Ecological network analysis of an urban water metabolic system: Model development, and a case study for Beijing

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A B S T R A C T
Using ecological network analysis, we analyzed the network structure and ecological relationships in an urban water metabolic system. We developed an ecological network model for the system, and used Beijing as an example of analysis based on the model. We used network throughflow analysis to determine the flows among components, and measured both indirect and direct flows. Using a network utility matrix, we determined the relationships and degrees of mutualism among six compartments – 1) local environment, 2) rainwater collection, 3) industry, 4) agriculture, 5) domestic sector, and 6) wastewater recycling – which represent producer, consumer, and reducer trophic levels. The capacity of producers to provide water for Beijing decreased from 2003 to 2007, and consumer demand for water decreased due to decreasing industrial and agricultural demand; the recycling capacity of reducers also improved, decreasing the discharge pressure on the environment. The ecological relationships associated with the local environment or the wastewater recycling sector changed little from 2003 to 2007. From 2003 to 2005, the main changes in the ecological relationships among components of Beijing’s water metabolic system mostly occurred between the local environment, the industrial and agricultural sectors, and the domestic sector, but by 2006 and 2007, the major change was between the local environment, the agricultural sector, and the industrial sector. The other ecological relationships did not change during the study period. Although Beijing’s mutualism indices remained generally stable, the ecological relationships among compartments changed greatly. Our analysis revealed ways to further optimize this system and the relationships among compartments, thereby optimizing future urban water resources development.

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1. Introduction

Beijing is one of the world’s ten largest cities, and is facing serious water shortages (Beijing Water Authority, 2007). In 2007, Beijing’s per capita water resource amounted to 148.2 m³, equal to only 8% of China’s per capita water resource and 2% of the mean global per capita water resource. Although rainfall increased in 2007, Beijing’s total water resource was only 2.4×10⁹ m³ in 2007, which was only 1.1 times that in 2006 and remained 36% less than the annual average from 1950 to 2007. At the end of 2007, the groundwater level had declined by 1.3 m compared with the 2006 level, and groundwater reserves had decreased by 0.6×10³ m³. By 2007, total water consumption had reached 3.5×10⁹ m³, with industrial, agricultural, domestic, and ecological water consumption of 0.6×10³ m³, 1.2×10³ m³, 1.4×10³ m³, and 0.3×10³ m³, respectively. This supply and demand data clearly indicates that water consumption greatly exceeds the available water resources. It is therefore urgent that we study Beijing’s urban water metabolic system so we can learn how to solve the serious water shortage and relieve conflicts between development of the urban economy and the water resource supply.

In the present study, we analyzed the supply and demand components of urban water metabolism as a means to identify bottlenecks in the ability of the available water resources to support urban development, and to reveal possible ways to rationalize the utilization of Beijing’s water resources. We were guided by some previous research on the theory of urban water metabolic systems. Tambo (1981) defined the concept of an urban water metabolic system, and proposed that such systems should ensure that the available supply could simultaneously meet the city’s water quality and quantity needs. More recently, Tambo (2002) proposed that water pollution results from an imbalance in the urban water metabolism. Yan and Wang (2005) noted that water problems result from temporally and spatially unbalanced inputs and outputs, leading to ecological stagnation and resource depletion, which in turn lead to disharmony in the system’s structure and functioning. Xiong et al. (2006) analyzed the metabolic mechanisms of an urban water metabolic system, and developed a conceptual model in which enhancing the system’s innate metabolic functions required a careful study of the system’s internal mechanisms to improve the hydrological cycle and...
increase the carrying capacity of the water environment (i.e., the maximum amount of water and the best water quality that can be provided to meet local civil and industrial needs).

There has been relatively little research on urban water metabolic processes. Bodini and Bondavalli (2002) studied the urban water metabolic system of Sarmato (Italy) using ecological network analysis, and developed a network model that divided the system into agricultural, industrial, domestic, service, groundwater well, and river units. By calculating various indices that described these water resources, such as the dependencies, circulating water, length of network paths, and structure of water throughflow, they were able to analyze the sustainability of Sarmato's water resource utilization. This study demonstrated the usefulness of ecological network analysis in studies of urban water metabolism. Some scholars have also studied such systems using water footprint analysis (Jenerette et al., 2006), system dynamics (Chai, 2009), and comprehensive index evaluation methods (Jeffrey et al., 1999; Lundin and Morrison, 2002).

Currently, research on urban water metabolism still focuses on assessing the system's current condition, which results in a fairly shallow understanding of the spatial and temporal scales of depletion and dislocation structures and of the functioning of the system. Key unresolved problems include how to portray the system's overall structural properties, how to analyze its functional characteristics, and how to achieve sustainable and healthy development by analyzing both the structure and the functioning of the system. Ecological network analysis can resolve these problems by examining the internal workings of the urban water metabolic system.

Ecological network analysis originated in the economic analysis of monetary flows. Hannon (1973) first applied economic input–output analysis (the Leontief model; Leontief, 1966) to investigate the distribution of ecological flows in an ecosystem. Since Patten and Finn first published their papers on the analysis of flows in ecological networks (Finn, 1976; Patten et al., 1976), there have been many studies of methods for and applications of ecological network analysis (e.g., Burns, 1989; Newman, 2002; Lenzen, 2003; Zorach and Ulanowicz, 2003; Ulanowicz, 2004). Ecological network analysis is currently one of the main methods for analyzing the interactions between an ecosystem's structure and functions by focusing on the flows among the compartments that define its structure. The approach can quantitatively analyze the direction of these ecological flows and the interactions among them in an ecological network, and can thus reveal the integrity and complexity of ecosystem behaviors (Fath, 2007). Ecological network analysis has been widely applied to study natural ecosystems, but has seldom been used in the analysis of urban ecosystems (Bodini and Bondavalli, 2002; Bailey et al., 2004a,b; Zhao, 2006).

In this paper, we used the conceptual breakthrough provided by ecological network analysis to develop an ecological network model of the urban water metabolic system by collecting, arranging, and analyzing data on the water supply, water demand, wastewater discharge, and water reuse. Based on this model, we examined the functional characteristics of the system to provide a theoretical and practical methodology for optimizing and managing the water resources and water environment of Chinese cities. To demonstrate how this model can be used, we performed a case study of Beijing's water use.

2. Methodology

2.1. Processes involved in the urban water metabolism

Using the trophic levels of natural ecosystems as a reference, we defined the compartments of the urban system as producers, consumers, and reducers, and determined the water flows among the system's components. Although urban systems are clearly not the same as natural systems, comparing them to natural ecosystems provides a simple metaphor that makes it easier to understand the meaning of the components and the flows among them. Based on this research, we developed a conceptual model of the processes in the urban water metabolism (Fig. 1). In this model, the producers are the ecological environment and the artificial wastewater collection system; the consumers are the industrial, agricultural, and domestic sectors; and the reducers are the wastewater recycling system. Due to the complex chain of relationships among these components, each component may play different roles at different times; for example, although the ecological environment serves as a producer, it must also consume water resources to sustain its own operation and it must reduce wastewater that it receives from the urban system. Similarly, the wastewater recycling subsystem (the reducer) both purifies urban wastewater and provides regenerated (recycled) water to support the operation of the urban system (i.e., acts as a producer). These changes in the roles of components result in a reticular system structure rather than a linear structure. Although metabolism is a purely biological concept, it can be applied by way of analogy to cities because the urban water
metabolic system is also a mechanism for processing resources and producing wastes. In this sense, cities function as “urban superorganisms” (Park, 1936) that exhibit metabolic processes. Using the trophic levels of natural ecosystems as a reference that makes the large flows of matter and energy less abstract, we defined the compartments of the urban water metabolic system as producers, consumers, and reducers, and determined the water flows among the system’s components.

In our model, there are clear links among the three key trophic levels: the local ecological environment, the terminal consumption sectors, and the wastewater recycling sector. The model follows all flows of water resources among these levels, but mainly reflects the utilization of fresh water, recycled water, and rainwater, as well as the reuse of water and the discharge of wastewater. The local ecological environment provides fresh water for the industrial, agricultural, and domestic sectors, but sometimes must also receive water from the external environment. The external environment includes neighboring regions located upstream from the study area within the same basin and other regions that are transferring their water resources to the study area as a result of large-scale hydrological engineering projects. In the case study we will subsequently discuss for Beijing, the external environment therefore includes upstream regions near the study area, such as the upper basin of the Hai River in areas such as Hebei Province, Shanxi Province, and Inner Mongolia. Water is also being transferred to Beijing through projects such as the Gangnan, Huangbizhuang, Wangkui, and Xidayang reservoirs in Hebei province. Other transfers include the project to export water from the Chetian Reservoir in Shanxi Province, the Yangtze River, and the Huanghe River under the South-to-North Water-transfer Project.

Under the currently limited water supply, the city must consider in depth how best to utilize fresh water and reuse wastewater. The industrial wastewater and domestic sewage are all discharged into the wastewater recycling system. Part of the treated wastewater can be recycled to recharge the ecological environment and for irrigation of municipal green space, washing of streets, agricultural irrigation, and industrial utilization. Rainwater can also be collected to recharge the ecological environment and provide supplemental water for the industrial, agricultural, and domestic sectors. In addition, the industrial sector reuses much of its water to solve the problem of high water consumption. During the utilization of water resources, there is discharge of wastewater produced by the industrial, agricultural, and domestic sectors.

2.2. Ecological network model of the urban water metabolism

By analyzing the urban water metabolism processes in the conceptual model, we developed an ecological network model of the system (Fig. 2). All water flows among compartments can be represented by directional lines that connect nodes in the network, resulting in an ecological network model for the urban water metabolic system that consists of a series of directional flows along metabolic pathways (Zhang et al., 2009a, b). In the model in Fig. 2, we have defined 18 metabolic pathways that reflect the flows among these six compartments (Table 1). Note that in Fig. 2 and Table 1, $f_{ij}$ represents the flow from compartment $j$ to compartment $i$, and $z_i$ represents the flow into compartment $i$ from outside the water metabolic system.

2.3. Throughflow and utility analysis

By describing the trophic levels and interactions among compartments, ecological network analysis allows quantitative analyses of the actors and relationships in the components of an ecological network, thereby revealing the integration and complexity of ecosystem behaviors. Network throughflow analysis is similar to input–output analysis. In the present paper, we chose network throughflow analysis to study the flows in the urban water metabolic system. Nondimensional, input-oriented intercompartmental flows from compartment $j$ to compartment $i$ ($g_{ij}$) are defined as:

$$g_{ij} = f_{ij} / T_j$$

(1)

where $f_{ij}$ is the flow from compartment $j$ to compartment $i$ and $T_j$ is the sum of the intercompartmental and boundary outflows from compartment $j$.

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**Fig. 2.** Ecological network model of the urban water metabolic system. Note: Based on these compartment definitions, we included the following flows in the model: $f_{12}$, rainwater for recharging the ecological environment; $f_{13}$, wastewater discharged into the ecological environment by the industrial sector; $f_{14}$, wastewater discharged into the ecological environment by the agricultural sector; $f_{23}$, sewage discharged into the ecological environment by the industrial sector; $f_{24}$, recycled water used to recharge the ecological environment and discharged wastewater; $f_{33}$, rainwater collection from the ecological environment; $f_{34}$, fresh water utilized by the industrial sector; $f_{35}$, rainwater utilized by the industrial sector; $f_{36}$, recycled water utilized by the industrial sector; $f_{43}$, fresh water utilized by the agricultural sector; $f_{44}$, wastewater utilized by the agricultural sector; $f_{45}$, rainwater utilized by the agricultural sector; $f_{46}$, recycled water utilized by the agricultural sector; $f_{53}$, fresh water utilized by the domestic sector; $f_{54}$, rainwater utilized by the domestic sector; $f_{56}$, recycled water utilized by the domestic sector; $f_{63}$, wastewater disposal by the industrial sector; and $f_{65}$, sewage disposal by the domestic sector.
Table 1

Beijing's direct flows among compartments (F₁ to F₆, units: × 10⁸ m³) and the dimensionless indirect flow matrices (G₁ to G₆). For the compartments, subscripts have the following meanings: 1, local ecological environment; 2, rainwater collection sector; 3, industrial sector; 4, agricultural sector; 5, domestic sector; and 6, wastewater recycling sector. For the compartments, subscripts 1 to 5 represent the years 2003 to 2007, respectively. For the flow components, the i values are in the first column of the table, and the j values are across the top of the table; flows are from compartment j to compartment i.

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Note: Data on the water resources were obtained from Beijing’s Water Resources Bulletin (Beijing Water Authority, 2007); data on pollution discharge were obtained from the China Environment Yearbook (State Environmental Protection Administration of China, 2008).

where N (nᵢ) = G₀ + G¹ + G² + G³ + ... + Gₖ + ... = (I-G)⁻¹

(2)

In an urban water metabolism system, the sum of flows into the i-th compartment is equal to the sum of the flows out of the i-th compartment, Σj uᵢj = Σj uᵢj. From the matrix G = (gᵢⱼ), the dimensionless integral flow matrix N = (nᵢ) can be computed using the following convergent power series:

N = (nᵢ) = G₀ + G¹ + G² + G³ + ... + Gₖ + ... = (I-G)⁻¹

(2)

where I is the identity matrix, nᵢ represents the integral dimensionless value of gᵢⱼ which is calculated using a Leontief inverse matrix (Faith, 2004), and the matrix N represents the integrated flows of actions between any of the six compartments in the network (i.e., the flow gᵢⱼ). The self-feedback matrix (G²) reflects flows that return to the same compartment, the matrix G³ reflects the direct flows (i.e., only one step) between any of the six compartments in the network, G² represents the flows that pass through two compartments, k represents the number of steps in the system’s pathways, and Gᵏ (k ≥ 2) reflects the indirect flows of length k between compartments.

Based on the throughflow analysis, we can measure both indirect and direct flows. This is one of the most important properties of this form of analysis, since it lets us compare the strength of indirect flows (i.e., flows for which k > 1) with that of direct flows (i.e., flows for which k = 1). Indirect flows are calculated as the integral contributions minus the direct and initial cross-boundary input. The ratio of indirect (I) to direct (D) flows measures the relative strength of these two factors. Mathematically, this is simply the following ratio:

I / D = \left( \sum_{i=1}^{5} \sum_{j=1}^{5} (nᵢj - lᵢj - gᵢj) \right) / \left( \sum_{i=1}^{5} \sum_{j=1}^{5} gᵢj \right)

(3)
When the ratio is greater than 1, indirect flows are greater than direct flows, but when the ratio is less than 1, direct flows are greater than indirect flows. In natural ecosystems, analysis of many models has shown that these ratios are often greater than 1, indicating the non-intuitive result that indirect flows contribute more strongly to the flows than direct flows (Higashi and Patten, 1989). This shows that indirect flows must be studied carefully, since they may exert greater dominance than direct flows in a network. This clearly has implications for understanding feedbacks within a network and the balance between direct and indirect controls.

The nondimensional integral flow matrix can be redimensionalized by post-multiplying by the diagonalized through-flows vector \( \text{diag}(T) \) for transforming each column of \( N \), such that dimensional integral flow matrix \( Y = N \text{diag}(T) \). By calculating the sum of each column of matrix \( Y \), the column vector of matrix \( Y, y_l(y_1, y_2, y_3, y_4, y_5) \), can be obtained, and \( \sum y_l \) reflects the contribution of compartment \( j \) to other compartments. From the matrix \( Y \), a weight can be computed from the following formula:

\[
W = \frac{\sum y_l}{\sum \sum y_l}
\]

\( W \) reflects the contribution of compartment \( j \) to the system. The weight determined by the flows can then be applied to the actual measured values. This allows us to derive the contribution of each compartment and determine the support provided to every compartment by water of the urban metabolic system. The overall capability can therefore fully reflect the status and functions of each compartment in the urban water metabolic system, and can characterize their ecological trophic levels.

Network utility analysis is an ecological network approach that was first introduced by Patten (1991) to express the relative benefit to cost relationships in networks. In this method, a direct utility matrix is constructed and used to analyze the functions of the network (Fath and Borrett, 2006; Fath, 2007). In the present paper, we chose network utility analysis to study the utility values in the ecological network of the urban water metabolic system. From the network structure that we derived, we then analyzed the reciprocal relationships between pairs of elements in the network (Fath, 2007). In the network utility analysis, \( d_{ij} \) represents the utility of an intercompartmental flow from compartment \( j \) to compartment \( i \), and can be expressed as:

\[
d_{ij} = \frac{\text{f}_{ij}}{T_i}
\]

From matrix \( D \), which contains all \( d_{ij} \) values, a dimensionless integral utility intensity matrix \( U = (u_{ij}) \) can be computed:

\[
U = \left( u_{ij} \right) = D^0 + D^1 + D^2 + D^3 + \ldots + D^k = (I - D)^{-1}
\]

As in the throughflow analysis, the matrix \( U \) reflects the intensity and pattern of integrated actions between any of the six compartments in the network (i.e., the utility, \( u_{ij} \), and \( D \) represents the matrix containing utilities of flows along pathways involving from 0 to \( k \) steps.

In network utility analysis, the sign of an element in matrix \( U \) can be used to determine the pattern of interaction between compartments in the network. In general, the signs in the main diagonal of sign matrix \( Y \), which represents the sign matrix for matrix \( Y \), are positive, which means that each compartment is self-mutualistic and receives a self-promoting positive benefit from being part of the network (Patten, 1991). If \((su_{21}, su_{12}) = (+, +)\), compartment 2 exploits compartment 1. By analogy with a natural ecosystem, this means that compartment 2 benefits from the relationship (receives more utility than it transfers to compartment 1), but compartment 1 suffers (receives less utility than it transfers to compartment 2). If \((su_{21}, su_{12}) = (-, +)\), compartment 2 is exploited by compartment 1. By analogy, this means that compartment 1 receives more utility than it transfers to compartment 2, but compartment 2 receives less utility than it transfers to compartment 1. If \((su_{21}, su_{12}) = (−, −)\), then compartment 1 competes with compartment 2, leading to negative impacts for both compartments, whereas if \((su_{21}, su_{12}) = (+, +)\), the relationship between the two compartments represents mutualism, in which both compartments benefit from their interaction. If \((su_{21}, su_{12}) = (0, 0)\), then the relationship between the two compartments is neutral: neither compartment benefits nor suffers as a result of the relationship.

In this paper, we established a mutualism index \( M \) for the urban water metabolic system that reflects the proportions of positive and negative signs in the sign matrices. If we take the integral utility matrix as an example, the mutualism index of the urban water metabolic system can be expressed as follows:

\[
M = J(U) = S_+ / S_-
\]

Here, \( S_+ = \sum y \text{max}(\text{sign}(u_{ij}), 0) \) and \( S_- = \sum y \text{-min}(\text{sign}(u_{ij}), 0) \) (Fath, 2007; Lobanova et al., 2009). If the matrices have more positive signs than negative signs, this means that the urban ecological system exhibits mostly positive relationships between compartments and thus represents network mutualism (Fath, 2007).

This approach provides insights into the relationships among the system's components. During the analysis of urban water metabolic relationships based on the sign distribution and the ratio of the numbers of positive and negative signs in the network utility matrix, we can identify four intercompartmental ecological relationships: competition, exploitation, mutualism, and neutrality. Using the results of this analysis, we can identify potential directions for optimizing a city's water metabolic system.

2.4. Statistical data

To illustrate how the status of an urban water metabolic system can be analyzed by means of ecological network analysis, we chose Beijing as an example, and developed a measurement model to support analysis of the city. Beijing, the capital of China, is located in the northern part of the North China Plain. It covered an area of 16,808 km² and had a population of 15.81 × 10⁶ in 2006. Note that this represents the official number of registered urban residents; it does not include the large floating population of migrant laborers, which may be nearly as numerous as the official population. Beijing’s gross domestic product (GDP) reached 787.03 × 10⁹ yuan (RMB) in 2006. About 90% of the surface water flowing through Beijing comes from rivers and streams outside the municipality in neighboring regions such as Hebei Province, Shanxi Province, and Inner Mongolia. All are part of the much larger Hai River Basin, which drains into the Bohai Sea. Within Beijing municipality, there are five main rivers and more than 200 smaller rivers, most of which have dried out completely. The five main rivers are Chaobai and Beiyun in the east, Yongding and Juma in the west, and Jiyun in the northeast. Beijing’s external environment includes neighboring regions in the upper basin of the Hai River in Hebei Province, Shanxi Province, and Inner Mongolia. It also includes more distant regions that transfer their water resources to Beijing via large hydrological engineering projects such as the Gangnan, Huangbuzhuang, Wangkuai, and Xidayang reservoirs in Hebei province. Additional transfers include water from the Chetian Reservoir in Shanxi Province, the Yangtze River, and the Huanghe River under the South-to-North Water-transfer Project. The data used to calculate these flows were obtained from Beijing's Water Resources Bulletin and the China Environment Yearbook (Beijing Water Authority, 2007; State Environmental Protection Administration of China., 2008). The raw data include the total water resource; agricultural, domestic, and ecological water consumption; rainwater
usage; wastewater recycling; industrial, agricultural, and domestic wastewater discharge; industrial and domestic wastewater disposal; and industrial consumption of fresh water. Table 1 presents the matrices of direct flows in Beijing’s urban water metabolic system from 2003 to 2007 (F₁, F₂, F₃, F₄, and F₅, respectively).

3. Results and discussion

3.1. Metabolic structure

Based on the water flows among the compartments, we constructed the dimensionless integral flow matrices (N₁ to N₆ for 2003 to 2007, respectively) and the dimensionless indirect flow matrices (I₁ to I₆ for 2003 to 2007, respectively). From these matrices (Table 2), we calculated the ratio of indirect to direct flows (I/D for 2003 to 2007) for Beijing. From 2003 to 2007, the ratios of indirect to direct flows (I/D) were 5.40, 5.56, 13.24, 15.06, 15.06, and 27.91, respectively. Beijing’s I/D ratio therefore increased continuously throughout the study period. In 2007, Beijing’s I/D ratio was 5.2 times the 2003 value. Like a natural ecosystem, an urban water metabolic system exhibits ratios greater than 1. In terms of the water flows, these high ratios mean that more water flows via indirect pathways than via direct pathways, and that the cumulative flow ending in a node is larger for indirect pathways than for direct pathways. These results show that indirect flows contribute much more strongly than direct flows to the system, and that Beijing’s urban water metabolic system is dominated by indirect flows, with many feedback paths. In fact, the level of indirect dominance is much higher than that typically found in ecosystems regarding energy metabolism flows since water has a much higher potential for recycling with less dissipation loss along each step.

Based on the water metabolic flows among the compartments, we constructed the dimensionless integral flow matrices (N₁ to N₆ for 2003 to 2007, respectively) and the corresponding redimensionalized integral matrices (Y₁ to Y₆ for 2003 to 2007, respectively). From these matrices, we calculated the integral output flow matrices (Y₁,2003, Y₁,2004, Y₁,2005, Y₁,2006, and Y₁,2007, respectively) and the weight matrices (W₁ to W₅ for 2003 to 2007, respectively) for Beijing (Table 3). Based

Table 2

The dimensionless integral flow matrices (N₁ to N₆) and indirect flow matrices (I₁ to I₆, units: ×10⁸ m³) for Beijing. For the compartments, subscripts have the following meanings: 1, local ecological environment; 2, rainwater collection sector; 3, industrial sector; 4, agricultural sector; 5, domestic sector; and 6, wastewater recycling sector.
on these results, the role, status, and function of each compartment can be defined. Fig. 3 summarizes the weights of each component of the system.

In terms of the producer weight (compartments 1 + 2), the producers accounted for 0.480 to 0.482 of the total weight (1.0) from 2003 to 2007. For the overall water supply structure, the proportion of the supply from collected rainwater has increased from 0.023 to 0.068 during the study period and the proportion of water provided by recycling increased from 0.106 to 0.135, leading to a decrease in the supply from the local environment from 0.459 to 0.413. If the changes are 0.045 for the proportion of the supply from collected rainwater and 0.029 for the proportion of water provided by recycling, the total increase is 0.045 + 0.029 = 0.074. So if nothing else changes, the final proportion for the supply from the local environment should be 0.459 − 0.074 = 0.385. The difference of 0.028 between 0.413 and the calculated value of 0.385 results from an increase in demand on the local environment. This means that rainwater collection and wastewater recycling represent an increasingly large proportion of the total water supply, thereby reducing pressure on the external environment. The creation of the rainwater collection system has therefore improved the potential supply of water resources from the local ecological environment and better meets the increasing demand for water consumption, thereby sustaining Beijing’s socioeconomic development. Because an increasing amount of rainwater is collected within the urban area (e.g., as runoff from paved surfaces), less water must be taken from the local environment. This improves the potential supply from the local environment because an amount equal to the rainwater collection no longer must be withdrawn from the local environment. Because water recycling and water-use efficiency are also both increasing, the net result is that a smaller proportion of the water comes from the local environment and a larger proportion comes from within the system.

The consumers (compartments 3 + 4 + 5) accounted for 0.412 of the total weight in 2003, and this decreased to 0.385 in 2007 (Fig. 3). Consumption by the industrial sector has decreased from 0.038 to 0.017 of this total, and that of the agricultural sector has decreased from about 0.129 to about 0.094. In contrast, water consumption by the domestic sector has increased from 0.245 of this total to 0.274. Under these conditions (a decrease in industrial and agricultural water consumption and a small increase in domestic consumption), the overall demand for water resources by consumers has decreased, indicating that the water utilization efficiency of these sectors has improved, thereby relieving some of the water consumption pressure.

Reducers are necessary in any ecosystem. In an urban water metabolic system, the biological degradability of wastes is low and most wastes must be artificially disposed of or decomposed by enterprises involved in waste recovery, disposal, and utilization. The artificial characteristics of the urban water metabolic system mean that the reducers must play an even more important role than in a natural system. As in a natural ecological system, the reducers in the urban water metabolic system are also considered to be producers because of their role in recovering water and returning it to the system. Their currently low contribution to the system (reaching a maximum proportion of 0.141 in 2006) has caused problems such as a lack of water resources and pollution of the water environment. Thus, it will be vital to increase the contribution of the wastewater recycling compartment to the urban water metabolic system. The reducer’s weight (compartment 6) has increased from 0.106 in 2003 to 0.135 in 2007. The recycling capacity and recharge capacity of the reducers have increased continuously, relieving some of the demand pressure of urban development on fresh water from the local environment, and this has also relieved the discharge pressure of urban development on the local water environment.

3.2. Metabolic relationships

Based on the metabolic flows among compartments, the integral utility matrices (U to U5) among compartments can be computed using network utility analysis. Based on the signs of the elements in matrices U1 to U5 for Beijing, Table 4 presents the sgn(U) matrices for the city, and these matrices permit an analysis of the metabolic relationships among the components of Beijing’s water metabolic system.

In the sgn(Y) matrices, there are 15 pairs of ecological relationships after excluding the self-mutual values (for which i = j); (s121, s112), (s131, s113), (s141, s114), (s151, s115), (s161, s116), (s222, s212), (s232, s213), (s242, s214), (s252, s215), and (s262, s216).

From 2003 to 2005, the ecological relationships between the domestic and industrial sectors changed from mutualism to an exploitation relationship and back again, with (s252, s215) changing from (+, +) to (−, +), and then to (+, +), which indicates that during this period, industrial development changed from mutualism with the
domestic sector, to diverting water from the domestic sector to sustain industrial production (exploitation), and then back to mutualism with the domestic sector. The relationships between the local environment and the domestic sector were $(s_{51}, s_{15}) = (+, -)$ initially, and then $(+, +)$, which represents the change from an exploitation relationship to mutualism. The changes in the relationship between the agricultural and domestic sectors were $(s_{54}, s_{45}) = (-, -)$ initially, and then $(-, +)$, which represents the change from competition to an exploitation relationship. This indicates that during this period, Beijing’s agricultural development changed from competition with the domestic sector to diversion of water from the domestic sector (exploitation).

Except for the ecological relationships mentioned above, the nature of the other 12 pairs of ecological relationships did not change during the study period. The ecological relationships between the rainwater collection, industrial, and agricultural sectors and the local environment, and between the industrial and domestic sectors and the rainwater collection sector, were all exploitation relationships, with $(s_{31}, s_{13}) = (s_{41}, s_{43}) = (s_{52}, s_{25}) = (+, -)$, which represents the pressure of consumer demands for water on the producers. The ecological relationship between the domestic and wastewater recycling sectors was also exploitation, with $(s_{65}, s_{56}) = (+, -)$, which indicates that the domestic sector is exploited by the utilization of recycling water because the fresh water supply cannot meet the water demands of the domestic sector.

The ecological relationships between the wastewater recycling sector and the local environment, and between the wastewater recycling sector and the industrial sector, were exploitation relationships, with $(s_{65}, s_{62}) = (s_{64}, s_{46}) = (+, +)$, which indicates that the discharge of treated wastewater is restricted by the local environmental capacity and that the reducers contribute supplemental ecological water to meet urban water demands; during the process of wastewater discharge, the industrial sector generated great pressure on the wastewater recycling sector.

The ecological relationships between the agricultural and rainwater collection sectors, and between the agricultural and industrial sectors, were competition relationships, with $(s_{42}, s_{24}) = (s_{43}, s_{34}) = (-, -)$, which reflects competition among these sectors for utilization of the local water resources.

The ecological relationships between the rainwater collection and agricultural sectors, and between the agricultural and wastewater recycling sectors represent mutualism, with $(s_{64}, s_{46}) = (+, +)$. The results reflect the mutualism between the rainwater collection and wastewater recycling sectors: the increased output of the rainwater collection sector relieves the demand being placed on the wastewater recycling sector, and the increased output of the wastewater recycling sector reduces the pressure on the rainwater collection sector. This also reflects the mutualism between the agricultural sector and the wastewater recycling sector during the process of treatment of wastewater discharge by the reducers and utilization of the treated water by agriculture.

By 2006, the ecological relationships between the industrial sector and the local environment had changed from exploitation to competition, with $(s_{31}, s_{13}) = (s_{64}, s_{46}) = (+, +)$. The results reflect the mutualism between the rainwater collection and wastewater recycling sectors: the increased output of the rainwater collection sector relieves the demand being placed on the wastewater recycling sector, and the increased output of the wastewater recycling sector reduces the pressure on the rainwater collection sector. This also reflects the mutualism between the agricultural sector and the wastewater recycling sector during the process of treatment of wastewater discharge by the reducers and utilization of the treated water by agriculture.

By 2007, this relationship changed again, with $(s_{31}, s_{13}) = (+, -)$, which represents a change from competition to exploitation, indicating that the
Table 4
Beijing’s integral utility matrices (U1 to U5) for the city’s water metabolic system, and the corresponding sign (sgn) matrices. For the compartments, subscripts have the following meanings: 1, local ecological environment; 2, rainwater collection sector; 3, industrial sector; 4, agricultural sector; 5, domestic sector; and 6, wastewater recycling sector. For matrices U and sgn(U), the subscripts 1 to 5 represent the years 2003 to 2007, respectively. For the six compartments, the i values are in the first column of the table, and the j values are across the top of the table; flows from compartment i to compartment j.

\[
\begin{array}{ccccccc}
U1 & & & & & & \\
1 & 0.78 & -0.03 & -0.12 & -0.17 & 0.00 & 0.06 \\
2 & 0.39 & 0.92 & -0.21 & -0.08 & -0.76 & 0.23 \\
3 & 0.09 & 0.02 & 0.77 & -0.02 & 0.23 & 0.29 \\
4 & 0.39 & -0.01 & -0.06 & 0.92 & 0.00 & 0.03 \\
5 & 0.40 & 0.05 & 0.09 & -0.09 & 0.76 & -0.17 \\
6 & -0.45 & 0.06 & -0.39 & 0.10 & 0.50 & 0.57 \\
\end{array}
\]

\[
\begin{array}{ccccccc}
\text{Sgn}(U1) & & & & & & \\
1 & + & - & - & - & + \\
2 & + & + & - & - & + \\
3 & + & + & + & - & + \\
4 & + & - & + & + & + \\
5 & + & + & - & - & + \\
6 & - & + & + & + & + \\
\end{array}
\]

\[
\begin{array}{ccccccc}
U2 & & & & & & \\
1 & 0.62 & -0.04 & -0.16 & -0.18 & -0.09 & 0.12 \\
2 & 0.10 & 0.93 & -0.14 & -0.03 & -0.75 & 0.25 \\
3 & 0.23 & 0.00 & 0.83 & -0.06 & 0.15 & 0.28 \\
4 & 0.31 & -0.02 & -0.08 & 0.91 & -0.05 & 0.06 \\
5 & 0.52 & 0.03 & -0.02 & -0.15 & 0.65 & -0.14 \\
6 & -0.24 & 0.06 & -0.26 & 0.07 & 0.58 & 0.64 \\
\end{array}
\]

\[
\begin{array}{ccccccc}
\text{Sgn}(U2) & & & & & & \\
1 & + & - & - & - & + \\
2 & + & + & - & - & + \\
3 & + & + & - & - & + \\
4 & + & + & - & - & + \\
5 & + & + & - & - & + \\
6 & - & + & + & + & + \\
\end{array}
\]

\[
\begin{array}{ccccccc}
U3 & & & & & & \\
1 & 0.76 & -0.03 & -0.11 & -0.18 & 0.05 & 0.10 \\
2 & 0.36 & 0.91 & -0.19 & -0.08 & -0.65 & 0.30 \\
3 & 0.01 & 0.03 & 0.83 & 0.00 & 0.27 & 0.31 \\
4 & 0.38 & -0.02 & -0.05 & 0.91 & 0.03 & 0.05 \\
5 & 0.40 & 0.06 & 0.08 & -0.09 & 0.71 & -0.20 \\
6 & -0.38 & 0.07 & -0.26 & 0.09 & 0.48 & 0.54 \\
\end{array}
\]

\[
\begin{array}{ccccccc}
\text{Sgn}(U3) & & & & & & \\
1 & + & - & - & - & + \\
2 & + & + & - & - & + \\
3 & + & + & - & - & + \\
4 & + & + & - & - & + \\
5 & + & + & - & - & + \\
6 & - & + & + & + & + \\
\end{array}
\]

\[
\begin{array}{ccccccc}
U4 & & & & & & \\
1 & 0.76 & -0.04 & -0.09 & -0.16 & 0.09 & 0.12 \\
2 & 0.31 & 0.91 & -0.14 & -0.07 & -0.50 & 0.32 \\
3 & -0.01 & 0.04 & 0.87 & 0.00 & 0.27 & 0.32 \\
4 & 0.38 & -0.02 & -0.04 & 0.92 & 0.04 & 0.06 \\
5 & 0.40 & 0.07 & 0.08 & -0.08 & 0.67 & -0.25 \\
6 & -0.38 & 0.09 & -0.18 & 0.08 & 0.44 & 0.51 \\
\end{array}
\]

\[
\begin{array}{ccccccc}
\text{Sgn}(U4) & & & & & & \\
1 & + & - & - & - & + \\
2 & + & + & - & - & + \\
3 & - & + & + & + & + \\
4 & + & + & - & + & + \\
5 & + & + & - & - & + \\
6 & - & + & + & + & + \\
\end{array}
\]

\[
\begin{array}{ccccccc}
U5 & & & & & & \\
1 & 0.76 & -0.04 & -0.09 & -0.16 & 0.09 & 0.12 \\
2 & 0.23 & 0.93 & -0.09 & -0.05 & -0.35 & 0.22 \\
3 & 0.02 & 0.04 & 0.89 & 0.01 & 0.27 & 0.32 \\
4 & 0.38 & -0.02 & -0.05 & 0.92 & 0.05 & 0.06 \\
5 & 0.37 & 0.08 & 0.07 & -0.08 & 0.69 & -0.25 \\
6 & -0.42 & 0.11 & -0.16 & 0.09 & 0.46 & 0.53 \\
\end{array}
\]

\[
\begin{array}{ccccccc}
\text{Sgn}(U5) & & & & & & \\
1 & + & - & - & - & + \\
2 & + & + & - & - & + \\
3 & + & + & - & - & + \\
4 & + & + & - & + & + \\
5 & + & + & - & + & + \\
6 & - & + & + & + & + \\
\end{array}
\]

industrial production placed a heavy demand on the local environment’s water resources. By 2006, the ecological relationship between the agricultural and industrial sectors had changed from competition to exploitation, with \((su_{43}, su_{24})\) changing from \((-,-)\) to \((-,+)\), which indicates competition between the two sectors for utilization of the local water resources, and that the industrial sector diverted water from the agricultural sector. Among the three consumers (the industrial, agricultural, and domestic sectors), the industrial sector had the strongest exploitation of water resources. By 2007, this relationship changed again, with \((su_{43}, su_{24}) = (-,-)\), which represents a change from exploitation to competition, indicating competition between the two sectors for utilization of the local water resources.

Based on the signs in the redimensionalized integral utility matrices \(Y^i\), the urban water metabolic system of Beijing reveals an overall degree of mutualism, with mutualism indices all greater than 1 and a mean of 1.59 between 2003 and 2007. The mutualism index declined slightly in 2004 (to 1.25), but recovered again during the rest of the study period, reaching a maximum of 1.77 in 2006. Although the mutualism indices changed relatively little, the analysis of the sign values earlier in this section shows that the ecological relationships within the urban system changed greatly.

4. Conclusions and recommendations

As Beijing’s water consumption still greatly exceeds the available water resources, it is therefore urgent to study the city’s urban water metabolic processes to solve or alleviate the serious water shortage and relieve conflicts between development of the urban economy and the available water resource.

Using ecological network analysis, we constructed a simple network model for the urban water metabolic system, and used the model to analyze Beijing’s urban water metabolic system and demonstrate the approach. We were able to analyze the mechanisms inherent in the system from the perspective of water flows and the
ecological relationships among the components. We have three main conclusions based on our study results:

1. From 2003 to 2007, the ability of producers to provide water resources for Beijing has decreased continually, largely as a result of decreasing support from the local environment. During the same period, the consumer demand for water resources decreased constantly, largely as a result of decreasing demand for water by the industrial and agricultural sectors. The ability ofreducers to supply water resources also improved constantly, and the discharge pressure on the regional water environment decreased.

2. The changes in the ecological relationships among components of Beijing’s water metabolic system mostly occurred between the local environment, the industrial sector, the agricultural sector, and the domestic sector from 2003 to 2005, but by 2006 and by 2007, the major changes were between the local environment, the agricultural sector, and the industrial sector. The other ecological relationships did not change during the study period.

3. By comprehensively analyzing the structure and functions of the urban water metabolic system, we can propose some ways to further optimize the ecological structure and the ecological relationships among the components of the system. To ensure that water supplies stabilize or improve, the rainwater collection and recycling components of the system must continue to improve, and water consumption by the industrial, agricultural, and domestic sectors must continue to decrease, perhaps by increasing reuse and recycling of water. However, it will not be sufficient to just stabilize water consumption, since the declining water table in the study area suggests that water continues to be used unsustainably, and measures must be taken to allow recharge of this water resource.

Although most urban water metabolic systems are more complex than the model we developed in this study, the model nonetheless provides a useful means of analyzing the main components of the system and their functional relationships. Using throughflow and utility analysis, we revealed the structure of the system and the types of ecological relationships among its components, and were able to use the results to interpret the problems facing the system. In the future, the model should be further optimized to provide a more precise simulation of the complexity of the real urban water system.

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