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Research on dynamic model of optimal simulation system for urban water resources sustainable utilization based on complex scientific management

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ABSTRACT

Based on the thinking tools of complex scientific management system and the principles of system dynamics, an optimal system dynamics model for urban water resources sustainable utilization is established. Based on the entropy theory in the optimization model, the integrated weights of the key factors are obtained by using the "structure entropy weight method" combined with subjective valuation method and objective evaluation method; weights and related parameters are substituted into the system, taking the Liangzi Lake District of Hubei Province as an example, the trend of water resources optimization level is simulated under three different programs of traditional urbanization, urban and rural water saving, new urbanization. The research results show that the new urbanization scheme can achieve the best level and get the maximum comprehensive benefits compared with the traditional urbanization and urban and rural water-saving schemes, which is a better plan for water resources development and utilization. This study can be used as a reference for the discussion of new urbanization water resources sustainable utilization optimization decision-making method.

Keywords: Exploring graph; Urban water resources; Sustainable utilization; System dynamics

1. Introduction

The evaluation of the sustainable use of water resources is a very important topic at home and abroad. According to statistics, about 1.5 billion people in 80 countries in the world are facing the threat of fresh water shortage. In 2025, nearly 1.4 billion people in the world will live in a severely water-deficient environment, and nearly 1 billion people will face extreme water shortages [1]. At present, the situation of urban water resources in China is very serious. Correctly assessing the state of sustainable utilization of urban water resources is the prerequisite for water resources planning, rational use of urban water resources, and sustainable urban water resources utilization.

A lot of explorations from different perspectives were made in relevant research and fruitful results were achieved. The research content involves water resources carrying capacity [2], evaluation of sustainable use of water resources [3], simulation prediction [4], rational allocation of water resources [5–7], and development trend of water resources supply and demand [8]. Since the issue of sustainable utilization of water resources involves many factors such as economic development and ecological environment, there are mutual restrictions and influences among various factors. It is difficult to use common analysis methods to comprehensively analyze the structure and function of the system. Based on system dynamics theory, the systematic analysis of the optimal level of sustainable utilization of water resources using system dynamics method can compensate for the separation of natural factors and social factors in static analysis. It is convenient to depict different water resources with different parameters. Continuously utilize the trend of change in the optimization level and get effective policy control models. In view of this, this paper takes the Liangzi Lake District of Hubei Province as the

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research object, and a preliminary system model of urban water resources sustainable utilization is built based on the exploration tool of the complex scientific management system thinking tool; on this basis, water supply and demand, social-economic and ecological subsystems status quo, evolution rules, feedback effects and action mechanisms between subsystems were discussed, a dynamic model for the optimal use of water resources is proposed. By adjusting and controlling the parameters, the different water resources optimization schemes of urbanization and water resources coordinated development were simulated. Different models were compared and selected, and corresponding countermeasures for sustainable and optimal utilization of water resources have been put forward.

2. A preliminary system model for urban water resources sustainable utilization based on exploration graph

Exploration graph is the perspective illustration by using a complex scientific management system thinking model. Through the investigation of the overall environment, the researchers use a larger environmental consideration to create it based on their own experience, knowledge and information and create imagination. The formation of this graph is a process of collective creation. It shows all the factors that will influence or may affect the research topic [9,10].

The steps for forming an exploration graph of the sustainable use of urban water resources are as follows:

First, 6–8 experts related to the research topics were convened to discuss the decision-making issues; secondly, the moderator asked questions based on the decision-making questions and the experts thought; and thirdly, the experts presented their opinions according to their respective backgrounds and experiences. A number of ellipses on the paper indicate the factors that affect the theme; fourth, after the experts express themselves fully, the visual analysis of the elliptical representation area starts from the whole, eliminating redundant and synthetically identical elements, and connecting the same types of factors. Connect, and then use random circles to circle various factors, add ellipses to the ellipse of the deleted factors; fifth, name each irregular circle, use an ellipse to represent each; sixth, use two-way arrows to indicate the factors. The interactive relationship between them is classified as an interactive exploration graph. After the careful arrangement, exploration graph of urban water resources sustainable utilization evaluation is formed, namely, the preliminary system model of urban water resources sustainable utilization, as shown in Fig. 1.

3. Construction of optimization simulation model for water resources sustainable utilization based on system dynamics

3.1. Research method - system dynamics model

The system dynamics model is a computer simulation model system based on the theory and method of system dynamics, which is used to study the dynamic behaviour of complex system [11,12]. It is not based on abstract assumptions, but on the premise of the existence of the real world. It does not pursue the "best solution," but instead seeks opportunities and ways to improve the system's behaviour from the whole. Technically, it is not based on the theory and method of system dynamics, which is used to study the dynamic behaviour of complex system. It does not rely on the derivation of mathematical logic to obtain an answer, but rather establishes a dynamic simulation model based on actual observations of the system and obtains a description of the system's future behaviour through computer experiments. The general process of system dynamics modelling is put forward: identify the problem; propose the structural assumption of the system; start from the assumptions, design the system's causality diagram, flow diagram, and list the equations; define the parameters, simulation, and test or modify the model (parameters), strategic analysis and decision-making.

3.2. Simulation hypothesis and system boundary setting

According to the construction steps of the simulation model, the boundary of the model needs to be delimited, but the boundary of the model system is actually only an abstract outline, which needs to circle the problems considered for the purpose of modelling into the system and separate other issues that are not considered. The system boundaries should contain concepts and variables that have important relationships with the issues under study. Therefore, according to the preliminary model of the system analyzed above and the purpose of constructing the simulation model of supply and demand optimization, the key factors are selected to study the action intensity of different factors on their respective safety level, so as to dynamically predict the optimization level of urban water resources sustainable utilization and maximize the comprehensive benefits.

The basic assumptions of this research are as follows:

(1) Factors related to the optimal system for the sustainable utilization of water resources are divided into four parts: water supply subsystem - water demand subsystem - social and economic subsystem - ecological environment subsystem. Only the important factors of previous research are considered, and other minor factors are ignored.

(2) Resource variables such as urbanization rate, environmental investment rate for GDP ratio, sewage treatment rate, water quota, etc. will change with time, but this change is slower, so they are entered into the model as constant form, and does not occur during simulation. They will be changed only when the policy changes the regulation model;

(3) The relevant variables in the ecological environment subsystem are only calculated as auxiliary variables and are not calculated as state variables.

3.3. Simulation flow graph model for urban water resources sustainable utilization

The method of SD rate-variable fundamental in-tree is used to establish the model. First the system is divided into different subsystems, and starts from the relationship of

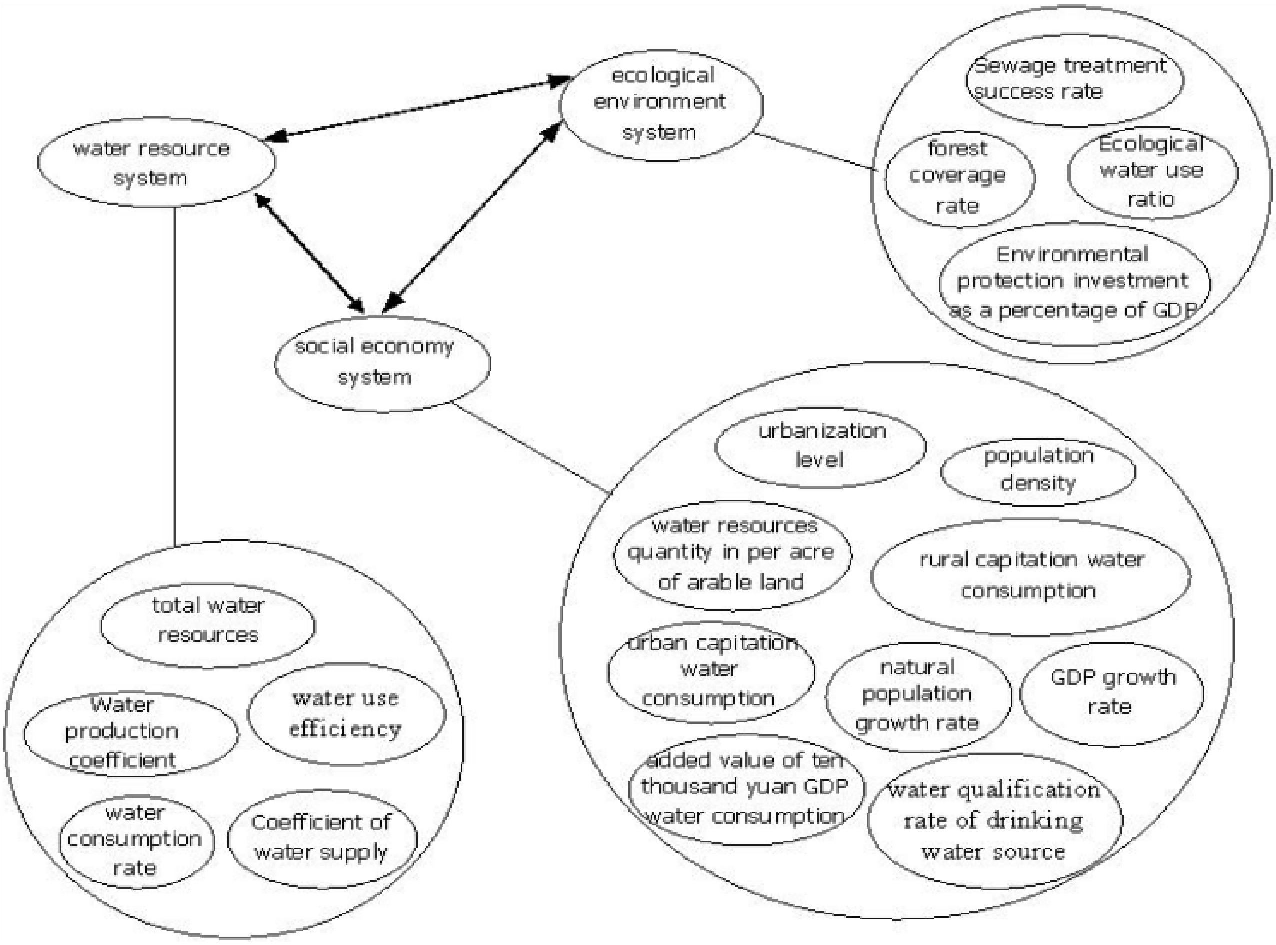

Fig. 1. A preliminary model of urban water resources sustainable utilization.

resources, population, economy, society and environment, interaction and mutual restraint in the system, and four subsystem simulations are constructed respectively. Then, matrix, feedback loop and other related theories are used to carry out a comprehensive integration of various subsystems to generate a dynamic simulation model of water resources sustainable optimization simulation system model.

The water supply system is mainly affected by the reclaimed water reuse, the available water supply, the GDP in the Liangzi Lake region etc. The main influencing factors of water demand subsystem are four aspects: water demand for life, water demand for production, urban public ecological water demand, gap of supply and demand, and interact with other factors. The social and economic system is affected by the total population, total water requirements, GDPs of Liangzi Lake region, industrial added value and other factors. The subsystem of ecological environment is mainly influenced by factors such as discharge of waste water, reclaimed water reuse, forest coverage and other factors.

According to the system dynamics in-tree model, the sub-system risk simulation flow graph model can clearly identify the factors that affect the sustainable utilization of water resources and the resulting results. From the feedback effect and action mechanism between the subsystems, the simulation model of the four subsystems is integrated, and the dynamic model of the urban water resources sustainable utilization optimization system is constructed as shown in Fig. 2, which shows the urban water resources system completely. Different factors are connected by the influence coefficient. The size of the influence coefficient determines the correlation strength between these factors. The optimization level of water resources system is controlled by the management level of each subsystem.

3.4. Selection of simulation variables and establishment of system dynamics equation

According to Fig. 3, the main variables in the model are as follows:

There are four level variables: management level of water demand subsystem, management level of water supply subsystem, management level of social - economic subsystem and management level of ecological environment subsystem.

There are four rate variables: Water demand subsystem management capacity increase/decrease, water supply subsystem management capacity increase / decrease, social and economic subsystem management capacity increase/decrease, ecological environment subsystem management capacity increase/decrease.

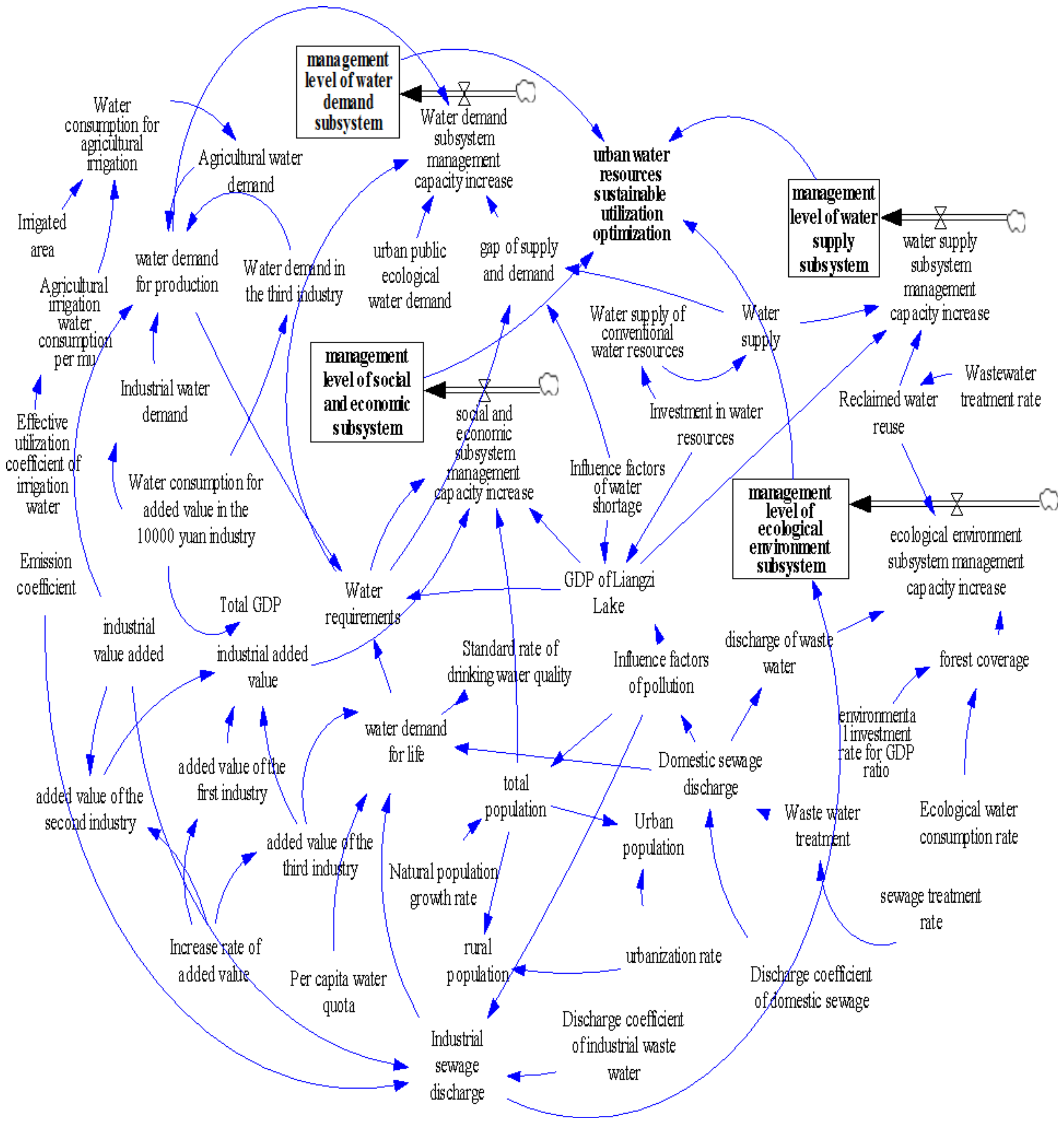

Fig. 2. Dynamic model of the urban water resources sustainable utilization optimization system.

There are 25 auxiliary variables such as water demand for life, water demand for production, total population, discharge of waste water etc.

Constants: Those system parameters that change little or not at the time considered are considered constant. The parameters in the model are constant values, table functions, initial values, and so on.

There are 33 system dynamic equations in the model, including 4 level variable equations, 4 velocity variable equations and 25 auxiliary equations.

3.5. Simulation parameter determination and model test

The determination of the parameters in the model is the precise definition of the role of each relevant variable, and it is the basis for model application and simulation. The assignment of variables first requires collecting a wide range of practical data, and then using relevant mathematical methods to meet the needs of system dynamics variables, and ultimately determine the parameter values. The mail concern is the determination of the constant value, the determination

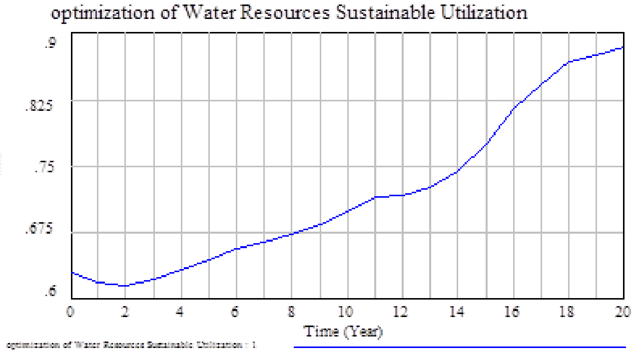

Fig. 3. Tendency chart for the optimization of water resources sustainable utilization.

of the initial value of the level variable, the determination of weight. Among them, the determination of constants and initial values, such as the amount of water resources, the supply of water resources, and social-economic development data, have been were calculated and compiled through the "Hubei Statistical Yearbook" (2010–2017) and the "Hubei Water Resources Bulletin" (2010–2017) and "Environmental Bulletin of Hubei Province" (2010–2017).

The determination of weights involves several aspects of weighting. First, proportion of the management level of water demand subsystem, proportion of the management level of water supply subsystem, proportion of the management level of social-economic subsystem, and proportion of the management level of ecological environment subsystem in the entire water resources sustainable utilization optimization system. Secondly, the proportion of impact factors in the water demand subsystem, the water supply subsystem, the social-economic subsystem, and the ecological environment subsystem. Thirdly, when there are multiple sub-factors in the partial impact factor, the proportions of the factors needs to be determined. The structural entropy weight method is used to obtain the weight of each indicator. The steps are as follows [13]:

a) The Delphi method forms the "initial sort". According to the Delphi method, a questionnaire was sent to a group of experts, and the importance of the index set to be evaluated in the questionnaire was judged. By statistical feedback, the experts' ranking opinion finally formed was "initial sorting".

b) The "literacy" analysis of the "initial sort" was carried out. Experts' initial sorting is prone to have potential deviations and uncertain trace-ability data because of subjectivity. Therefore, qualitative analysis is needed in the previous step (a), and entropy theory is used to calculate its entropy value to reduce its bias and uncertainty.

Suppose there are k experts, and obtain k tables. Each table corresponds to an index set, denoted as $U = (u_1,u_2,..,u_n)$. Index set corresponding to the "typical sort" array, denoted as $(a_{i1}, a_{i2}, ..., ai_n)$. Sorted matrix is obtained by the k index tables, denoted by $A = (a_{ij})_{k\times n}$, $i = 1, 2, ..., K; j = 1, 2, ..., n$ which a_{ij} shows the evaluation of the expert i to the indicator u_j.

For the qualitative and quantitative transformation of "initial sequencing", the entropy function of the definition transformation is as follows:

$$x(I) = -\lambda p_n(I) Inp_n(I) \tag{1}$$

In them, make $p_n(I) = \frac{m-1}{m-1}$ take $\lambda = \frac{1}{In(m-1)}$, $\frac{x(I)}{\left(\frac{m-1}{m-1}\right)} - 1 = u(I)$ the Eq. (1) can be reduced to:

$$u(I) = -\frac{\ln(m-I)}{\ln(m-1)} \tag{2}$$

I is sorting number, which is given by experts according with the "typical sort". m is transformation parameter, and make $m = j + 2$, $I = a_{ij}$ into the Eq. (3), $h_{ij}(u(a_{ij}) = h_{ij}$ is obtained, $H = (h_{ij})_{k\times n}$ is membership matrix. The "consensus" of index u_j from K experts, is the average degree of knowledge, denoted by $h_j = h_{1j} + h_{2j} + ... h_{kj}/k$. Uncertainty generated by the perception known as the "degree of understanding of the blind", namely Q_j:

$$Qj = \left| \frac{\{[\max(h1j, h2j, ..., hkj)] - [\min(h1j, h2j, ..., hkj) - hj]\}}{2} \right| \tag{3}$$

To each u_j, overall degree of understanding of k experts about u_j is x_j, $x_j = h_j(1-Q_j)$. Evaluation vector of K experts about u_j is $X = (x_1, x_2, ..., x_n)$.

c) Normalized,

$$W_j = \frac{x_j}{\sum_{i=1}^{m} x_j} \tag{4}$$

Taking the determination of the first level weights as an example, the experts are divided into three groups. Then, these experts are asked to judge the importance of the evaluation index separately, and the "initial sorting" of "expert opinion" is collected. The weights are calculated by the structural entropy weight formula (1) - (4), as shown in Table 1.

Based on the data of 8 years from 2010 to 2017, using the above-mentioned established system dynamics flow diagrams and equations, the target value of the water resources optimization level of the system is set to the dimensionless value of 0.9. VENSIM -PLE software is used to simulate and verify the model, and then the initial value is adjusted and modified by experts; the established model meets the requirements of system dynamics and has high credibility.

4. Simulation scheme and analysis of simulation results

4.1. Simulation operation

The time boundary of the model simulation is from 2017 to 2037, and the running step is 1 years. The initial value is

Table 1
The first level weights

Calculation	Water demand subsystem	Water supply subsystem	Social-economic subsystem	Ecological environment subsystem
The first group	1	3	2	3
The second group	3	4	1	2
The third group	2	2	1	4
h_j	0.8480	0.6582	0.9538	0.6582
Q_j	0.0067	0.0122	0.0231	0.0122
x_j	0.8423	0.6502	0.9318	0.6502
W_1	0.2740	0.2115	0.3031	0.2115

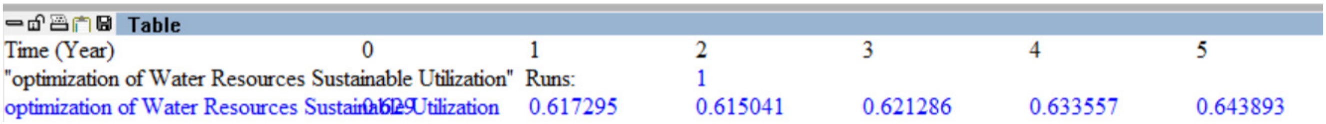

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Table
Time (Year)                                              0          1          2          3          4          5
"optimization of Water Resources Sustainable Utilization" Runs:                1
optimization of Water Resources Sustain0.629Utilization  0.617295   0.615041   0.621286   0.633557   0.643893
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Fig. 4. Value of the optimization model of water resource sustainable utilization.

substituted into the equation. After clicking "run a simulation", the system enters the simulated state. After clicking on the optimized utilization of water resources and then clicking the Graph button, the simulation running curve can be formed. The trend of the development of sustainable utilization of water resources can be clearly seen from the graph, as shown in Fig. 3.

From Fig. 4, it can be seen that, the optimization model of water resources sustainable utilization overall showing a slow upward trend from 2017 to 2037, the number of optimized water values in 2037 is 0.883303, less than 0.9. It has not yet reached the level of goal setting value system optimization. Click the Table button, the specific value of the optimization model of water resource sustainable utilization is obtained in the entire simulation cycle (20 years), as shown in Fig. 4.

4.2. Selection of program for parameter change

Under different development conditions, the optimal operation system of urban water resources sustainable utilization is different. In order to obtain the comprehensive development and utilization of water resources with both social and economic benefits and eco-environmental benefits through a parametric regulation model, by adjusting the combination of several variables, three simulation schemes are established. They are a traditional urbanization development program, urban and rural water-saving development program and new urbanization development program. The three simulation plans are respectively represented by no. 1, no. 2 and no. 3. The traditional urbanization program (no. 1) is to keep the current parameters unchanged; the urban and rural water-saving program (no. 2) is based on the traditional urbanization plan, the urbanization rate and irrigation rate are increased, the per capita water consumption quota is reduced and other parameter values are changed; the new urbanization program (no. 3) is based on the urban and rural water-saving development plan, and the parameters such as the sewage treatment rate and reuse rate, and increase the water investment funds are increased.

The parameters of the three schemes are input to the system, and the simulation results are obtained through the simulation of the three schemes, as shown in Fig. 5. The results show that the traditional program has not reached the optimization level in the 20th year, and the urban and rural water-saving program has reached the optimization level target value in the 18th year, while the new urbanization program reached the optimization level target value in the 16th year, which is which is two years earlier than the water-saving program.

The variation trend of water requirement gap of supply and demand, GDP of Liangzi Lake and reclaimed water reuse are shown in Figs. 6–9.

Figs. 6–9 present the results of three programs. It can be seen from that, the gap between the supply and demand of water resources in the traditional program has been increasing year by year; the water supply and demand gap in the water saving program has increased year by year, but the contradiction between the supply and demand of water resources has been improved under the water saving measures. and the gap has been gradually reduced since 2035; in the new urbanization program, the supply and demand gap first increased and then decreased. By 2037, the balance between water supply and demand was basically achieved, the water supply capacity became surplus, and the GDP and recycled water reuse amount was the highest among the three programs. Comparing with the other two development programs, under the new urbanization development plan in Liangzi Lake District, the water resources supply can basically meet the needs of social and economic development, the highest gross domestic product can be obtained with the least water consumption. The efficiency of water use is the highest, the degree of water shortage and water environment pollution, and its impact on social and economic development are also lower than those of the other two development schemes. The results show that the new urbanization program is the preferred option among the three options.

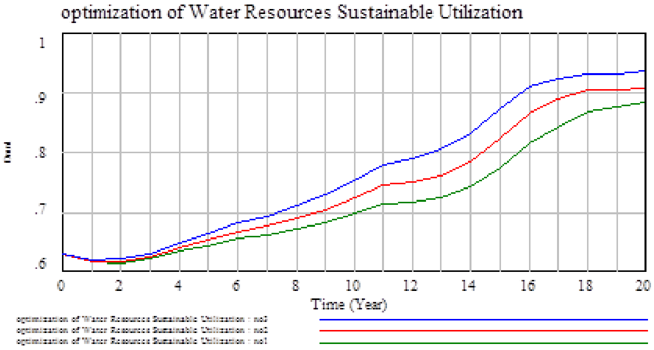

Fig. 5. Tendency charts for the optimization of water resources sustainable utilization of three plans from 2017 to 2037.

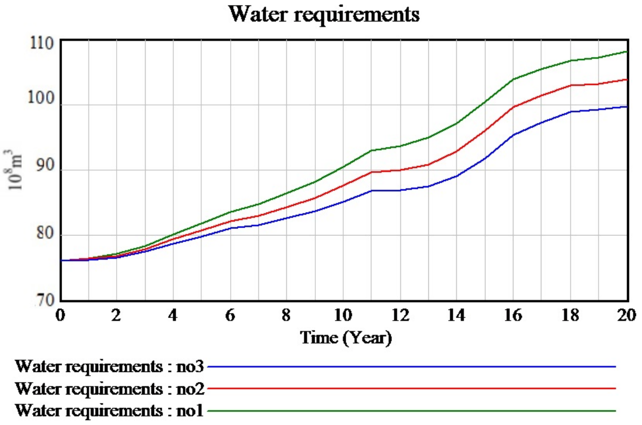

Fig. 6. Tendency charts for the water requirements

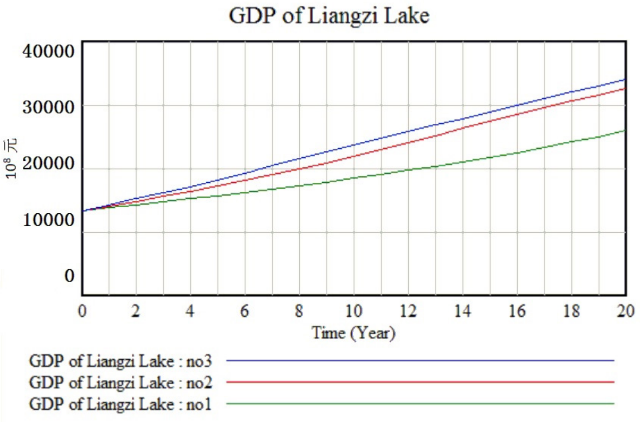

Fig. 7. Tendency charts for GDP of Liangzi lake.

5. Conclusion

Based on the complex scientific management theory, a preliminary system model of water resources sustainable utilization optimization is constructed in this paper. On this basis, Liangzi Lake District in Hubei Province is taken as the research object and the system dynamics model of urban water resources sustainable utilization is proposed. The model can make up for the separation of natural factors

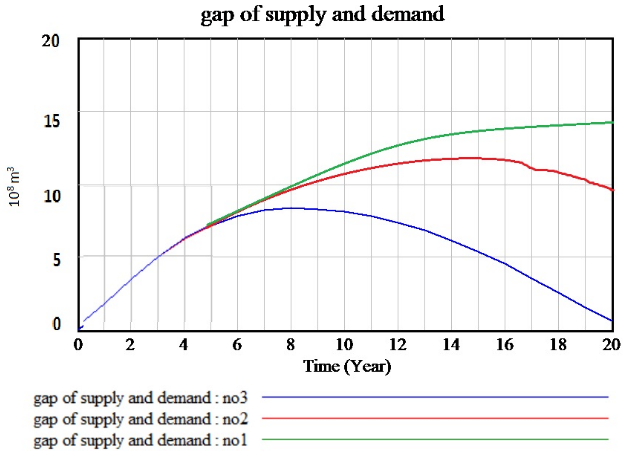

Fig. 8. Tendency charts for the gap of supply and demand.

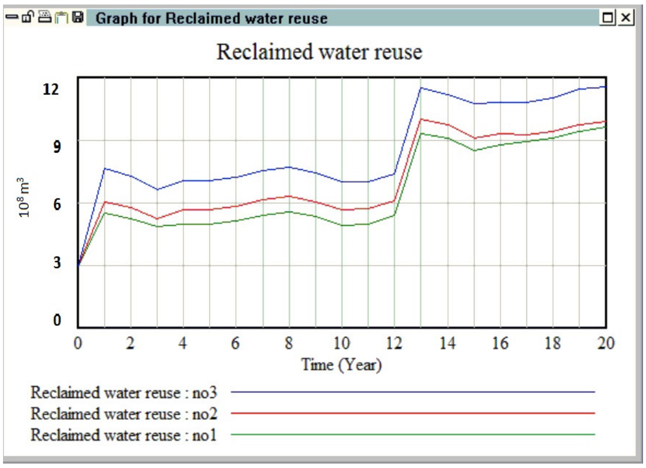

Fig. 9. Tendency charts for the reclaimed water reuse.

and social factors in static analysis, and it is convenient to describe the trend of sustainable utilization of water resources under different plans. In this model, the structure entropy weight method is used to determine the weight of the index. By setting different parameters, the trend of water resources optimization level is simulated in Liangzi Lake from 2017 to 2037 under three different programs of traditional urbanization, urban and rural water saving, new urbanization. The research results show that the new urbanization plan is the best of the three programs. In order to alleviate the shortage of water resources and serious water pollution in Liangzi Lake region, it is necessary to actively promote the recycling of water resources and bring the recycled water, surface water and groundwater into the unified allocation of water resources.

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References

[1] S.R. Basu, H.A. Main, Calcutta's water supply: demand, governance and environmental change, Appl. Geography., 21(1) (2001) 23–44.

[2] C. Wang, Y. Hou, Y. Xue, Water resources carrying capacity of wetlands in beijing: analysis of policy optimization for urban wetland water resources management, J. Cleaner Prod., 161(9) (2017) 1180–1191.

[3] I. Halkijevic, Z. Vukovic, D. Vouk, Indicators and a neuro-fuzzy based model for the evaluation of water supply sustainability, Water Resour. Manage., 31(12) (2017) 3683–3698.

[4] X.U. Xukan, Y. Zhao, C. Cheng, Early-warning grading of sustainable utilization of water resources in Xi'an city, Water Resour. Protect., 33(5) (2017) 25–30.

[5] M.H. Davijani, M.E. Banihabib, A.N. Anvar, S.R. Hashemi, Optimization model for the allocation of water resources based on the maximization of employment in the agriculture and industry sectors, J. Hydrology, 533(1) (2016) 430–438.

[6] D. Liu, S. Guo, Q. Shao, P. Liu, L. Xiong, L. Wang, X. Hong, Y. Xu, Z. Wang, Assessing the effects of adaptation measures on optimal water resources allocation under varied water availability conditions, J. Hydrology, 556(1) (2018) 759–774.

[7] Z. Hu, Y. Chen, L. Yao, C. Wei, C. Li, Optimal allocation of regional water resources: from a perspective of equity–efficiency trade off, Resour. Conserv. Recycl., 109(5) (2016) 102–113.

[8] X. Ying, L.I. Jingzhi, D. Jiang, Optimized decision-making of water resources supply and demand system in changsha-zhuzhou-xiangtan urban agglomeration based on the analog simulation, Acta Geograph. Sinica, 68(9) (2013) 1225–1239.

[9] X. Xu, X. Zheng, Qualitative analysis tools: probe graph, cycle graph and structure graph, Technol. Econ., 29(5) (2010) 1–6.

[10] L. Shi, Y. Li, Research of urban water resources sustainable utilization evaluation model based on the exploration diagram, Energy Educ. Sci. Technol. Part A: Energy Sci. Res., 32(6) (2014) 5239–5244.

[11] M.M. Matinzadeh, J.A. Koupai, A. Sadeghi-Lari, H. Nozari, M. Shayannejad, Development of an innovative integrated model for the simulation of nitrogen dynamics in farmlands with drainage systems using the system dynamics approach, Ecol. Model., 347(3) (2017) 11–28.

[12] G. Li, Y. Li, X. Jia, L. Du, D. Huang, Establishment and simulation study of system dynamic model on sustainable development of water-Energy-food nexus in beijing, Manage. Rev., 28(10) (2016) 11–26.

[13] L. Shi, F. Luo, Research on risk early-warning dynamic evaluation of logistics service supply chain-based on structure entropy weight-Markov analysis, J. Software Eng., 9(4) (2015) 858–867.