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Functional assessment of interconnected aquatic ecosystems in the Baiyangdian Basin—An ecological-network-analysis based approach

Xufeng Mao, Zhifeng Yang*

State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, China

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ABSTRACT

Many individual aquatic ecosystems are hydraulically interconnected and form specific network structures that display integral characteristics. The functional assessment of individual aquatic ecosystems is important, yet inadequate, for developing effective protection and restoration policies in basins, in which multiple interconnected aquatic ecosystems are involved. Here, we developed a framework to use ecological network analysis for functional assessment of a large system composed of various aquatic ecosystems in the context of network-based management. Five storage factor-included network indices were used to characterize the system functioning that was defined here as a performance with a certain of system activities and organization. A deviation index (D), combining normalized input, internal and output ascendency, was used to analyze the degree and causes of system functional variation. China's Baiyangdian Lake, a typical aquatic ecosystem, was taken as a case study. The results demonstrated that these storage factor-included network indices could well depict the system attributes and provide integral functional assessment of the aquatic ecosystems network in the Baiyangdian Basin. The functions of the aquatic ecosystems network presented distinct seasonal fluctuations, and there was a continuous decline in system functioning over the period of 1959–1978. Both natural and human causes contributed to the functional degradation, while the latter one dominated the degradation. Current study provided an example of how the network analysis might improve the understanding of the integral functioning of interconnected aquatic ecosystems.

1. Introduction

Different types of aquatic ecosystems, such as rivers, lakes, marshes, estuaries, are important ecosystems of the earth, which perform many important ecological functions. For example, they recycle nutrients, store and purify water, augment and maintain stream flow, and provide habitats for a wide variety of living organisms (Rubec and Hanson, 2009). The functional assessment of aquatic ecosystems is an essential step for ecologists to develop effective ecosystem-based management strategies for ecosystem restoration and preservation. One can understand the status and variation of ecosystems function under the impacts of human activities. Much research has been done to assess the variation of aquatic ecosystems functions in a range of sampling sites (Brinson and Rheinhardt, 1996; Patrícioa et al., 2004, 2006; Christiana et al., 2009; Xu et al., 2011).

However, aquatic ecosystems are not isolated spaces but complex habitats, in which many biotic and abiotic connections at present. Among the abiotic connections, the flow of water creates permanent or temporary links among multiple aquatic ecosystems, which are, perhaps, the most important ones (Amezaga et al., 2002). These hydrological connections provide significant support (e.g., nutrients, information and energy transport) for maintaining ecosystem function.

Due to the closure characteristics (Molle et al., 2010), many aquatic ecosystems are, linked by complex hydrological processes in basins, acting as an integral system with specific network structure and functions at certain temporal and spatial scales (Mao et al., 2010). Thus, a comprehensive understanding of integral characteristics of these interconnected aquatic ecosystems, instead of an individual aquatic ecosystem, is also essential to maintain and restore their ecological functions in basins. Many studies have revealed the importance of preserving the ecological integrity of these aquatic ecosystems rather than an individual unit in achieving the effective protection and restoration of aquatic ecosystems (Tilley and Brown, 1998; Acreman and Dunbar, 2004; Wang and Jawitz, 2006; Cohen and Brown, 2007; Yang et al., 2009; Bodin and Saura, 2010). Sustainable use of aquatic ecosystems must explicitly consider the spatial and temporal interconnections among various aquatic ecosystems in basins (Amezaga et al., 2000).

Since many aquatic ecosystems are interconnected in basins, the functional assessment of individual aquatic ecosystems seems insufficient in providing enough information for holistic and sustainable ecosystem management. Without considering this pattern

* Corresponding author. Tel.: +86 10 58807596; fax: +86 10 58800397.
E-mail address: zfyang@bnu.edu.cn (Z. Yang).

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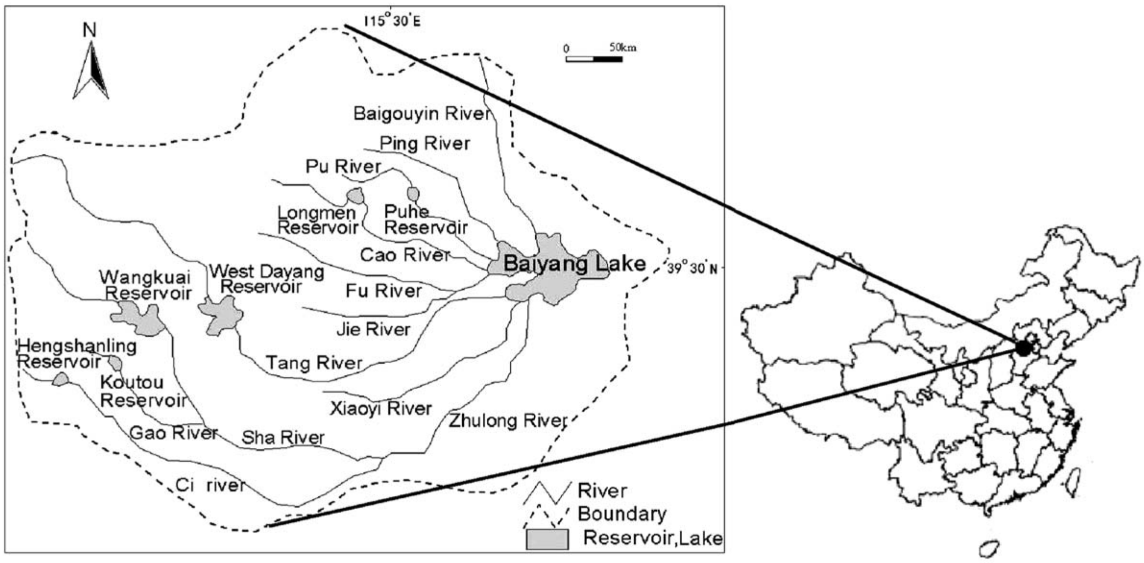

Fig. 1. The Baiyangdian Basin and its geographical location in China.

of connectivity, one cannot assess the ecosystem functions properly (Leibowitz et al., 2000). Integral functional assessment of these interconnected aquatic ecosystems is necessary but hard to realize. On the one hand, the current management practices are characterized by non-sustainable spatial divisions, aquatic ecosystems tend to be managed on an individual basis because of their size and limited jurisdictional area (e.g., Christiana et al., 2009). On the other hand, most research focused on establishing methods for the functional assessment of an individual aquatic ecosystem (e.g., Patrícioa et al., 2004, 2006; Christiana et al., 2009; Xu et al., 2011), no previous experience (to the best of our knowledge) can be used as reference for the functional assessment of multiple connected aquatic ecosystems.

Ecological network analysis (ENA) was developed initially to evaluate trophic networks but has broad applications (Ulanowicz, 1980, 1986, 1997; Fath and Patten, 1999). It can evaluate a system from the viewpoint of connectivity and flows (Schramski et al., 2006, 2007; Baird et al., 2009; Borrett and Salas, 2010; Zhang et al., 2010a,b). By ENA one can identify many indices of ecosystem functioning (e.g., Ascendency, Total System Throughput, Finn Cycling Index) and relate them to environmental or ecological phenomena (e.g., eutrophication, succession, disturbance), which provide important information for ecosystems management (Heymans et al., 2002; Tobor-Kaplon et al., 2007; Christiana et al., 2009).

In this paper, we tried to establish a new ENA-based method to better understand the integral functional characteristics of a system organized by associated aquatic ecosystems. We applied it to a case study of the Baiyangdian basin in Northern China to demonstrate the new method's effectiveness. The paper is organized as follows: Section 2 presents the method and data used to measure the holistic function of the aquatic ecosystem network in the Baiyangdian Basin. Section 3 reports and interprets the studied results and Section 4 discusses some considerations of the current study. Section 5 concludes with a simple retrospect to the entire paper.

2. Materials and methods

2.1. Study area

The Baiyangdian Basin is located in the middle of the North China Plain and covers an area of 31,199 km^2 (38.3-40.4°N, 113.39-116.11°E) (Fig. 1). It is in the semi-arid zone characterized by continental monsoons. Its average annual precipitation is 556 mm. There is a distinct seasonality in the annual rainfall pattern with about 80% (445 mm) occurring from June to September (Dong, 2009). The mean annual air temperature varies from 7.5 °C to 12.7 °C.

In this basin, the Baiyangdian Lake is of great economic and ecological significance. It is the largest remaining freshwater lake in Northern China. The lake serves as a sink for the water of nine rivers, including the Ci, Gao, Sha, Xiaoyi, Tang, Fu, Cao, Pu and Ping River. These nine upstream rivers are significant watercourses with two primary functions: firstly, to drain flood water during the flood season and, secondly, to transport water and nutrients into the lake, maintaining the viability of fish and other wildlife in the Baiyangdian Lake. Six large- or middle- scale reservoirs, including Hengshanling, Koutou, Wangkuai, West Dayang, Longmen and Pu reservoirs, have been constructed since the 1950s and have played a significant role in water resources allocations in the basin. The Baiyangdian Lake and the nine rivers together with the six reservoirs form a typical network, where all the aquatic ecosystems are hydraulically interconnected with each other.

The Baiyangdian Basin used to offer many important environmental and economic services in the past. In the last four decades, it is facing severe problems of ecological degradation due to the rapid population growth and fast economic development. Due to increasing water withdrawal, reservoirs shutoff, and underground-water exploitation, the phenomena of 'low' or 'no' inflows from upstream rivers into the lake becomes more and more frequent, resulting in the shrinkage of the Baiyangdian Lake and the obvious reduction of biodiversity in the lake (Zhong et al., 2008; Dong, 2009). Although great effort has been made to protect the Baiyangdian Lake in recent years, such as long distance water transfer from upstream reservoirs or other watersheds into the lake, the problem of ecological degradation in the Baiyangdian Lake continues. One key cause is the poor planning of the use and allocation of the basin's water resources because of the limited understanding of the integral characteristics of the ecological functions (Dong, 2009).

2.2. Data sources

We used the data of a 20-year period from 1959 to 1978 to demonstrate the following newly established method. Since the