Research on Metabolic Steady State Model of Urban Complex Water Circulation System from the Perspective of Quantitative Coupling

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***Abstract*—Urban complex water circulation system as a complex and open ecosystem, once the water metabolism imbalance will cause urban water security problems. In this paper, we use the system dynamics as the basic analysis tool, from the perspective of water quality and water coupling metabolism, according to the Haihe River Basin in Tianjin as a case study object, analysis of urban complex water circulation system metabolic steady-state structure mechanism, and on this basis, the system dynamics model of metabolic steady state of urban complex water circulation system is established, and the complex metabolic process of water and quantity of urban complex water circulation system is clarified, which provide the theoretical basis for the development of urban water metabolic steady-state control policies and programs so as to achieve the goal of reducing the probability of urban water safety.**

***Index Terms*—urban complex water circulation system, water metabolism, system dynamics**

I. INTRODUCTION

The urban water cycle is accompanied by the continuous expansion of social and economic activities, the competition of water in different industries, the contradiction between environmental capacity and discharge, the shortage of urban water resources and the increase of urban water environment pollution, which leads to the weakening of the natural attributes of urban water cycle and the enhancement of social attributes, showing the “natural – social” dual characteristics [1], and the healthy operation of urban water cycle is based on urban water metabolism to achieve the amount of supplement and quality improvement. Urban water cycle is currently facing the economic and social activities of the excessive disturbance and human activities strong interference, making the water cycle system imbalance uncertainty factors are increasingly complex, thus affecting the urban water metabolism process of steady-state imbalance, leading to urban water security and water supply and demand problems. According to the research data at home and abroad, it is found that the research of urban water metabolism has been explored in the study of its theory, structure and sustainable development. However, its theoretical basis and basic characteristics need to be studied deeply, and in the process of water metabolism water quality and water quantity changes in the study is relatively rare [2]. The metabolic steady - state structure model of urban complex water circulation system is proposed, and the mechanism of urban water metabolism is revealed from the perspective of deeper urban water metabolism. In this paper, the concept of complex system is introduced, and the concept of sustainable metabolism of urban complex water circulation system is studied with quantitative coupling as the fundamental perspective, the concept and theoretical system of urban water metabolism are perfected, and the implementation of man-made measures is realized to maintain and ensure the urban complex water circulation System of metabolic process of stable operation, so as to achieve the purpose of ensuring urban water security and water supply and demand [3, 4].

II. MATERIAL AND METHODS

In this paper, the complex system concept is introduced into the process of metabolic steady-state structure and its model of urban complex water circulation system, and the system dynamics is used as the basic analysis tool [5, 6], the Haihe River Basin in Tianjin city as the goal of city, the metabolic steady-state structure and its system dynamics model of urban complex water circulation system were analyzed, and the metabolic boundary of urban complex water circulation system based on water quality and water was determined and its metabolic subsystem was divided, construct urban complex water cycle System metabolic structure feedback loop and select the metabolic structure of the variable parameters, and then to achieve the city complex water cycle metabolic steady-state model construction and water quality and water quantity coupling metabolic process evolution simulation. The research method is as follows:

A. Determination of Metabolic Boundary of Urban Complex Water Circulation System Based on Water Quality and Water Quantity

Determining the metabolic boundary of the urban complex water circulation system is to clarify the boundaries of the studied system and to ensure that all relevant factors are included in the research boundary and to ensure that the system boundary is closed. The object of this study is the Haihe River Basin in Tianjin. This area has a complete administrative structure, industrial structure, resource system and relatively stable population structure, so it can be regarded as a system for research. In addition, the delineation of the metabolic boundary of urban complex water circulation system will be faithful to the excavation of the urban complex water circulation system body and its water quality and water quantity coupling metabolic logic, and as a guide to the system involved in a large number of statistical significance and quantification of the constant and variables to judge and make a screening. However, due to the complex relationship between the metabolic processes of urban complex water circulation system, not only in the internal sub-structural system, but also there is an exchange of inseparable material energy between the outside world, which leads to the ambiguity of the metabolic boundary. The above considerations, the delineation of metabolism boundary will be based on the following criteria: a. There is a strong and frequent material exchange with the metabolic process; b. Within the boundaries of the elements of the relationship between easy to grasp; c. Data is sufficient and available and statistical caliber consistent.

B. Identification of Metabolic Subsystem of Urban Complex Water Circulation System Based on Water Quality and Water Quantity

Urban complex water circulation system is a complex system involving population growth, economic development, resource consumption and ecological environment with strong influence of social and economic activities, and its metabolic system is interlocking and constraining each other. According to the actual situation of the target city, based on the metabolic structure of urban complex water circulation system, the metabolic subsystem of urban complex water circulation system is divided into three subsystems: urban water metabolism supply subsystem, urban water metabolism generation subsystem and urban water metabolism treatment subsystem (as shown in “Fig. 1”), the three parts can be through the material and energy input and output interrelated to form a city water quality and water coupling metabolic structure of the feedback loop [7, 8].

The urban water metabolism supply subsystem is used to estimate the total supply of water resources in the study area. The water supply here refers to the total supply of water, including the existing water in the area, the use of sewage regeneration, rainwater harvesting and the amount of water transferred from the area. The availability of these water sources can be estimated from local water resource development rates, renewable wastewater use rates, rainwater harvesting rates, and quotas for external water transfers.

The urban water metabolism generation subsystem is used to assess the needs of different objects for water and the amount of sewage discharged. The main water bodies including domestic water, industrial production water, agricultural production water, service industry, production water and ecological water use, etc. Among them, the demand for domestic water can be estimated by the size of the population and the per capita consumption in the region, and the demand for industrial economic water can be estimated by GRP and GRP water consumption in different industrial sectors in the region. Life and tertiary industry sewage emissions can be estimated by population size and per capita sewage discharge load, the second industry sewage emissions can be GRP and unit GRP sewage discharge load estimates.

The urban water metabolic treatment subsystem is used to estimate the amount of sewage discharged into natural water bodies. The subsystem mainly includes the following cases: unprocessed direct discharge, the user after the discharge, after sewage treatment facilities and water treatment facilities, such as emissions after treatment. Among them, the amount of water discharged after the treatment of sewage treatment facilities and water treatment facilities can be estimated by the sewage treatment rate in the area.

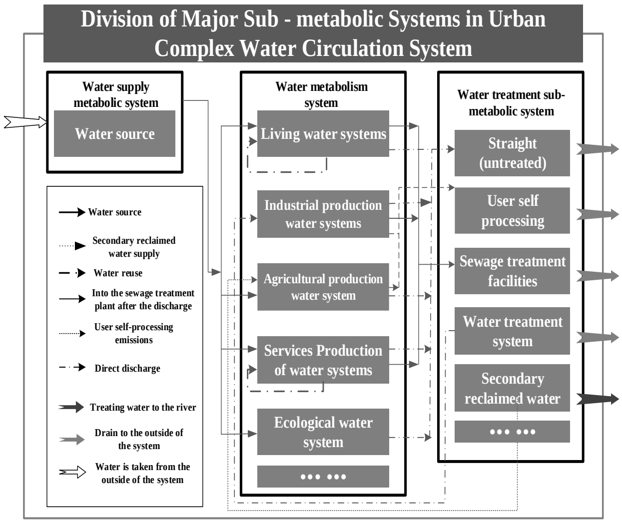

Figure 1. Urban complex water circulation system the main sub-metabolic system division.

C. Construction of Metabolic Structure Feedback Loop in Urban Complex Water Circulation System

Based on the SD simulation modeling technology, the important prerequisite for the construction of the metabolic steady-state structure model is to clarify the logical relationship between the sub-metabolic simulation structures and the inter-causal causal relationship between them. This series of causal logical relations constitute a closed Structure of the feedback loop. Therefore, according to the SD simulation modeling technique, the internal logic relationship between the metabolic whole process and the metabolic simulation structure of the urban complex water circulation system is analyzed deeply, and then the feedback loop is constructed.

There are four parameters in the metabolic process of urban complex water cycle system: the total population of the city, the irrigated area, the number of livestock and the industrial added value. There are three feedback loops associated with the metabolic process of the complex water circulation system in the city, as shown in “Fig. 2”.

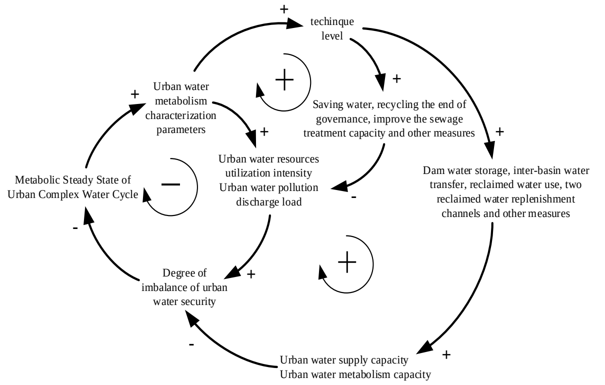

Figure 2. Basic feedback loop of metabolic processes in urban complex water circulation systems.

The first feedback loop: urban water metabolic characterization parameters (total urban population, irrigated area, number of livestock, industrial added value) →+ urban water use intensity and urban water pollution emissions load →+ urban water safety status imbalance and Urban water supply and demand disorder degree →- urban complex water cycle metabolic steady state →+ urban water metabolism characterization parameters (+ positive feedback, - negative feedback).

The second feedback loop: urban water metabolic characterization parameters (total urban population, irrigated area, number of livestock, industrial added value) →+ technical level →+ take certain measures →- urban water use intensity and urban water pollution discharge load →+ urban water safety status imbalance and urban water supply and demand disorder degree →- urban complex water cycle metabolic steady state →+ urban water metabolism characterization parameters.

The third feedback loop: urban water metabolism characterization parameters (total urban population, irrigated area, number of livestock, industrial added value) →+ technical level →+ take certain measures →- urban water supply capacity and urban water pollution capacity →+ urban water safety status imbalance and urban water supply and demand disorder degree $\rightarrow^{-}$ urban complex water cycle metabolic steady state $\rightarrow^{+}$ urban water metabolism characterization parameters.

D. Selection of Metabolic Structural Variable Parameters in Urban Complex Water Circulation System

Based on the coupled metabolic structure feedback loop of urban water quality and water supply, the main variables and parameters (such as urban population, agroforestry area, industrial water reuse rate, reclaimed water supply, etc.) can be described in the metabolic steady state structure of urban complex water circulation system, according to the correlation between the variables and the parameters, the construction of the logical equations of the variables and the determination of the value of the table functions are carried out for each sub - metabolic system [9]. Finally, the relationship between the sub-metabolic system and the parameter variables in the feedback loop is extracted, and the flow relation among the variables is shown in “Fig. 3”, and the dynamic simulation of the system is simulated, and then the construction of the subsequent steady-state model is carried out. In addition, in order to ensure the rationality and accuracy of the model, the value of the variable parameters mainly comes from the annual survey of the target city, the environmental management target assessment results, the environmental quality report, the relevant planning, census, economic census and other information.

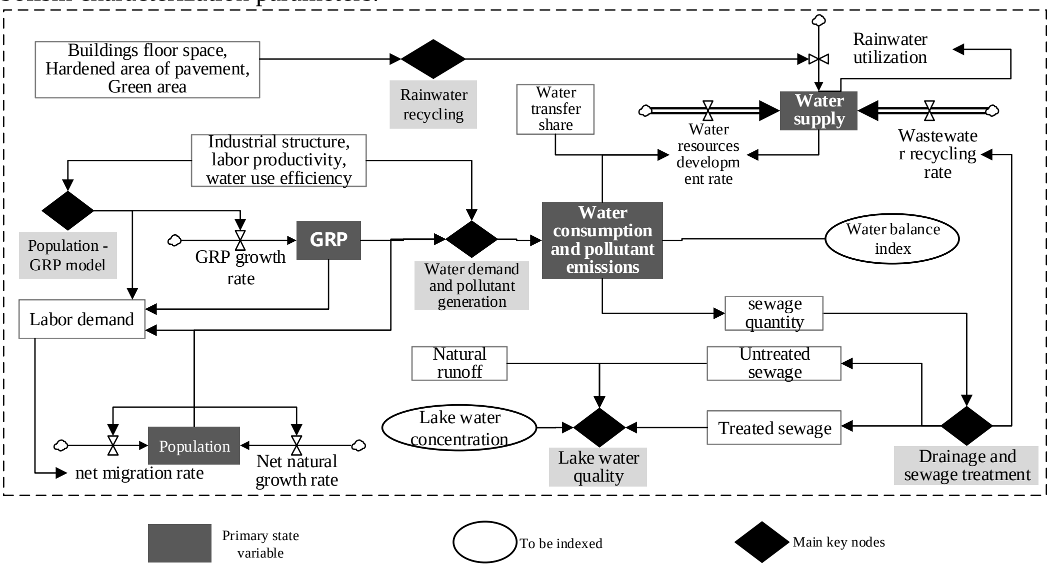

Figure 3. Schematic diagram of the flow relation of the main parameter variables in the metabolic process of urban complex water circulation system.

III. RESULT

A. Construction of Metabolic Steady - state Model for Urban Complex Water Circulation System

The metabolic steady state structure and its conceptual model of urban complex water circulation system are the necessary prerequisites for the steady state control of water metabolism. From the perspective of complex water circulation system, the identification of metabolic steady-state structure and the construction of its conceptual model are designed to analyze the water quantity and water quality characteristics of supply, consumption and discharge units in urban natural water cycle and social water cycle (dual water cycle), explores the relationship between the interaction of water quality and water quantity content and the transformation relationship between the constituent elements, and clarifies the internal structure and its relationship between the sustainable development of water quality and water supply in urban complex water circulation system.

Using system dynamics simulation modeling technology as the basic analysis tools, based on the domestic and foreign research status quo and development trend, the concept of complex system is introduced into the complex water circulation system of the city, and its metabolic steady-state structure and conceptual model are defined and analyzed to analyze the trend of evolution, the key elements of the metabolic steady-state structure of the system are identified and the abstract generalization of the model is carried out, the definition of metabolic homeostasis structure behavior subject and its behavior characteristics, explore the relationship between the elements of the interaction and transformation, and provide the theoretical basis for the management of the metabolic process of urban complex water circulation system and the guarantee of the safety status and supply and demand of urban water quality and water. The system dynamics model is shown in “Fig. 4”:

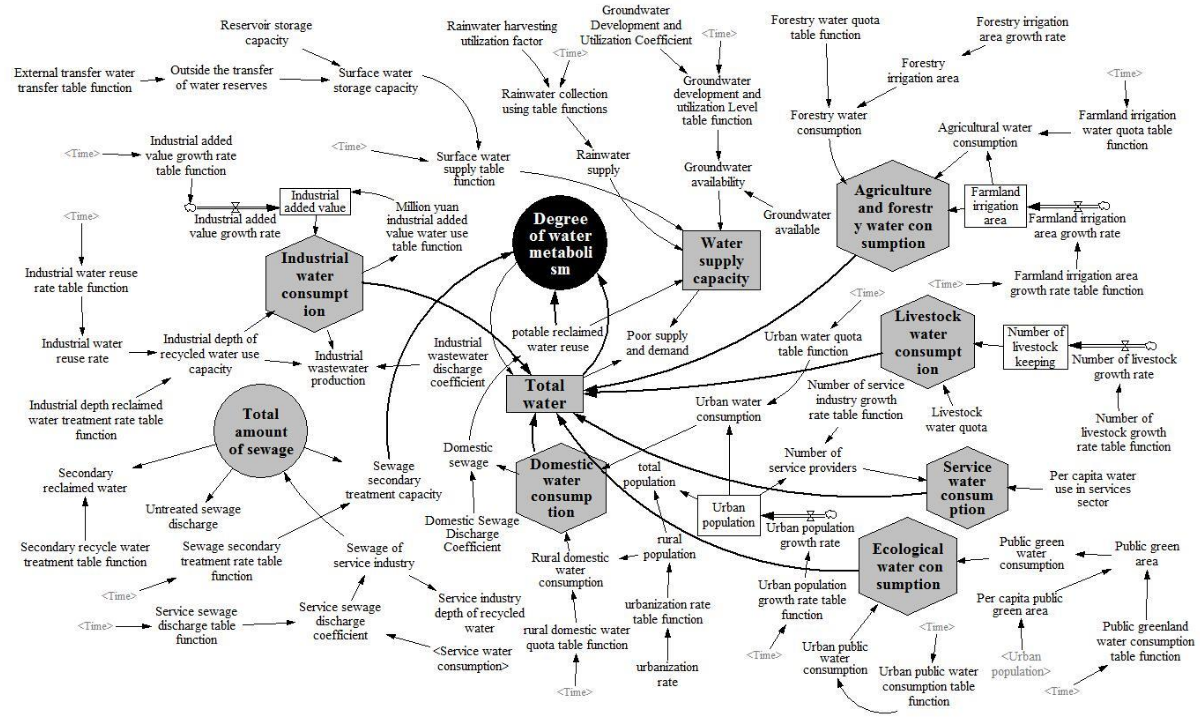

Figure 4. System dynamics model of metabolic steady - state model for urban complex water circulation system.

B. Metabolic Steady State Model Test for Urban Complex Water Circulation System

The model test includes the system validity test and the sensitivity test. Based on the purpose of modeling and the basic idea of system dynamics model test, the system dynamics model was established by Vensim software, the dynamic model of metabolic steady state system of urban complex water circulation system was tested, the validity test of the model is the key link of the model detection, which can be compared by the historical actual value and the simulation results. The model is selected from 2010s to 2020s, based on 2010s as the base year, the simulation step is 5 years, compared with 2010s to 2014s the actual data and simulation data test model, model validity test using historical statistics Mainly from the "Tianjin Statistical Yearbook" and other relevant data. According to the historical data from 2010s to 2014s as the test basis, some indicators change over time, these indicators are given in the form of table function, and the relationship between variables is not clear indicators are given in the form of table function. In this paper, the relative error method was used to test the metabolic steady-state model of urban complex water circulation system. The total population (unit million), GRP (unit billion), water supply (unit billion m^3), treated from sewage plant (unit million tons) as the main variable, 2010s to 2014s compared to the actual data and simulation data, the summary results shown in Table 1, as can be seen from Table 1, 2010s to 2014s the main variables of the actual historical data and simulation data of the maximum average error of all the small 5%, high accuracy of fitting, relative error test results are ideal. It can be seen that the dynamic model of metabolic steady-state system of urban complex water circulation system in Haihe River Basin of Tianjin can reflect the operation of metabolic process of the regional system to a great extent.

Table I.
Test Error Values for Each Major Variable.

Variable (year)		2010s	2011s	2012s	2013s	2014s
Population/Million	Actual	12.99	13.55	14.13	14.27	15.17
	Simulation	12.85	13.52	14.17	14.73	15.30
	deviation	1.09%	0.16%	0.26%	0.07%	0.89%
GRP/Billion	Actual	9224.46	11307.28	12893.88	14442.01	15726.93
	Simulation	9198.69	11226.56	13097.86	14876.34	16479.87
	deviation	0.38%	0.71%	1.58%	3.01%	4.79%
Water supply/Billion m^3	Actual	689.70	744.83	772.18	786.31	812.49
	Simulation	679.55	721.87	758.91	799.86	836.74
	deviation	1.47%	3.08%	1.72%	1.72%	2.98%
Treated from sewage plant /Million t	Actual	65235.0	67180.0	74473.0	78694.0	82316.0
	Simulation	63874.1	68076.4	73552.1	79515.6	85672.9
	deviation	2.09%	1.33%	1.24%	1.04%	4.08%

IV. DISCUSSION

In this paper, the metabolic steady-state model of urban complex water circulation system is taken as the main line, from the perspective of complex water circulation system, using the system dynamic simulation technology to identify the complex metabolic evolution boundary of urban complex water circulation system, division of urban complex water circulation system metabolic subsystem, construct the feedback loop of metabolic structure of urban complex water circulation system, based on the above analysis, the metabolic steady state model of urban complex water circulation system is established, which reveals the mechanism of metabolic structure of urban complex water circulation system. According to the target city (city of Tianjin Haihe River Basin) water safety related data in recent five years, the system dynamics model of metabolic steady state of urban complex water circulation system was established, and the evolution simulation of water quality and water quantity coupling metabolic process in urban complex water circulation system was carried out, and the model was validated. Through the study of the metabolic boundary of the complex water circulation system and the internal metabolic structure of the system, the water metabolism process of the target city has been seriously affected by human activities and has been in a state of disorder.

According to the detailed analysis of the metabolic process of the complex water circulation system in the target city, the main reason for the disorder of the water metabolism process is the large amount of pollutants discharged by the pollution source, the sewage treatment effect can not meet the current demand，and low water efficiency and over-exploitation of water quality and water quantity can not be recycled in time to be added. In order to deal with these problems, and achieve the healthy operation and sustainable development of the target city's water metabolism process, we put forward the following measures: reduce the proportion of the secondary industry, increase the proportion of tertiary industry and technology-intensive industries; improve the treatment rate of waste water and decontamination rate, increase the reuse rate of waste water; improve water efficiency and rainwater utilization, increase the amount of urban water to compensate for the lack of water, etc. With the acceleration of urbanization in China and the continuous expansion of urban scale, the healthy operation of metabolic processes in urban complex water circulation system will encounter more and more challenges. This study will provide a reference for the relevant departments to formulate the policy and behavior of water metabolism imbalance and its concurrent problems.

V. CONCLUSION

Economic and social activities and human high-density activities, resulting in the impact of urban water metabolism and water safety uncertainty factors surge, but the current research failed to keep pace with the times and fully consider the complex factors on the impact of urban water cycle system, Therefore, the article uses the system dynamics model, from the perspective of a deeper level of urban water metabolism, reveals the city's internal water metabolism mechanism and improve the urban water security theory system, in order to solve the increasingly complex urban water cycle, water metabolism to provide new ideas and method. In addition, due to the complexity of urban water cycle system and simulation results have a certain relative error, the study of this paper there are some limitations, only for the relevant departments to provide a reference to policy development. The importance and innovation of this study is to explore the principle of metabolic process of complex water circulation system in the city from the microscopic point of view, analyze the influence of various uncertain factors on the healthy operation of the metabolic process of urban complex water circulation system, and to implement the more refined governance means to provide theoretical support, so as to ensure the city's water security and water supply and demand.

ACKNOWLEDGEMENTS

This research is supported by the Opening Foundation of Tianjin University State Key Laboratory of Hydraulic

Engineering Simulation and Safety (Grant No. HESS-1701); the Project of Tianjin Science and Technology Plan (Grant No. 16ZXFWGX00090) .

REFERENCE

[1] J. Chen, “Urban binary water circulation system evolution and safe and efficient water use mechanism,” *Science Press*, Beijing, 2014.
[2] W. Zeng, “Water metabolism, water regeneration and water environment carrying capacity,” *Science Press*, Beijing, 2015.
[3] J. Chen, J. Xu, “Conceptual discrimination on the urban water security under the perspective of non-traditional security,” *Advaances Water Science*, vol. 3, pp. 443-450, 2015.
[4] T. A. Farooqui, M. A. Renouf, and S. J. Kenway, “A metabolism perspective on alternative urban water servicing options using water mass balance,” *Water Research*, vol.106, pp. 415-428, 2016.
[5] Y. Luo, S. Yao, “Based on the SD model of Changsha city water resources carrying capacity research,” *China Rural Water and Hydropower*, vol. 1, pp. 42-46, 2015.
[6] C. Wang, G. Yang, and X. He, “Study on water resources carrying capacity based on system dynamics,” *China Rural Water and Hydropower*, vol. 9, pp. 212-215, 2016.
[7] H. Wang, Y. Jia, and G. Yang, “Comprehensive simulation of binary water cycle and its associated processes in Haihe River Basin,” *Science Bulletin*, vol. 12, pp. 1064-1077, 2013.
[8] H. Wang, W Yang, and G. Yang, “Integrated simulation of the dualistic water cycle and its associated processes in the Haihe River Basin,” *Chinese Science Bulletin*, vol. 58, pp. 3297-3311, 2013.
[9] H. Dong, G. Wang, “Study on Simulation and Development Countermeasures of Economy-environment Composite System in Shandong Peninsula Blue Economic Zone,” *Soft Science*, vol. 2, pp. 103-108, 2017.