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System dynamics-based ecological network analysis of Beijing's reclaimed water system

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ABSTRACT

Considering the potential risks of using reclaimed water, the uncertain relationship between the use of reclaimed water and the stability of the network of reclaimed water systems needs to be investigated. This study takes Beijing as the study area and uses relevant data affecting the demand, supply and use of reclaimed water from 2012 to 2020. A model of reclaimed water supply and demand was constructed using a system dynamics approach to characterize the changes in reclaimed water supply and demand from 2021 to 2050, and to identify changes in water use between the domestic, industrial and environmental sectors in economic, social and environmental scenarios. Based on the ecological network analysis method, the system metabolic efficiency, redundancy and sectoral relationship characteristics of the reclaimed water network were analyzed. This reveals the robustness of the reclaimed water system and the metabolic relationships between the sectors of the system, and assesses the role of different policy scenarios on the stability of the reclaimed water system. The results show that the error between the simulated and realistic values of the reclaimed water system is less than 10%. The established reclaimed water system dynamics model can provide accurate feedback on the causal relationship between reclaimed water variables and clarify the characteristics of the changes in reclaimed water supply and demand. The simulation showed that Beijing's reclaimed water supply will increase slightly from 2013 to 2050 at a rate of 2.65%, which is much lower than the multi-year average growth rate of reclaimed water demand of 3.96%. The future increase in reclaimed water use will need to be achieved by upgrading the reclaimed water supply. This study analyses the reclaimed water consumption capacity under different policy contexts and provides a reference for water conservation in the industrial sector in Beijing.

Keywords: reclaimed water use; reclaimed water use potential; reclaimed water network

1. INTRODUCTION

Water scarcity is a key factor limiting the economic and social development of cities[1]. As the carrying capacity of water resources increases, deep treatment of wastewater or rainwater to form a stable and controllable supply of reclaimed water has become an important factor in mitigating urban water security problems[2]. With economic development and increased environmental awareness, the government and enterprises will increase investment in reclaimed water treatment technology and facilities to improve the quality and stability of reclaimed water supply, thus alleviating the problem of urban water shortage. Review of China's reclaimed water development history, Beijing took the lead in exploring the use of reclaimed water, in 2003, the first in the country to achieve the use of reclaimed water "zero" breakthrough, the current supply of reclaimed water accounted for about 29% of the total supply of water resources for ecological replenishment, industry, municipal miscellaneous use and other areas of the city's socio-economic development. It is a great contribution to the social and economic development of the city. With the acceleration of urbanization, high industrial demand is accompanied by higher water intensity[3]. In this context, the Beijing Municipal Government promulgated the "Beijing Municipal Wastewater Treatment and Resource Utilization Development Plan

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in the 14th Five-Year Plan Period" in June 2022, proposing to focus on promoting the substitution of reclaimed water for production and domestic use. How economic development and increased awareness of environmental protection will affect the safety of water systems is a pressing issue in the field of water resource use.

System dynamics provides an effective tool for modelling and analyzing complex systems with a variety of correlations to provide supporting information for sustainable management of urban water resources[4-5]. Urban water supply system management strategies can be better assessed by considering effective internal relationships between the various components of urban water supply systems, such as population, climate change, water supply and demand, infrastructure conditions, tariffs and costs, etc[6]. The method's prediction of the future is based on modelling the interaction mechanism between variables in the historical period, which makes it difficult to portray the changes in system structure and efficiency due to policies from a system-wide perspective, and therefore difficult to obtain targeted policy recommendations.

Ecological network analysis (ENA) is widely used in urban water systems to analyse the interrelationships of metabolic effects on water quality or water resource use among system components, and to provide effective information for the sustainable use of water resources. By constructing an ecological network model, the flow and metabolic relationships between components in the water ecological network model are analyzed to analyse water quality metabolism problems[7-8]. Scientists have extensively studied water quality and quantity relationships between different sectors of the water system, using conceptual and numerical models to inform water planning and decision making[9-11]. However, few studies have combined system dynamics and ecological network analysis approaches to assess the potential for the use of reclaimed water systems. A small number of scholars have provided a methodological perspective to construct and visualize the information content of a system dynamics model, representing the interactions between sectors in the dynamics model as a network[12]. This helps to explore the impact of external interventions on the potential for recycled water use in terms of the relationship between water use and sectoral structure.

In summary, system dynamics is suitable for studying the feedback relationships between variables in a complex system, and ecological network analysis reflects the characteristics of the system from a holistic perspective. The combination of system dynamics and ecological network analysis makes it possible to characterize the interactions between different sectors of the system in the form of a network, so that the interrelationships and structural characteristics of the different sectors of a complex system can be represented visually. System dynamics can be modeled and simulated to reasonably predict the development trend of variables, and by processing the predicted data from system dynamics into network data and applying it to the ecological network model, it is possible to predict and analyse the characteristics of the system network and better assess the feasibility of the policy. Previous quantitative studies on the potential of recycled water use have focused on the interactions between variables, and there is a relative lack of research on assessing the internal structure and external functional characteristics of the future recycled water system, and there is an urgent need to study the flow and structural functions of each sector from the perspective of assessing the overall performance of the complex system of water resources. To this end, this study takes Beijing as an example, constructs a reclaimed water system model using system dynamics, simulates and predicts the changes of reclaimed water under different policy scenarios from 2021 to 2050 by combining with scenario analysis, provides the ecological network with the five major inter-sectoral flows of domestic, industrial, wastewater treatment, reclaimed water and ecological, and converts the system dynamics model into a network by combining with an ecological network analysis method to assess the robustness level and system performance of the reclaimed water system. The system dynamics model was converted into a network to assess the robustness level and metabolic efficiency of the system, to show the regulating effect of increasing the proportion of reclaimed water used by the city on the structure and function of the water system, and to determine the water use structure of the various sectors in the city's reclaimed water system and the inter-sectoral interactions and control relationships.

2. METHODS

2.1 Study area

Beijing is located in the northern part of the North China Plain (115.7° -117.4° E, 39.4° -41.6° N), with a total area of 16,410.5 square kilometers. The major rivers flowing through the area include the Yongding River, the Chaobai River, the North Canal and the Xiema

River, etc. Most of them originate from the mountains in the north-west of the city, meander south-east, flow through the plains and eventually join the Bohai Sea. Beijing's water resources are characterized by: (1) Insufficient natural endowment of water resources, with an annual per capita water resource of about 150 cubic meters, well below the United Nations standard for extreme water scarcity. Average annual rainfall is unevenly distributed in time and space, with rainfall during the flood season from June to September accounting for about 80% of the year; groundwater development has reached its maximum limit and is difficult to recover in the short term. (2) The development and use of recycled water has great potential. 2020, the city's daily capacity of sewage treatment plants over the scale of 6,879,000 cubic meters, sewage treatment rate of 84.6%. Beijing's total water supply is 4.06 billion cubic meters, of which groundwater and recycled water are the main sources of water supply, accounting for 33.3% and 29.6% of the total water supply, respectively, and the amount of recycled water accounted for 8.2% of the country's recycled water consumption, ranking first in the country.

2.2 *SD model of Reclaimed Water System*

The Reclaimed Water System (RWS) is influenced by social, economic, environmental, technological and other factors, and the internal relationship is complicated. The administrative boundary of Beijing is used as the physical boundary of the system. The time boundary is from 2012 to 2050, of which 2012 to 2020 is the time interval for model testing, and the results of some variables simulated in this period and the actual historical data are tested for errors to ensure a high degree of simulation of the model. The time step of the model is set to 1 year and the boundary length is 39 years. The model consists of three subsystems: recycled water supply, demand and use.

2.3 *Policy scenarios*

Table 1 Policy program options

	GDP growth rate	Investment growth rate	Demand factor for recycled water for road sweeping and landscaping	Proportion of reclaimed water used for river and lake recharge
BAU	0.08	0.163	0.23	0.82
Ec1	+10%			
Ec2		+10%		
En1			+10%	
En2				-10%

Based on the applicability of the use of recycled water in the study area to economic development and environmental protection policies, four economic and environmental policies were used in this study: growth in GDP, growth in drainage investment, increase in recycled water for sanitation and greening, and increase in recycled water for recharging rivers and lakes.

2.4 *ENA framework of Reclaimed Water System*

2.4.1 Build a framework

Ecological network analysis was used to assess the metabolism of the reclaimed water system and to construct a conceptual network structure model (Figure 1). The ecological network model of the reclaimed water system was classified from an ecological perspective as an ecological network model with the urban ecosystem as the producer, the industrial and domestic sectors as the consumers, and the wastewater treatment and reclaimed water sectors as the decomposers. Based on the system dynamics simulation to obtain the paths and flows between the sectors, the network of the reclaimed water system was inputted with the projected data from 2025-2050, and the network nodes were analyzed in terms of their interrelationships and system efficiency using network utility and robustness, respectively .

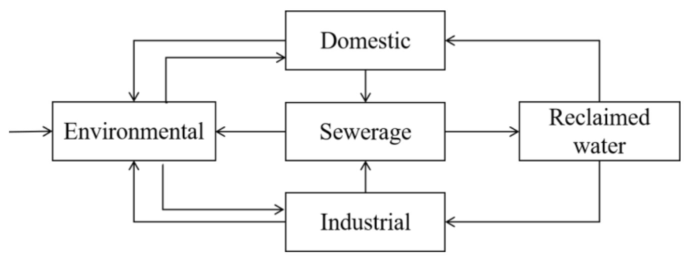

Fig. 1 Schematic diagram of the network model of RWS in Beijing

2.4.2 Network utility analysis

The network utility analysis method is used to study the interactions between nodes in the ecological network of the urban wastewater system. The reciprocal and antagonistic relationships between nodes in the system are reflected by introducing the system utility index (U) and calculating the integral utility matrix U and the corresponding $SignU$ matrix.

2.4.3 Network robustness analysis

AMI (average mutual information) is used to quantify the amount of flow diversity that is hindered by structural constraints. The higher the index, the more constrained the flow structure of the system, i.e. the more concentrated the flows in the network, the fewer the dispersal paths and the more efficient the metabolism. H_c (Conditional entropy) is the number of alternatives associated with the average input and output of a sector in the network and is used to measure the diversity and flexibility between nodes in the network. The higher the value, the more alternative paths exist between the nodes in the recycled water network and the more resilient the system is to perturbations.By considering the interplay of efficiency and redundancy, a broad but quantitative measure of the sustainability of complex networks, known as the robustness metric, has been created. The robustness metric is used to assess the ability of a network to maintain its structural and functional stability in the face of various disturbances and attacks.

3. RESULTS AND DISSCUSSION

3.1 Error analysis

According to the error situation between the simulated values and the real values, it can be seen that the error range of the total population, industrial water demand, sewage treatment volume is within 7%, and the reclaimed water supply has a big difference with the real value (within 10%). Overall, the difference between the simulated values and the real values of the four variables, namely, total population, industrial water demand, sewage treatment volume, and reclaimed water supply, is within 10%, which is a reasonable error range for the system dynamics simulation.

3.2 Scenario analysis

Based on the simulation results, it is found that the multi-year average growth rate of reclaimed water demand is 3.96%, which is faster than the growth rate of reclaimed water supply (2.65%), and reclaimed water consumption is expected to reach 1,918 million m^3 in 2050. Among them, in 2012-2019, the supply of reclaimed water is higher than the demand for reclaimed water and there is an oversupply. After 2019, the demand for reclaimed water from the relevant sectors will continue to increase due to the increasingly widespread use of reclaimed water, which can reduce the amount of new water used in industry, municipal water use, and sanitation and greening.

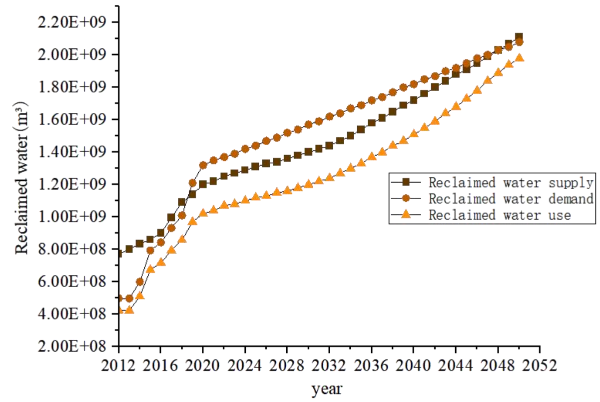

Fig. 2 Reclaimed water volume in Beijing under base scenario, 2012-2050

3.3 Network node relationship analysis

The reclaimed water system network was constructed based on the system dynamics model to determine the inter-sectoral water flow between ecological environment, domestic, industrial, wastewater treatment plant and reclaimed water use, and to form the inter-sectoral network data flow. The U and $SignU$ are applied to obtain the direct utility matrix and the dimensionless integral utility matrix for 2025-2050. The direct utility matrix represents the net inputs and outputs of each sector as a proportion of the total inputs, and the dimensionless integral utility matrix represents the total direct and indirect utilities.

3.4 Network characteristics analysis

The baseline scenario projections were used to examine the changes in the metabolic efficiency index and the redundancy index of the reclaimed water network.The mean values of the AMI and Hc for the period 2020-2050 were 1.42 ± 0.01 and 0.39, respectively, and the trends of the indices were not the same (Figure 3). During the period 2020-2050, the AMI index peaked in 2030 and 2040 at 1.45 and 1.51, respectively, while H_c peaked only in 2030 with the same value as in 2020 (0.41) and maintained a decreasing and then increasing trend thereafter. The effect of economic growth and small ecological applications of reclaimed water on the metabolic efficiency index (AMI) of the reclaimed water system is very weak.

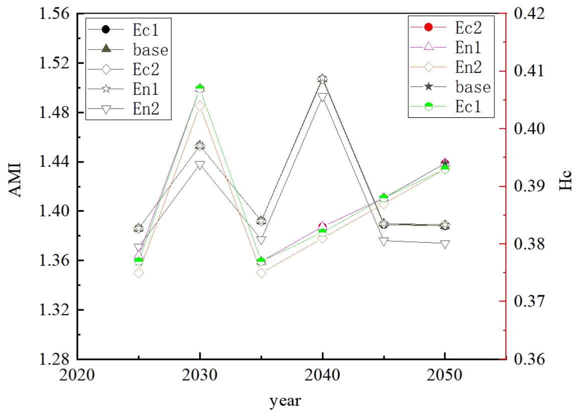

Fig.3 RWS efficiency and redundancy index for each scenario in Beijing, 2020-2050

4. CONCLUSIONS

In this study, the future supply and demand of reclaimed water is predicted by constructing a reclaimed water system dynamics model. Key sectors in the system dynamics model are used as key nodes in the reclaimed water ecological network to further analyse the metabolic pathways and processes of the reclaimed water system. By analyzing the metabolic characteristics and metabolic relationships of the network, the metabolism of Beijing's reclaimed water use system is evaluated in depth, and the main causes of unhealthy metabolic processes and key sectors are identified. In order to illustrate the impact of different policies on reclaimed water use, different economic and environmental scenarios are set up to analyse the changes in the metabolic state of the reclaimed water system and to illustrate the role of economic growth and environmental protection on the metabolism of the system from a systemic perspective. It is found that small changes (10%) in GDP growth and ecological recharge have little effect on the steady state of the system, and that policy shocks need to be increased to observe the critical state of the system's network characteristics.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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