approach to construct an urban WR CC model and conducts a comprehensive evaluation of the WE CC, with a view to providing a reference for the future evaluation and prediction of the WE CC and the formulation of WE management programmes.

3. Application of system dynamics modelling in urban water resources management

This study applies the SD model to urban WR management, mainly by dividing the subsystems of the model, analysing the intrinsic structure of the subsystems and the correlation between the subsystems, clarifying the causal feedback relationship between the subsystems and variables, and reflecting more intuitively the impact of the change of the part of the system on the system as a whole.

3.1. System dynamics modelling

SD is a discipline on the ground of the principle of information feedback and guided by the theories of management, decision theory and system theory. The model combines information theory and cybernetics, integrates structure and function, matter and information, science and experience, and is a cross-discipline with strong synthesis. It combines computer technology to qualitatively and quantitatively analyse and solve nonlinear, multiple-feedback and high-order complex problems, involving many fields such as the natural environment and human society, and is a branch of system science. The SD method has a good application prospect in dealing with multiple feedback, high order and nonlinear complex problems. At the same time, the SD method can study and analyse the evolutionary trend of dynamic problems with high operability. Therefore, in this study, the SD approach will be used to construct a WR management optimisation model to optimise the allocation by predicting the CC of the WE. The set of equations within the SD model enables the quantification of system variables, which are mainly divided into rate variable equations, state variable equations, and table functions with auxiliary variable equations. The state variable equation is the equation for calculating the cumulative situation of the state variable, and the main type of equation is the integral equation, whose formula is shown in Eq. (1).

$$L_k = L_j + \mathrm{DT} \times \left(\mathrm{In}_{jk} - \mathrm{Out}_{jk}\right) \quad (1)$$

where *L* denotes the state variable, *j*,*k* denotes two moments, DT denotes the time interval, and In and Out are the input and output efficiencies, respectively. Secondly, the rate variable equation is used to calculate the rate variable, and the main type of the equation is a differential equation, which is given in Eq. (2).

$$\frac{L_k - L_j}{\mathrm{DT}} = \mathrm{In}_{jk} - \mathrm{Out}_{jk} = \frac{\mathrm{DL}}{\mathrm{DT}} \quad (2)$$

where DL denotes the change in state stock during the time interval. The auxiliary equations are equations for calculating auxiliary variables, mainly for the calculation of data introduced as auxiliary in the system. The table function is mainly applied to the relationship is non-linear between the indicator variables, cannot be calculated with auxiliary equations, the use of graphs to present this kind of non-linear relationship [12]. The WE system is a complex coupled system that contains multiple factors and complex internal factor relationships. In this study, the SD model is applied to urban WR management, and variables that do not have a significant impact on the WE system should be excluded when the model boundary is drawn. The relation in the SD subsystem and the urban water management problem is shown in Fig. 1.

3.2. System dynamics-based prediction study of water environment carrying capacity

According to the characteristics of the services provided by the urban WE, the service functions of the WR system are generally divided into two main categories: one is the economic function with direct use value, which refers to the function of the WR system to provide economically efficient products or services; the other is the ecological function with indirect use value, which refers to the function of the WR system to maintain the ecological security of the WR system and its neighbouring areas [13]. The ecological function is the function of a water resource system to maintain its own ecological security and that of its neighbouring regions [13]. Water resource systems are similar to water ecosystems, and this paper draws reference to water ecosystem service functions, which are divided into the following five categories, as shown in Fig. 2.

This paper follows the relevant principles of evaluation index construction, and refers to the construction methods of experts and scholars at home and abroad for the evaluation index system of WE CC. Combined with the actual situation of the WE system in the study area of this paper and its own characteristics, the guideline layer and indicator layer of the WE CC evaluation index system are constructed with reference to the DPSIR evaluation index model widely used in the evaluation of environmental systems [13,14]. Driving force indicators mainly refer to the indicators of social and economic aspects, which are the most primitive and basic indicators to prompt changes in the WE CC level, and this paper selects population as the driving force indicator of WE CC. This paper selects the water consumption of 10,000-yuan GDP, the total amount of wastewater discharge, chemical oxygen demand (COD) emissions, total phosphorus emissions, ammonia nitrogen

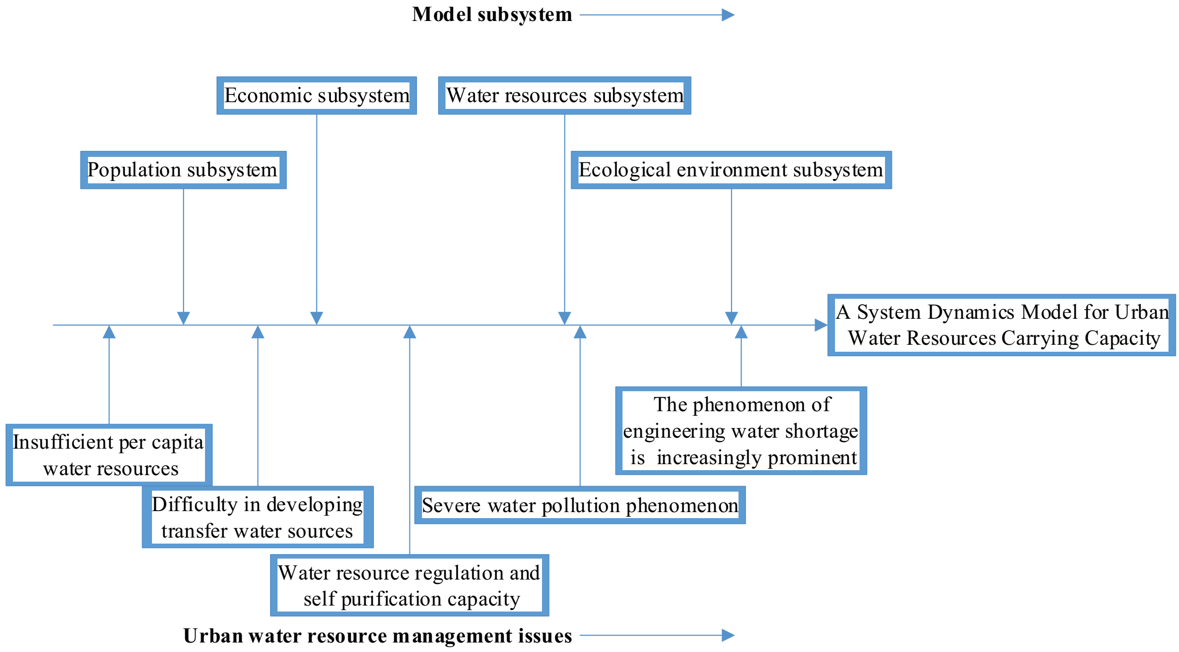

Fig. 1. Relationship between system dynamics subsystems and urban water resource management issues.

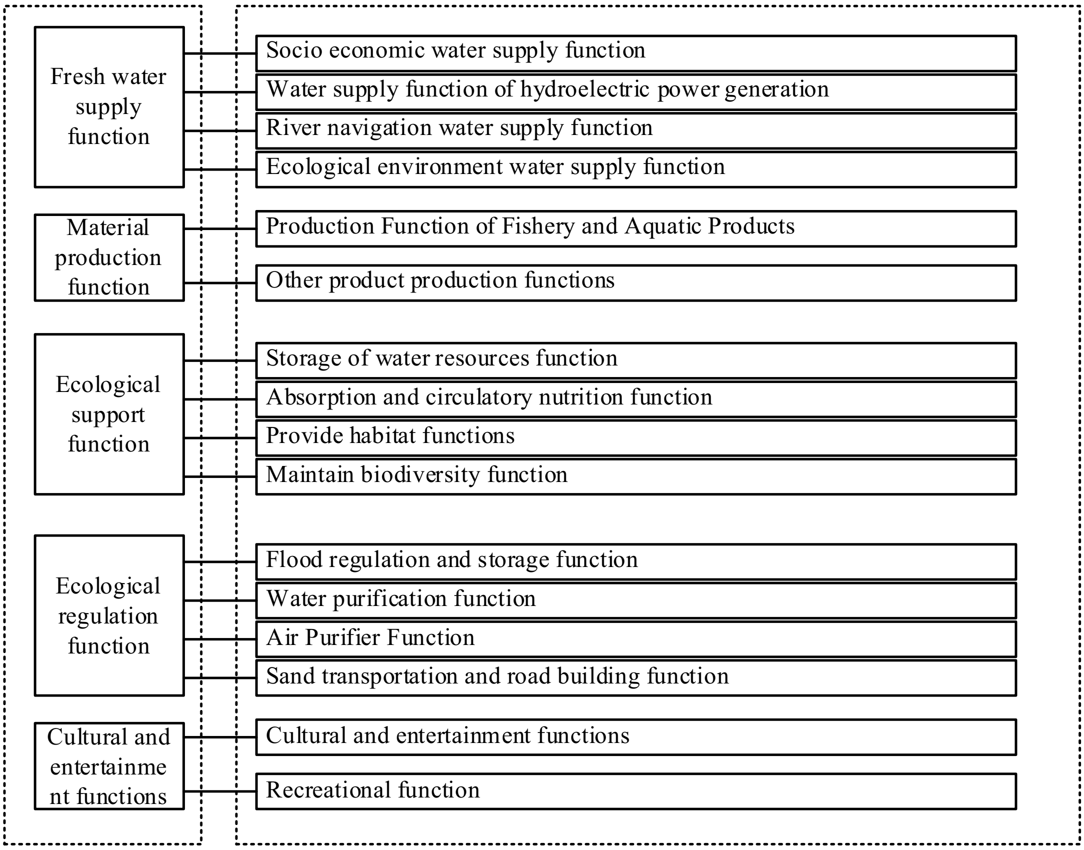

Fig. 2. Water resource system service functions.

emissions and total nitrogen emissions as the pressure indicators of the CC of the urban WE. The state indicators indicate the state of the WE system under the influence of driving force and pressure indicators, mainly including the state of exploitation and utilisation. In this paper, the degree of WR development and utilisation and per capita WR are selected as state indicators of urban WE CC. The impact indicators mainly reflect the impact of WE system on social economy, life production, etc. This paper selects the total water supply as the impact indicators of WE CC [15–17]. Response indicators mainly include the formulation of policies and regulations, investment in human and material resources to protect the WE system, etc. Due to the inconvenience of quantification of policies and regulations and other factors, this paper mainly through the ecological water consumption ratio and environmental protection investment accounted for the proportion of the regional GDP and other aspects of the response indicators to consider.

Evaluation indicators are divided into positive, negative and moderate indicators [61], of which, the larger the positive indicators, the stronger the CC of the WE, such as: per capita WR, total water supply, etc.; the larger the negative indicators, the weaker the CC of the water environment, such as: population, 10,000-yuan of GDP water use, etc.; and moderate indicators of the value of the value of the more tend to a certain value or a certain interval, it is indicated that the WE has a stronger CC. The table shows that the WR per capita is the weakest. As can be seen in the Table 1, the per capita WR, total water supply, ecological water consumption, and environmental protection investment as a proportion of regional GDP are positive indicators of WR management; while population, water consumption of 10,000-yuan of GDP, wastewater discharge, COD emissions, total phosphorus emissions, total nitrogen emissions, and the degree of WR development and utilisation are negative indicators.

In this paper, through the forwarding of indicators and data standardisation, the use of principal component analysis, the calculation of the correlation coefficient matrix and other steps to get the final evaluation of the CC of the WE based on the WE CC score, the higher the score of the WE CC indicates that the WE has a stronger capacity to carry the WE, the lower the WE pressure. In order to achieve the consistency of the WE CC level embodied in each evaluation index, before the evaluation of the WE CC, the WE CC indicators are usually positively processed, of which only the reverse indicators and moderate indicators need to be adjusted to get the adjusted evaluation indicators, the larger the value of the indicators, indicating that the WE CC is better. First of all, the formula for forwarding the reverse indicator is shown in Eq. (3).

$$y_i = \max\{x_i\} - x_i \tag{3}$$

where x_i denotes the inverse indicator value, y_i denotes the normalisation result, and i denotes the indicator number. In this study, the evaluation of environmental CC in WR

Table 1
Evaluation index system of urban water resources carrying capacity

Target layer	Criterion layer	Indicator layer	Serial number	unit
Comprehensive score of water resources carrying capacity	Driving force layer	Population	X_1	Ten thousand people
		Water consumption per 10,000 yuan of GDP	X_2	m^3
	Pressure layer	Total amount of wastewater discharge	X_3	10^8 m^3
		COD emissions	X_4	10^4 t
		Total phosphorus emissions	X_5	10^4 t
		Ammonia nitrogen emissions	X_6	10^4 t
		Total nitrogen emissions	X_7	10^4 t
	State layer	Degree of water resource development and utilization	X_8	%
		Per capita water resources	X_9	m^3/people
	Affected layer	Total water supply	X_{10}	10^8 m^3
	Response layer	Proportion of ecological water use	X_{11}	%
		Proportion of environmental protection investment in regional GDP	X_{12}	%

management is elaborated by principal component analysis, and the indicators are firstly standardised as shown in Eq. (4).

$$x_{ij} = \frac{a_{ij} - \bar{a}_j}{\sigma_j} \tag{4}$$

where a_{ij} denotes the normalised indicator data, $\bar{a}_j$ denotes the data mean, and σ_j denotes the data standard deviation. Secondly, the correlation coefficient matrix is calculated and its formula is showcased in Eq. (5).

$$r_{ij} = \frac{\sum_{z=1}^{n}\left(x_{zi} - \bar{x}_i\right)\left(x_{zj} - \bar{x}_j\right)}{\sqrt{\sum_{z=1}^{n}\left(x_{zi} - \bar{x}_i\right)^2 \sum_{z=1}^{n}\left(x_{zj} - \bar{x}_j\right)^2}} \tag{5}$$

where r_{ij} represents the correlation coefficient between the two indicators. After deriving the correlation coefficient matrix, the eigenvalues of the matrix are calculated by Jacobi method, the eigenvalues are arranged in order from the largest to the smallest, and then the unit eigenvector corresponding to the largest eigenvalue is decomposed. After calculating the eigenvectors, the contribution ratio of each eigenvalue to the total eigenvalues is calculated, and the larger the ratio is, the more information is reflected by the principal components. The formula for the contribution rate and cumulative contribution rate is shown in Eq. (6).

$$\begin{cases} e_i = \lambda_i / \sum_{i=1}^{p} \lambda_i \\ e'_z = \sum_{i=1}^{z} \lambda_i / \sum_{i=1}^{p} \lambda_i \end{cases} \tag{6}$$

where e_i and e'_z denote the contribution rate and cumulative contribution rate, λ denotes the eigenvalue, and p is the maximum number of eigenvalues. When the cumulative contribution rate e'_z is greater than or equal to 85%, it demonstrates that the information covered by the first z principal components has met the evaluation requirements, so $y_1, y_2, \ldots, y_z$ is taken as the index principal component. After deriving the principal components, the loadings of the principal components are calculated, and the formula is shown in Eq. (7).

$$u_{ij} = \sqrt{\lambda_i \alpha_{ij}} \tag{7}$$

where u_{ij} denotes the principal component loadings. In this study, the weights of the principal components will be further calculated, when the eigenvalues of the principal components are larger, it means that the more information is covered, and therefore the larger the going to take the median value, so its formula is shown in Eq. (8).

$$w_i = \frac{\lambda_i}{\sum_{i=1}^{z} \lambda_i} \tag{8}$$

Finally, the principal component loadings were multiplied with the standardised indicator data to obtain the score of each principal component, and then the composite score was calculated based on the principal component weights, whose formula is shown in Eq. (9).

$$F = \sum_{i=1}^{z} y_i w_i \tag{9}$$

The technical methods used in this paper mainly include SD, hierarchical analysis and principal component analysis [18]. SD is a comprehensive discipline based on the principle of information feedback, guided by the theories of management, decision theory and system theory, combined with computer technology, to qualitatively and quantitatively analyse and solve nonlinear, multiple-feedback and high-order complex problems. This paper applies the principle of SD to construct a SD model of urban WE CC as shown in Fig. 3.

4. Empirical analysis of predictions for water resources management evaluation under system dynamics modelling

To validate the SD model constructed in this study, a city in southwestern China was used as a sample for empirical analysis in this study. The rainfall in this region ranges from 1,000 to 1,350 mm, with obvious dry and wet seasons, and rainfall is dominated by the months of May to September. This region presents the problems of uneven spatial and temporal distribution of precipitation, insufficient WR per capita, perceived difficulties in the development of transit water sources, poor self-purification ability with voluntary storage, and increasingly prominent water pollution phenomenon in WE management.

4.1. Historical testing of system dynamics models

In this study, a city in southwestern China is taken as a sample, and the time boundary of the SD model is set as 2005~2030, with 2019 as the base year, and the historical statistical data years are 2005~2019, and the validity of the model is examined through the comparison of the model simulation results and historical statistical data, and the model simulation predicts the years of 2020~2030, of which, the near-term planning level year The model simulation forecast year is 2020~2030, of which, the near-term planning level year is 2020~2022, the medium-term planning level year is 2022~2025, and the far-range planning level year is 2025~2030. In order to get better simulation effect, the time step is set to 1 y. Firstly, the population and water supply indicators in the SD model are examined historically, and the specific results are shown in Fig. 4.

As shown in Fig. 4, the absolute error of the SD model is 1.12% at the maximum in the indicators of the actual value of the population and the simulated value of the model. And in the actual and predicted values of total water supply indicators, the absolute error of the SD model constructed in this study is controlled within 0.5%.

As shown in Fig. 5, in the indicators of actual and model simulation values of wastewater discharge, the absolute error of the system dynamics model has a maximum value of 0.33% and a minimum error of 0.03%. In the actual and predicted values of total COD discharge indicators, the absolute error of the SD model constructed in this study is mostly controlled within 0.1%.

4.2. Sensitivity analysis of the system dynamics model

In this paper, in order to examine the robustness of the SD model of the city's WE CC, 10 more sensitive parameters in the model were calculated. Seven indicators, including resident population, total GDP, proportion of environmental protection investment to regional GDP, total water supply, total water consumption, COD emission and total wastewater discharge, were selected in each subsystem for calculation and analysis. The sensitivity of the whole system to these parameters, that is, sensitivity, is reflected through the influence of these parameters on the selected indicators

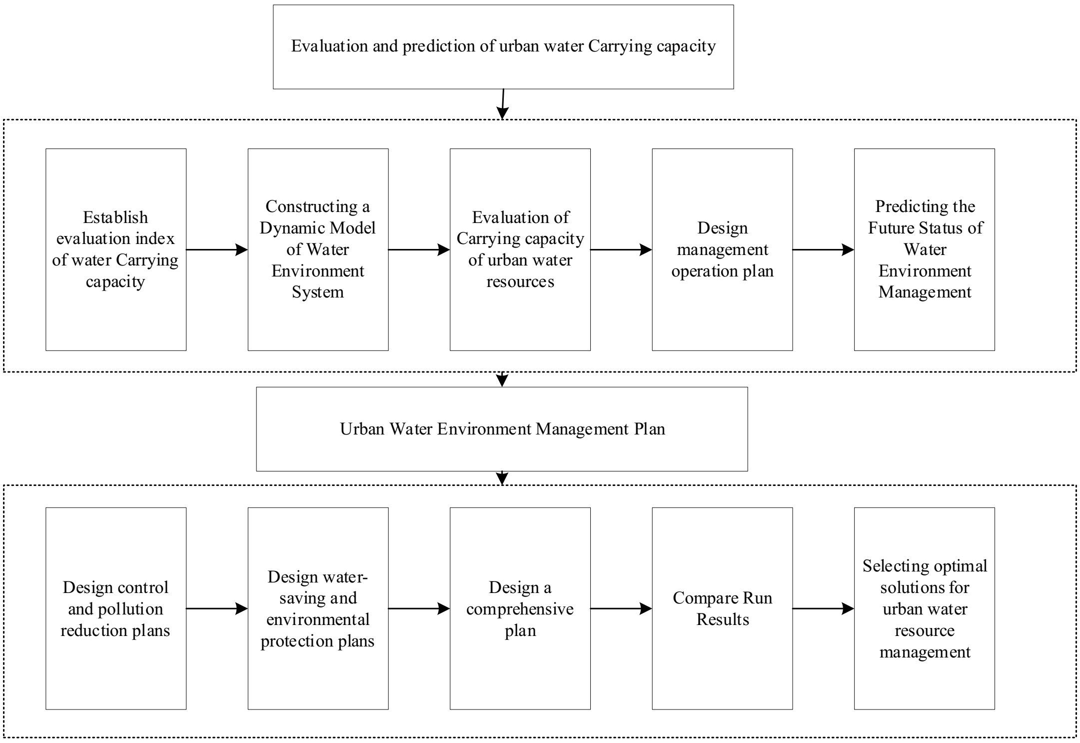

Fig. 3. Construction route of urban water carrying capacity system dynamics model.

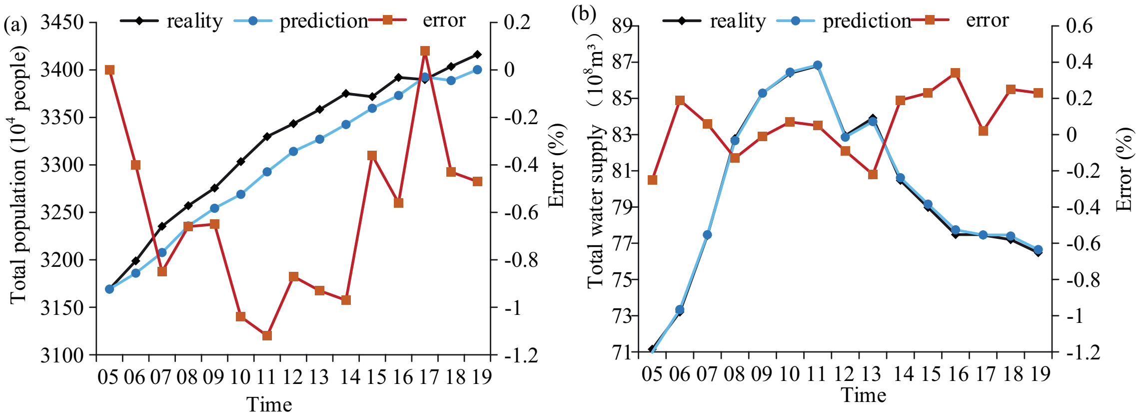

Fig. 4. Historical testing of population and water supply indicators in system dynamics models. (a) System dynamics model population history test and (b) historical verification f water supply in system dynamics models.

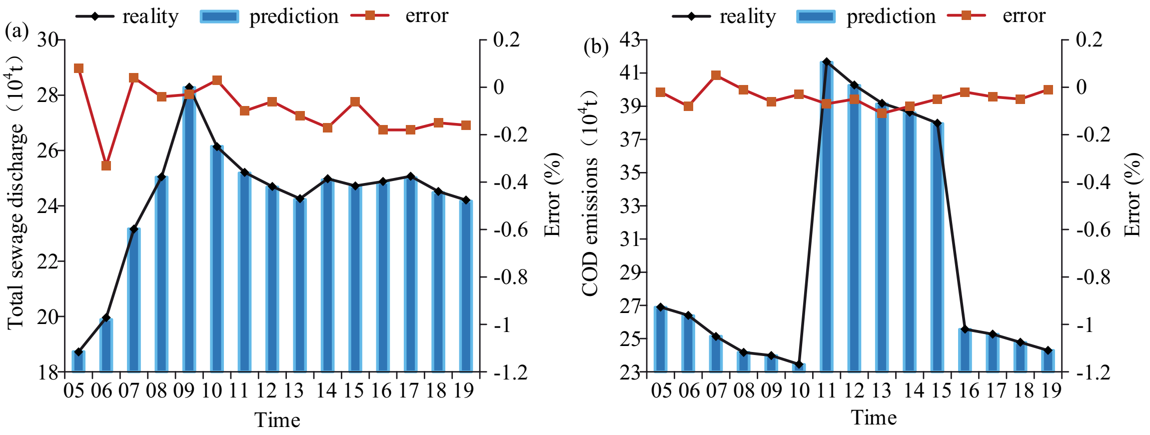

Fig. 5. Historical verification of sewage and chemical oxygen demand discharge indicators in system dynamics models. (a) Historical testing of wastewater discharge indicators in system dynamics models and (b) historical verification of COD emission indicators in system dynamics models.

in each subsystem. The specific experimental outcomes are indicated in Table 2.

From the results of sensitivity calculation, we can get that the sensitivity of the system to each parameter is low, and only the sensitivity to the water consumption of 10,000 yuan secondary industry GDP is more than 20%, which indicates that most of the parameter changes do not have much influence on the model, and compared with other subsystems, the model is more sensitive to the parameters of the economic subsystems, which is also consistent with the actual situation. Through the validity test of the three aspects, it can be considered that the SD model of urban WE CC constructed in this paper meets the requirements of validity and reliability, and has the ability to predict and study the short-term WE CC of urban cities.

4.3. Evaluation of the carrying capacity of the water environment by system dynamics modelling

Firstly, the 12 evaluation indexes are normalised, and then the principal component analysis is applied to standardise the evaluation indexes that have achieved normalisation through mathematical software MATLAB programming, and the specific results are shown in Fig. 6.

According to the evaluation value of the standardised treatment in Fig. 6 above, the scale was subjected to principal component analysis to obtain the eigenvalues, contribution rates and cumulative contribution rates of the principal components, as showcased in Table 3.

Table 3 showcases that the contribution values of y_1, y_2, y_3 and y_4 are 35%, 30.3%, 16% and 12.7%, respectively, and the cumulative contribution value is 93.9%, which means that it can reflect 93.9% of the information of the original data, which is greater than 85% of the principle requirements, and the eigenvalues of y_1, y_2, y_3 and y_4 are greater than 1, which indicate that y_1, y_2, y_3 and y_4 can reflect the impact of the majority of indicators on the CC of WE. environmental CC, and can be used as the principal components of the 12 indicators reflecting the WE CC of this southwestern city. According to the results of principal component analysis, the loads of the four principal components are calculated, as shown in Table 4.

As shown in Table 4, the weights of the four principal components can be calculated after deriving the principal

Table 2
Sensitivity analysis and calculation results of system dynamic model of water carrying capacity

Serial number	Variable parameter name	Permanent population	Total GDP	Proportion of GDP	Total water supply	Total water consumption	COD emissions	Total wastewater discharge	Average sensitivity
1	Permanent population growth	5.1	0	0	0	0.95	3.85	1.3	1.6
2	Urbanisation rate	0	0	0	0.01	4.38	67.33	24.85	13.79
3	GDP growth rate of tertiary sector of the economy	0	57.8	53.54	0	5.45	3.15	10.08	18.58
4	Water consumption per 10,000 yuan of secondary sector of the economy GDP	0	0	0	0.02	48.09	29.4	67.18	20.67
5	Urban per capita domestic water consumption	0	0	0	0.01	11.69	67.33	24.85	14.84
6	COD discharge concentration in domestic sewage	0	0	0	0	0	67.33	0	9.62
7	Wastewater discharge rate of secondary sector of the economy	0	0	0	0.02	0	29.4	67.18	13.8
8	Water quota for urban landscaping and green spaces	0	0	0	0	0.22	0	0	0.03
9	Growth rate of environmental protection investment	0	0	113.53	0	0	0	0	16.22
10	Wastewater reuse rate	0	0	0	0.03	0	0	0	0.01

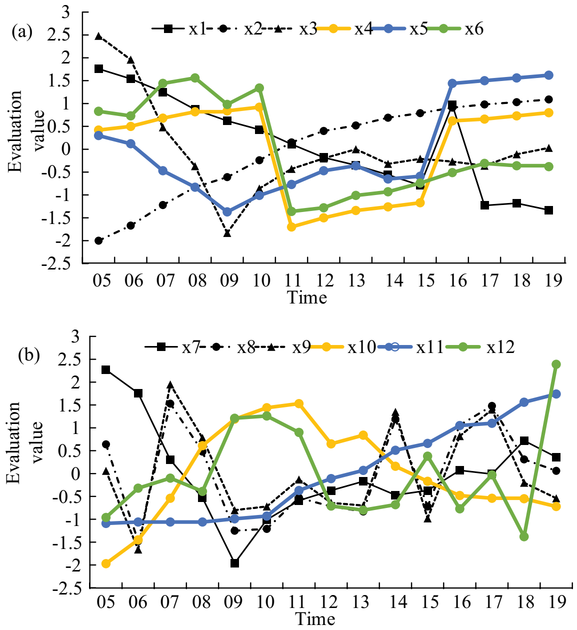

Fig. 6. Standardized value of water carrying capacity assessment index from 2005 to 2019. (a) Indicators x_1 to x_6 and (b) Indicators x_7 to x_{12}.

component loadings, in which the weights of y_1, y_2, y_3, y_4 are 0.37, 0.32, 0.17, and 0.13, respectively. from the principal component loadings, the results of the principal component weight calculations, as well as the standardised matrix for the evaluation indicators of the CC of the WE of this city for the period of 2005~2019, we obtain the first, second, second, third, fourth principal component scores and comprehensive scores of the period of 2005~2019, the calculation outcomes are demonstrated in Fig. 7, three and four principal component scores and comprehensive scores, the calculation outcomes are demonstrated in Fig. 7.

As can be seen from the comprehensive score and ranking of the city's WE CC from 2005~2019: the city's WE CC showed a decreasing trend from 2005~2009, and the pressure on the WE was alleviated from 2010~2019, and the CC of the WE was improved year by year, in which the comprehensive score of the WE CC ranked the first in 2019, and the comprehensive score was the lowest in 2009. The positive and negative of the comprehensive score of WE CC does not represent the absolute level of WE CC, but indicates the relative level of that year's WE CC compared with the average level, and the comprehensive score of WE CC in 2012~2019 is positive, and the WE CC is higher than the average level. 2005~2011 WE CC is lower than the average level.

4.4. Experiments in optimising urban water management programmes

This study analyses the water quantity forecast, water quality forecast and WE CC prediction results of Southwest cities from 2019 to 2030 obtained under the status quo continuation scenario of operational simulation, and designs the following three WE management scenarios to improve the

Table 3
Calculation results of principal component eigenvalues, contribution rates, and cumulative contribution rates

Principal component	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}	y_{12}	y_{13}	y_{14}	y_{15}
Eigenvalue	4.2	3.6	1.9	1.5	0.5	0.1	0.1	0	0	0	0	0	4.2	3.6	1.9
Contribution rate (%)	35	30.3	16	12.7	4.3	1	0.5	0.1	0	0.o	0	0	35	30.3	16
Accumulated contribution rate (%)	35	65.3	81.3	93.9	98.3	99.3	99.8	99.9	100	100	100	100	100	100	100

Table 4
Principal component load calculation results

Principal component	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}
y_1	–0.94	0.98	–0.67	–0.39	0.26	–0.75	–0.53	0.07	0.05	0.43	0.79	0.19	–0.94	0.98	–0.67
y_2	–0.3	0.18	0.56	0.24	0.87	–0.17	0.74	0.68	0.4	–0.83	0.56	–0.45	–0.3	0.18	0.56
y_3	0.01	0.01	0.43	–0.58	0	–0.53	0.38	–0.6	–0.74	–0.14	0.06	–0.17	0.01	0.01	0.43
y_4	–0.14	0.06	–0.06	0.63	0.37	0.3	0.05	–0.37	–0.5	–0.17	0.22	0.63	–0.14	0.06	–0.06

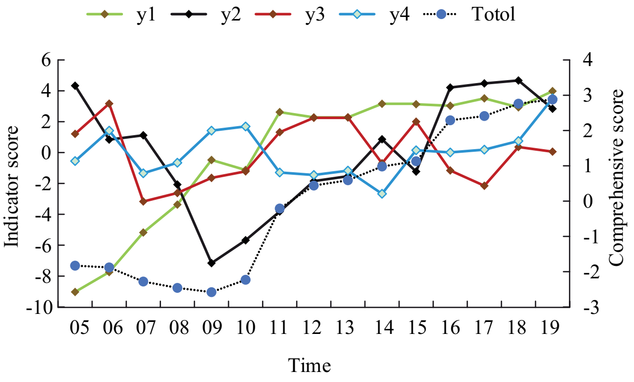

Fig. 7. Calculation results of comprehensive score of water carrying capacity in Chongqing from 2005 to 2019.

CC of the WE in the future. The first is the pollution control and reduction type programme, that is, on the basis of the continuation of the current situation, the purpose of reducing the self-purification pressure of the WE system is achieved by appropriately reducing the pollutant discharge concentration and the wastewater discharge rate. Secondly, the water conservation and environmental protection programme, on the basis of the continuation of the current programme, by reducing the amount of water used in life and production year by year, increasing the amount of ecological water consumption, increasing the reuse of wastewater, environmental protection investment, and speeding up the development of tertiary industries with low water consumption and high efficiency to achieve water conservation and environmental protection efforts. Finally, there is the integrated programme, which combines the pollution control programme with the water conservation and environmental protection programme to reduce the pressure on the water supply and self-purification of the WE system and to increase environmental protection efforts.

Combining Table 5 with the principal component analysis, it can be concluded that in the simulation results under the emission control and pollution reduction type scenario, the city's water resource environmental CC decreases year by year, and falls to the lowest in 2030, with a composite

Table 5
Comprehensive score of urban water carrying capacity from 2019 to 2030 under different management schemes

Management plan	Time	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}
Control and emission reduction plan	2020	3,409.83	31.45	24.09	23.24	0.218	3.43	5.06	15.71	1,460.75	78.23	1.6	3.18
	2022	3,444.01	29.42	23.58	21.29	0.27	3.19	4.81	16.34	1,446.25	81.38	1.53	2.83
	2025	3,495.93	26.62	23.05	18.86	0.25	2.88	4.57	17.29	1,424.77	86.12	1.42	2.38
	2030	3,584.2	22.59	22.27	15.07	0.23	2.4	4.16	20.29	1,389.68	101.06	1.25	1.78
Water-saving and environmentally friendly solutions	2020	3,409.83	30.57	24.56	24.23	0.31	3.54	5.16	15.75	1,460.75	78.46	4.98	3.65
	2022	3,444.01	25.34	25.4	24.04	0.32	3.5	5.33	16.39	1,446.25	81.62	4.87	4.26
	2025	3,495.93	19	26.97	23.73	0.34	3.44	5.66	17.34	1,424.77	86.37	4.68	5.32
	2030	3,584.2	11.7	31.03	23.31	0.4	3.33	6.52	20.35	1,389.68	101.35	4.28	7.4
Comprehensive plan	2020	3,409.83	30.57	23.73	22.56	0.24	3.32	4.98	15.75	1,460.75	78.45	4.98	3.65
	2022	3,444.01	25.34	22.86	19.53	0.23	2.91	4.67	16.38	1,446.25	81.6	4.87	4.26
	2025	3,495.93	19	22.26	15.96	0.24	2.4	4.44	17.33	1,424.77	86.3	24.68	5.32
	2030	3,584.2	11.7	23.08	11.36	0.27	1.73	4.44	20.33	1,389.68	101.27	4.28	7.45

score of –19. While under the water conservation and environmental protection type scenario, the city's resource environmental CC rises year by year, and falls to the highest in 2030, with a composite score of 10.7. While under the integrated scenario, starting from 2019, the city's WE CC composite score shows a rising trend year by year, the WE pressure decreases year by year, and the CC increases year by year. Among them, 2030 has the highest composite score and the best WE CC, while 2019 has the lowest score and the highest WE pressure. Overall, the integrated type scheme is better able to avoid future WE crises and improve the future CC of the urban WE compared to the water conservation and environmental protection scheme and the discharge control and pollution reduction scheme.

5. Conclusion

The study analyzed the level and trend of WE CC in a city in southwestern China from 2005 to 2019. Based on the specific values of evaluation indicators for each year, after forward processing, the principal component analysis method is used to obtain the comprehensive score of WE CC from 2005 to 2019, in order to determine the level and trend of WE CC from 2005 to 2019. The experimental results showed that the water resource management effect in the city was the worst in 2009, with a comprehensive score of –2.58. In 2019, the water resource CC was the best, with a score of 2.88. At the same time, the accuracy of the model was verified by comparing the error between historical actual data and SD model prediction data in this experiment. The results showed that the maximum absolute error of the SD model constructed in this study was 1.12% in the indicators of population actual value and model simulation value. In the actual and predicted values of the total water supply index, the absolute error of the SD model constructed in this study is controlled within 0.5%. The experimental results indicate that the SD model constructed in this study can be prioritized for application in urban water resource management and water CC analysis. At the same time, the prediction of the system model can optimize the mode of urban water management and adjust water resource management methods.

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