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

Yan Zhang [a], Zhifeng Yang [a,*], Brian D. Fath [b,c]

[a] State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China
[b] Biology Department, Towson University, Towson, MD 21252, USA
[c] Dynamic Systems Program, International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria

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ABSTRACT

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.

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 m^3, 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 2.4×10^9 m^3 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 0.6×10^9 m^3. By 2007, total water consumption had reached 3.5×10^9 m^3, with industrial, agricultural, domestic, and ecological water consumption of 0.6×10^9 m^3, 1.2×10^9 m^3, 1.4×10^9 m^3, and 0.3×10^9 m^3, 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

* Corresponding author. Tel./fax: +86 10 58807596.
E-mail address: zfyang@bnu.edu.cn (Z. Yang).

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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 rainwater 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

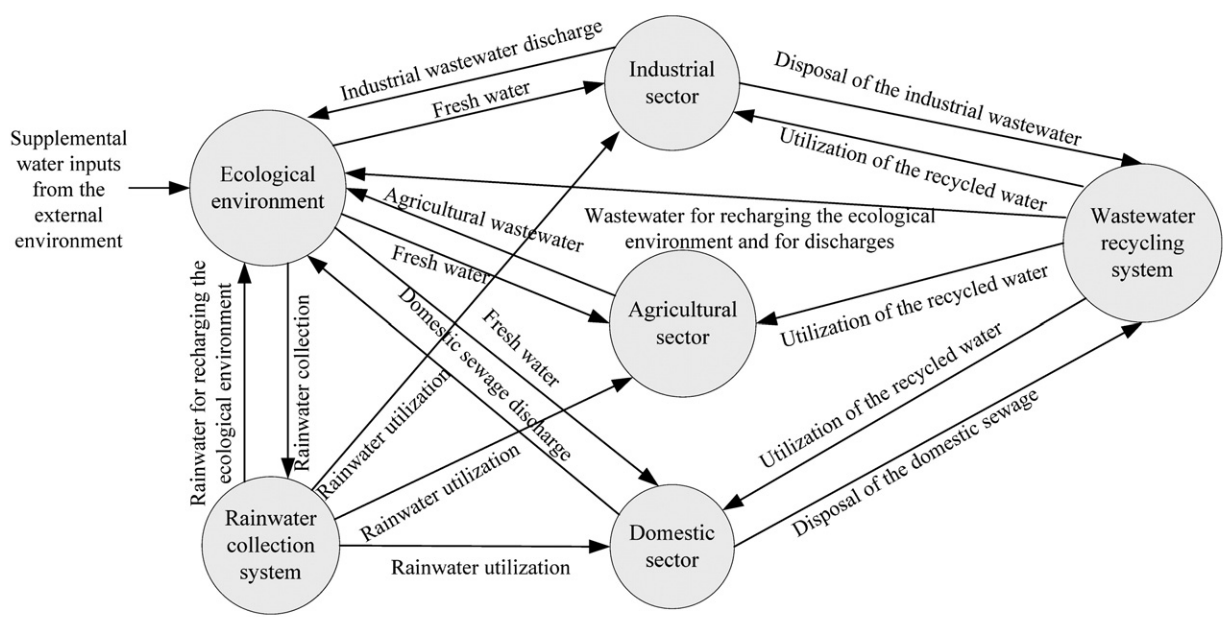

Fig. 1. A conceptual model of the water flows in the urban water metabolism.