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Network Analysis and Comparative Studies on Baiyangdian and Okefenokee Wetland Systems in China and US

X. F. Mao, Z. F. Yang*, and B. Chen

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

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ABSTRACT. Many individual wetlands are interconnected by complex hydrological processes, acting as a large wetland system (WS) with specific structure and function in certain temporal and spatial scale. An understanding of the holistic attributes of a WS is especially critical for the long-term persistence and biodiversity maintenance of various wetlands. In this study, we developed a framework to use ecological network analysis (ENA) in a holistic assessment to WSs. The Baiyangdian WS in China and the Okefenokee WS in USA were presented as two examples. Network models of two WSs were developed to facilitate the application of network analysis, in which network nodes represent river segments, lakes and reservoirs, and network links are directional representations of water flow between nodes. Using 25 network indicators, we compared two WSs to show how ENA can be used to provide a unified benchmark for holistic comparisons. Results show there is a large difference, such as system activity, inner organization and so on, between two WSs. The Baiyangdian WS is a sparsely connected system with a connectance of 0.13 while the Okefenokee WS is a well connected system with a connectance of 1.08. Comparing with the Okefenokee WS, the Baiyangdian WS has higher inner organization (2.25 bits versus 1.27 bits) but lower system activities (0.19 m^3y^{-1}/m^2 versus 0.34 m^3y^{-1}/m^2). System ascendency of the Baiyangdian WS is slightly lower than that of the Okefenokee WS (0.43m^3y^{-1}/m^2 versus 0.42 m^3y^{-1}/m^2). On the basis of the current results, we proposed the network-based indicators for assessing the holistic attributes of WSs. This study could provide a novel prospective and methodology for evaluating system attributes at the system level and contributes to the basin-wide wetland protection and water resources management.

Keywords: wetland system, ecological network analysis, system attributes, the Baiyangdian basin, the Okefenokee watershed

1. Introduction

As the key habitats and important landscapes, wetlands are the first major ecosystems to be protected by an international treaty. Wetlands are not isolated spaces but dynamic, complex habitats with biotic and abiotic connections at present. Among the abiotic connections, those related to the flow and quality of water is, perhaps, the most important ones (Amezaga et al., 2002). Hydrological conditions determine the seasonal fluctuations in the rainfall or inundation patterns, which create important links (e.g., lateral, vertical or longitudinal) among wetlands. Once individual wetlands are hydraulically connected, they present a specific network structure with holistic characteristics (Mao et al., 2010; Yang and Mao, 2011), acting as a whole wetland system (WS).

Researches on individual wetland sites, such as environmental flow requirements (Yang et al., 2005; Sun et al., 2009; Chen and Zhao, 2010), wetland functional assessment (Krause et al., 2003; Seilheimer et al., 2009; Xu et al., 2010), wetland restoration (Mitsch and Wang, 2000) and ecological sustainability (Cai et al., 2010, 2011), have provided useful information for the management of ecosystems. However, these researches are yet inadequate in providing holistic information for wetland management of basins, in which multiple wetlands are interconnected through various hydrological processes. The Baiyangdian Lake in northern China can be given as an example that exhibits the disadvantages of wetland management on an individual basis. It is the largest remaining fresh water in northern China, which served many important environmental and economic services in history. In recent four decades, it is facing a number of problems associated with severe ecological and environmental degradation. The frequencies of 'low' or 'no' inflows from upstream rivers into the lake have become more acute, resulting in shrinkage of the lake and a great reduction in productivity and biodiversity (Zhong et al., 2008). The primary reason that underlie above situation relates to poor planning in the use and allocation of the basin's water resources with a limited understanding of its integral role in local wetlands network (Dong, 2009). The lake has been managed in isolation, without considering its connections with upstream rivers and reservoirs. Actually, wetland management in many regions is characterized by conceptual, thematic and spatial divisions

* Corresponding author. Tel.: +86 10 58807951; fax: +86 10 58807951.
E-mail address: zfyang@bnu.edu.cn (Z. F. Yang).

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generated by the same fragmented worldview behind nonsustainable growth (Davis, 1993). Wetlands tend to be managed on an individual basis because of their size and limited jurisdictional area (Christiana et al., 2009).

The sustainable use of wetlands and water resources requires management approaches that incorporate explicitly the spatial and temporal interconnections among different wetlands in basins (Amezaga et al., 2000). Safeguarding and understanding the integral attributes of these connected wetlands is foremost (Amezaga et al., 2002), quite a few studies have revealed the importance of preserving the ecological integrity of a WS rather than an individual wetland in achieving effecttive protection and restoration of wetland ecosystems (Tilley and Brown, 1998; Cohen and Brown, 2007; Wang and Jawitz, 2006; Yang et al., 2009). However, it is difficult to understand the holistic attribute of these interconnected wetlands. There is absence of valid methods to deal with the above difficulty.

To get more information of WSs, we introduced ecological network analysis (ENA) method in the current study. This method can consider connectivity and evaluate a system from the viewpoint of connectivity and flows. We applied it to two case studies of the Baiyangdian basin in Northern China and the Okefenokee watershed in America to demonstrate the effectiveness of the method. Through the comparison of ENA indicators of two WSs, we probed into their different network attributes. To eliminate confusion, we have adopted the Ramsar Convention definition of wetlands, i.e., "areas of marsh, fen, peatland, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salt, including marine waters, the depth of which at low tide does not exceed six meters". This definition is suitable for the discussion (outlined below) as it deals with wetlands from a broad point of view.

The paper is organized as follows: Section 2 presents the method and data employed to measure the holistic attributes of two WSs. Section 3 reports and interprets the studied results and Section 4 discusses some considerations with the current study. Section 5 concludes with a simple retrospect to the entire paper. Specific objectives addressed here were as follows:

- To develop and analyze wetland networks for the holistic system assessment of interconnected wetlands.
- To explore the use of network analysis in detecting system-level information of wetland networks.

2. Methods

2.1. Study Area

The Baiyangdian Basin is located in the middle of the North China Plain and covers a surface area of 31,199 km^2 (39.4^o ~ 40.4^o N, 113.39^o ~ 116.11^o E) (Figure 1). The climate is characterized by continental monsoons with mean annual rainfall 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 about 7.5 °C at higher altitudes to about 12.7 °C in the lower part of the basin. The Baiyangdian Lake in this basin is the largest remaining freshwater lake in northern China. The lake serves as a sink for 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 nutrition, assuring the continued viability of flow conditions required for fish and other wildlife resources in Lake Baiyangdian. Six large- and middle-scale reservoirs, including Hengshanling, Koutou, Wangkuai, West Dayang, Longmen and Pu, were constructed in 1950s and have played a significant role in basin water resources allocations.

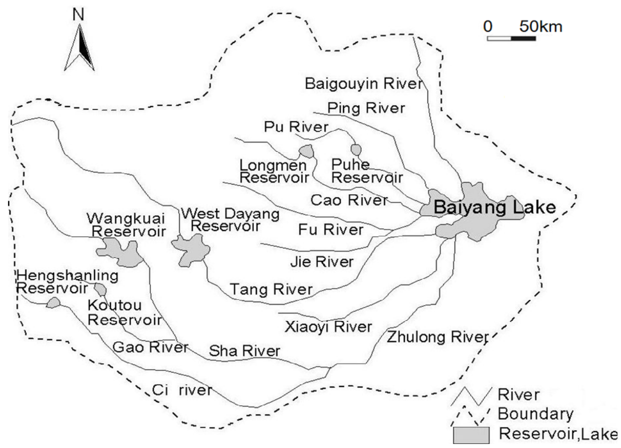

Figure 1. The Baiyangdian Basin in the north of China.

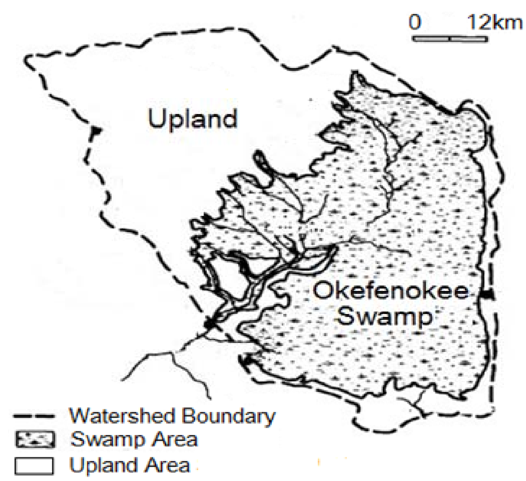

Figure 2. The Okefenokee watershed in USA (reconstructed from Patten and Matis, 1982).

In contrast to the largely modified Baiyangdian Lake, the Okefenokee Swamp is one of the largest natural freshwater wetland systems in the world though human alterations have also affected the amount of water flow and its variability in the wetland (Loftin, 1997). Management goals of the swamp include providing recreational opportunities for visitors while preserving the integrity of the numerous wetland ecosystems through the protection and restoration of the natural habitats (U.S. FWS, 2009). It is a swamp-dominated hydrological sys-

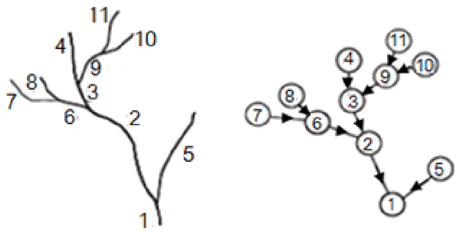

Figure 3. Ways of depicting a simple stream network for network analysis (reconstructed from Erős et al., 2011).

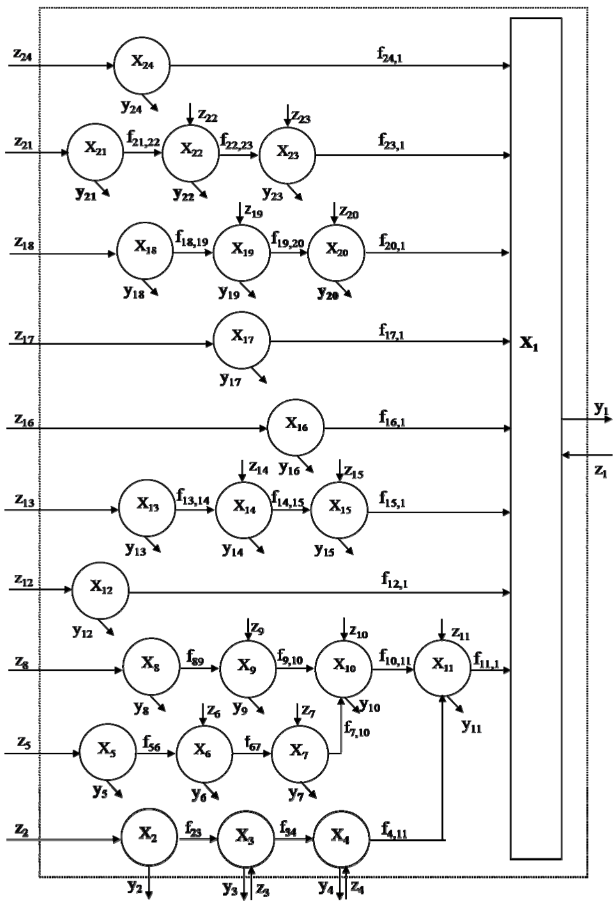

Figure 4. Network model of Baiyangdian wetland system (1-Baiyangdian Lake; 2-Upstream of Ci river; 3-Hengshanling Reservoir; 4-Downsream of Ci River; 5-Upstream of Gao River; 6-Koutou Reservoir; 7-Downstream of Gao River; 8-Upstream of Sha Rver; 9-Wangkuai Reservoir; 10-Downstream of Sha River; 11-Zhulong River; 12-Xiaoyi River; 13-Upstream of Tang River; 14-West Dayang Reservoir; 15- Downstream of Tang River; 16-Jie River; 17-Fu River; 18-Up-stream of Cao River; 19-Longmen Reservoir; 20-Downsream of Cao River; 21-Upstream of Pu River; 22-Pu river Reservoir; 23-Downsream of Pu River; 24-Ping River).

tem situating on the Lower Atlantic Coastal Plain of southeastern Georgia in the USA (Figure 2). The Okefenokee watershed has an area of 3,702 km^2, of which 1,891 km^2 or 51% is occupied by the Okefenokee Swamp; the remaining 1,811 km^2 or 49% is pine uplands (Rykiel, 1982). Its climate is humid subtropical with a mean annual precipitation of 1,285mm: hot and wet during May to September, warm and dry in October to November, cool and moist in December-February, and warm and moist during March to April (Rykiel, 1977). Detailed information can be gotten from Patten and Matis (1982).

2.2. Network Models Description

Reservoir and lake are directly considered as network nodes in our models. Ways of depicting a river network are illustrated in Figure 3. The segments and confluences are shown as the nodes and links, respectively (Erős et al., 2011). Six rivers, including the Ci, Gao, Sha, Tang, Cao and Pu, were further divided into upstream and downstream segments (as reservoirs were constructed within each of these rivers). By the above method, we developed a 24-node Baiyangdian WS network model depicted in Figure. 4. A 4-component network model of the Okefenokee Swamp is depicted in Figure 5. Four subsystems including upland surface, upland groundwater, swamp surface and swamp subsurface were considered as main nodes in the model (Patten and Matis, 1982).

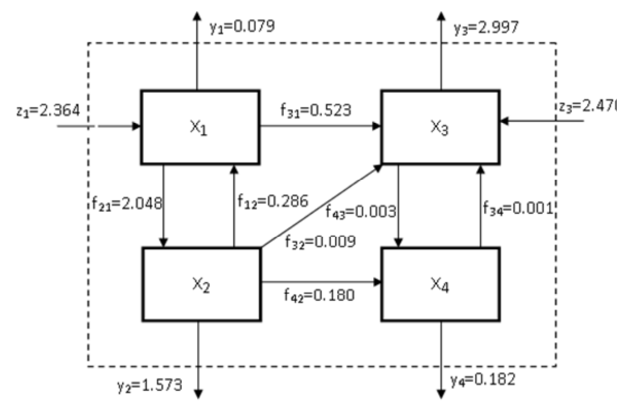

Figure 5. Quantified network model of Okefenokee wetland system (units: 10^8 m^{3}y^{-1}, 1-upland surface; 2-upland groundwater; 3-swamp surface; 4-swamp subsurface. Reconstruct from Patten and Matis, 1982).

In the above two models, f_{ij} represents statistic interflows (m^{3}y^{-1}) of water from compartment i to j; z_k and y_k represent boundary inputs (m^{3}y^{-1}) and boundary outputs (m^{3}y^{-1}) of the kth compartment, respectively; x_k denotes storage of component k. z_k is comprised of precipitation, and surface and ground water runoff from system boundary to system components. y_k includes the following items: (i) natural loss due to evapotranspiration, deep seepage, lateral leakage and so on; (ii) sheet and stream flow out of system boundary through watercourses; (iii) water abstraction for the purpose of industrial use, irrigation, and domestic water supply.

2.3. Ecological Network Analysis Theory and Techniques

ENA is a systems-oriented modeling technique for examining the structure and flow of materials in ecosystems. It places greater emphasis on the transfers between nodes rather than the characteristics of individual nodes (Ulanowicz, 1980, 1986,

Table 1. Algorithms for Network Indices *

NO.	Name	Symbol	Algorithms
1	Total System Throughput	TSTP	$=\sum_{i=1}^{n+2}\sum_{j=1}^{n+2}T_{ij}$
2	Average Mutual Information	AMI	$=\sum_{i,j}\frac{T_{ij}}{T_{..}}\log_2\left[\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}\right]$
3	Ascendency	A	$=\sum_{ij}T_{ij}\log_2\left[\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}\right]$
4	Import Ascendency	A_0	$=\sum_{j=1}^{n}T_{n+1,j}\log_2\left[\frac{T_{n+1,j}T_{..}}{T_{n+1.}T_{.j}}\right]$
5	Internal Ascendency	A_i	$=\sum_{ij=1}^{n}T_{ij}\log_2\left[\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}\right]$
6	Export Ascendency	A_e	$=\sum_{j=1}^{n}T_{j,n+2}\log_2\left[\frac{T_{j,n+2}T_{..}}{T_{.n+2}T_{j.}}\right]$
7	Overhead	Ø	$=\sum_{ij}T_{ij}\log_2\left[\frac{T_{ij}^2}{T_{i.}T_{.j}}\right]$
8	Overhead from Import	$Ø_0$	$=-\sum_{j=1}^{n}T_{n+1,j}\log_2\left[\frac{T_{n+1,j}^2}{T_{n+1.}T_{.j}}\right]$
9	Redundancy	R	$=-\sum_{ij=1}^{n}T_{ij}\log_2\left[\frac{T_{ij}^2}{T_{i.}T_{.j}}\right]$
10	Overhead from Export	$Ø_e$	$=-\sum_{j=1}^{n}T_{j,n+2}\log_2\left[\frac{T_{j,n+2}^2}{T_{.n+2}T_{j.}}\right]$
11	Development Capacity	C	$=-\sum_{ij}T_{ij}\log_2\left[\frac{T_{ij}}{T_{..}}\right]$
12	Import Capacity	C_0	$=-\sum_{j=1}^{n}T_{n+1,j}\log_2\left[\frac{T_{n+1,j}}{T_{..}}\right]$
13	Internal Capacity	C_i	$=-\sum_{j=1}^{n}T_{ij}\log_2\left[\frac{T_{ij}}{T_{..}}\right]$
14	Export Capacity	C_e	$=-\sum_{j=1}^{n}T_{j,n+2}\log_2\left[\frac{T_{j,n+2}}{T_{..}}\right]$
15	Ascendency / Capacity	A/C	=A/C
16	Internal Ascendency / Internal Capacity	A_i/C_i	$=A_i/C_i$
17	Overhead / Capacity	Ø/C	=Ø/C
18	Redundancy / Capacity	R/C	=R/C
19	Redundancy / Internal Capacity	R/C_i	$= R/C_i$
20	Import Ascendency / Ascendency	A_0/A	$= A_0/A$
21	Internal Ascendency / Ascendency	A_i/A	$= A_i/A$
22	Export Ascendency / Ascendency	A_e/A	$= A_e/A$
23	Link density	L/n	= L/n
24	Connectance	L/n(n-1)	= L/n(n-1)
25	Finn's cycling index	FCI	$=TST_c/TST_s$

* $T_{..}$ is the TSTP; (n+1) are boundary import; (n+2) are boundary export.

1997) and identifies and quantifies the direct and indirect effects in that system (Fath and Patten, 1999; Fath and Borrett, 2006). The tools of ENA involve identification and quantification of stocks and fluxes of key ecological "currencies" such as energy, carbon, nitrogen, and phosphorus that is exchanged in a network. Compared to dynamic models, the network approach is often atemporal-the organizational relations of stocks and fluxes are studied for a snapshot in time during which they are treated as unchanging (Fiscus, 2009).

In the present study, we focus on the ascendency theory developed by Ulanowicz (1980, 1986, and 1997). It is an important branch of ENA, which involves the joint quantification of overall system activity with the organization of component processes and can be used to specifically assess system functioning (Patrícioa et al., 2004). It has wide applicability that can provide a measure of the overall degree of organization inherent in purely physical flow fields, such as carbon, nitrogen, and phosphorus. This theory can be applied to any currency that is exchanged in a network (Pahl-Wostl, 1992, 1995). Hence, this tool was not only successfully applied to specific ecological systems, such as Chesapeake Bay (Ulanowicz and Tuttle, 1992), Mondego Estuary (Patrícioa et al., 2006) and Neuse River Estuary (Christiana et al., 2009), but also extended to other disciplines such as water use systems (e.g., Li et al., 2009), human food supply systems (e.g., Fiscus, 2009) and trade systems (e.g., Mao and Yang, 2011).

The ascendency theory comprises a set of analytical tools and computer algorithms for understanding the holistic and non-mechanistic nature of ecosystems. In this study, we focused on 25 network indicators described in Table 1. These indicators can be divided into three categories: whole-system indicators, component system indicators, and dimensionless ratio-based indicators. Five of the 25 ENA indicators describe the whole system, including Total System Throughput (TSTP), Average Mutual Information (AMI), Ascendency (A), Overhead (Ø), and Development Capacity (C). The TSTP reflects the level of system activity measured by the sum of the magnitudes of all the flow exchanges occurring in the system (Ulanowicz, 1997). The AMI represents the organization inherent in a system because it captures the average amount of constraint exerted upon an arbitrary amount of mass as it flows from any one compartment to the next (Rutledge et al., 1976). Ascendency is the production of TSTP and AMI that quantifies both the level of system activity and the degree of the organization (Ulanowicz, 1980). Development Capacity is measured by the diversity of the flows (calculated using the Shannon-Wiener formula), as normalized by the total system throughput (Ulanowicz and Norden, 1990). Overhead represents multiplicity of pathways; consequently, when it is high, it is said to reflect a system under rigorous environmental con-ditions (Ulanowicz and Norden, 1990), so it is generated by structural ambiguities deriving from multiplicities in system inputs, exports, dissipations and internal exchanges (Ulanowicz, 2002, Patrícioa et al., 2006). The sum of the Ascendency and Overhead is called the Developmental Capacity. It functions as a mathematical upper limit on ascendency, which is the maximum value that Ascendency can take.

Component system indicators break down some of the whole-system indicators into pieces that describe how imports, exports, respiration, and internal flows contribute to the whole-system indicator values. Specially，these are decomposed Ascendency (A_0, A_i, A_e, A_s), Overhead [$Ø_0$, Redundancy(R), $Ø_e$,

Table 2. Flows of Baiyangdian Wetland System Network Model (Units: 10^8 m^3 y^{-1})

Comp	1	2	3	4	5	6	7	8	9	10	11	12
Inputs	z_1	z_2	z_3	z_4	z_5	z_6	z_7	z_8	z_9	z_{10}	z_{11}	z_{12}
data	2.013	1.224	0.371	0.219	0.428	0.104	0.095	3.738	0.772	0.303	0.083	0.451
Comp	13	14	15	16	17	18	19	20	21	22	23	24
Input	z_{13}	z_{14}	z_{15}	z_{16}	z_{17}	z_{18}	z_{19}	z_{20}	z_{21}	z_{22}	z_{23}	z_{24}
data	3.437	0.826	0.225	0.152	0.707	0.875	0.238	0.098	0.303	0.038	0.084	0.304
Comp	1	2	3	4	5	6	7	8	9	10	11	12
Output	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}	y_{12}
data	7.914	0.095	0.745	0.597	0.037	0.126	0.119	0.146	1.223	0.309	0.926	0.122
Comp	13	14	15	16	17	18	19	20	21	22	23	24
Output	y_{13}	y_{14}	y_{15}	y_{16}	y_{17}	y_{18}	y_{19}	y_{20}	y_{21}	y_{22}	y_{23}	y_{24}
data	0.437	1.416	1.308	0.077	0.271	0.065	0.278	0.166	0.012	0.115	0.106	0.033
Comp	1	2	3	4	5	6	7	8	9	10	11	12
Interflow	-	f_{23}	f_{34}	$f_{4,11}$	f_{56}	f_{67}	$f_{7,10}$	f_{89}	$f_{9,10}$	$f_{10,11}$	$f_{11,1}$	$f_{12,1}$
data	-	1.129	0.775	0.375	0.391	0.369	0.345	3.593	3.141	3.480	2.637	0.329
Comp	13	14	15	16	17	18	19	20	21	22	23	24
Interflow	$f_{13,14}$	$f_{14,15}$	$f_{15,1}$	$f_{16,1}$	$f_{17,1}$	$f_{18,19}$	$f_{19,1}$	$f_{20,21}$	$f_{21,22}$	$f_{22,1}$	$f_{23,1}$	$f_{24,1}$
data	2.964	2.374	1.291	0.436	0.044	0.815	0.775	0.705	0.291	0.214	0.192	0.271

$Ø_s$] and Capacity (C_0, C_i, C_e, C_s) measures (Ulanowicz and Norden, 1990). A_0, $Ø_0$ and C_0 are, respectively, Ascendency, Overhead and Capacity generated by boundary import; A_i, R and C_i are, respectively, internal Ascendency, internal Overhead and internal Capacity, which generate from network interflows; A_e, $Ø_e$ and C_e are, respectively, Ascendency, Overhead and Capacity generated by boundary export; A_s, $Ø_s$ and C_s correspond, respectively, to dissipative Ascendency, dissipative Overhead, and dissipative Capacity. In our study, we make no distinction between export and dissipation. Thereafter, A_s, $Ø_s$ and C_s are equal to zero and are not considered further.

Ratio-based indicators can be used to quantify ecosystem health and condition (Ulanowicz, 1986, 1997). For examples, Ascendency over Capacity (A/C) describes network efficiency and is optimized at system maturity, while the internal ascendency to internal capacity ratio A_i/C_i examines internal network efficiency. Internal Ascendency over the Internal Capacity (A_i/C_i) describes internal network efficiency. Anther possibility is to examine the values of Redundancy over Capacity (R/C), which potentially describes the systems resilience to disruption (Ulanowicz, 1986). Overhead over Capacity ($Ø/C$) might show how the Capacity is limited by the Overhead. A_i/A gauges how much system ascendency is generated from interflow. The last three ratio-based indicators including Link density, Connectance and Finn's cycling index (FCI) depict the basic topological and flow characteristics of two WSs.

The above three categories of indicators can be used to specifically assess different system attributes of a WS. The TSTP reflects the system activity, which is affected by natural characteristics such as basin size, particular climate, landform, and general properties of soil and vegetation as well as water use by human. The organization by which the component processes are hydrologically linked can be detected by AMI. Ascendency that combines TSTP and AMI can be used to measure the system size and organization of WSs. Decomposed indicators are also correlative with hydrological conditions of a WS. For instance, A_0 may exhibit the characteristics of boundary input, which corresponds to local precipitation and surface runoff. A_e characters the boundary output, which closely correlates to natural and anthropogenic causes, such as evaporation and water abstraction. The internal measure A_i is generated by interflows between components, which is highly associated with environmental flow allocations of different wetlands. Dimensionless ratio-based indices, such as A/C and A_i/A, may provide a foundation for a holistic comparison of ascendency structure between different WSs. Software named NetMatCal was utilized for our calculations (Latham, 2006).

Ratio-based indicators can be used directly to compare the system characteristics of two WSs. However, non-ratio indicators are unsuitable for a direct comparison because land area of two WSs is different. To facilitate their comparisons, we used normalized indicators in this study. Normalized indicators can be calculated as the ratio between network indicators and basin (watershed) area, which can be explained as network indices generated in unit area (units: m^3y^{-1}/m^2).

2.4. Data Sources

Data in 1962 were used to quantify the Baiyangdian WS model. Hydrological, and weather monitoring have taken place the Baiyangdian Basin since 1956, so quantified flow data, including precipitation, runoff and evaportranspiration, can be obtained from hydrological yearbooks issued by the Water Resources Department of Hebei Province. Where databases were incomplete or absent, we used the mass balance method to quantify our networks. Details are reported in Table 2.

3. Results

As reported in Table 3, the ENA generated total 50 network indicators with respect to two WSs. The basic structures and flow characteristics of two WSs can be detected by connec-

Table 3. Comparisons of Network Information Indices, Connectance Indices and FCI Index

WS	1-Baiyangdian		2-Okefenokee		1 versus 2
Information Indices	Primary Value	Unit Value	Primary Value	Unit Value	
TSTP	60.33	0.19	12.71	0.34	Low
AMI	2.25	-	1.27	-	High
A	135.96	0.42	16.17	0.43	Low
A_0	18.21	0.06	5.66	0.15	Low
A_i	101.74	0.31	4.76	0.12	High
A_e	16.02	0.05	5.74	0.15	Low
Ø	170.50	0.53	18.65	0.50	High
$Ø_0$	73.72	0.23	5.91	0.16	High
R	33.47	0.10	5.80	0.15	Low
$Ø_e$	63.29	0.19	6.93	0.18	High
C	306.49	0.95	34.82	0.94	High
C_0	91.94	0.28	11.57	0.31	Low
C_i	135.21	0.42	10.56	0.28	High
C_e	79.31	0.24	12.68	0.34	Low
A/C	44%	-	46%	-	Low
Ø/C	56%	-	54%	-	High
R/C	11%	-	17%	-	Low
A_i/C_i	75%	-	45%	-	High
R/C_i	25%	-	55%	-	Low
A_0/A	13%	-	35%	-	Low
A_i/A	75%	-	29%	-	High
A_e/A	12%	-	36%	-	Low
Connectance indices					
Link density	2.96	-	3.25	-	Low
Connectance	0.13	-	1.08	-	Low
Finn's cycling index	0	-	0.15	-	Low

tance index and Finn's cycling index. The Baiyangdian WS is a sparsely connected network with a link density 2.96 and a connectance of 0.13, respectively. Contrarily, the Okefenokee WS is a well connected system with a link density of 3.25 and a connectance of 1.08, respectively. There is no recycling flow occurred in the Baiyangdian WS (FCI = 0) while the FCI index of the Okefenokee WS is 0.15. The hydrological interactions in the Okefenokee WS are much more diverse than that of the Baiyangdian WS.

Whole-level indices are useful for comparing the total system activities and the hydrological organization inherent in flow topology. For example, the Okefenokee WS (0.34 m^3y^{-1}/m^2) is far more active than the Baiyangdian WS (0.19 m^3y^{-1}/m^2). Two reasons may contribute to above results: Firstly, the Okefenokee WS is located in humid subtropical area with a mean annual precipitation of 1,285mm while the Baiyangdian WS is located in semi-arid zone with a mean annual precipitation of 556 mm. Hydrological activities in the former one will definitely be more active than that of the latter WS. Secondly, the area basis of the Baiyangdian WS is the entire basin, but some water quantity data were not included in our calculations. Index AMI is markedly higher in the Baiyangdian WS (2.25) than that of the Okefenokee WS (1.27). We attribute it to their distinct network structures. The Okefenokee WS exhibits greater complexity than the Baiyangdian WS with chain structure. The *Ø* and *C* of the Baiyangdian WS are slightly higher than those of the Okefenokee WS. When the ascendency is regarded, one may notice that the indicator is 0.43 (m^3y^{-1}/m^2) of the Okefenokee WS, which is slightly higher than the corresponding indicator in the Baiyangdian WS (0.42 m^3y^{-1}/m^2). Ascendancy may be viewed as an indicator of efficient system performance (Ulanowicz, 1997). However, we are not going to draw a conclusion that the Okefenokee WS is more efficient than that of the Baiyangdian WS. These network indicators reflect only the network characteristics of a WS. We suggest that time series studies can be developed to detect the dynamics of a WS.

Comparing with system-level indicators, component indicators reflect more specific information of system properties. For example, A_0 and A_e of the Baiyangdian WS are, respectively, 0.06 and 0.05 m^3y^{-1}/m^2), which are much lower than those of Okefenokee WS (0.15 and 0.15 m^3y^{-1}/m^2). Contrarily, A_i is significantly higher in the Baiyangdian WS (0.31 m^3y^{-1}/m^2) than that of the Okefenokee WS (0.12 m^3y^{-1}/m^2). We considered that it is closely correlated to their topological flow characteristics. For the Baiyangdian WS, it is acyclic network with strong connection (interflow) between upstream components and downstream components. As to the Okefenokee WS, it is a well connected network with moderately or weak connections (interflow) between system components. As mentioned above, Overhead and Capacity of two systems are equal but differ apparently in component Overhead and Capacity. The Baiyangdian WS has less Redundancy (0.10 m^3y^{-1}/m^2) than the Okefenokee WS (0.15 m^3y^{-1}/m^2).

Dimensionless ratio-based indicators can represent holistic organization of a WS or contribution of different parts of flow to overall system performance. The fraction of the development capacity that appears as ordered flow (A/C) is 44% in the Baiyangdian WS, which is slightly lower than the corresponding fraction of the Okefenokee WS (46%). Conversely, Overhead over Capacity ($Ø/C$) of the Baiyangdian WS (56%) is slightly higher than that of Okefenokee WS (54%) (Notice that the A and $Ø$ will always vary in opposite direction). The internal network efficiency of the Baiyangdian WS (0.75) is much higher than that of Okefenokee WS (45%). It also indicates that the Okefenokee WS has more redundancy for the development of internal hydrological organization. For example, the R/C_i and R/C of the Okefenokee WS are, respectively, 55% and 17%, whereas the corresponding indicators of the Baiyangdian WS are 25% and 11%, respectively. The ratio-based component Ascendency exams how much the system ascendency is generated from inputs, interflows and outputs. One can easily find that the distribution of Ascendency in Okefenokee WS is more homogeneous than that of the Baiyangdian WS. Three indicators, including A_0/A, A_i/A and A_e/A in the Okefenokee WS are, respectively, 35%, 29% and 36%, whereas the corresponding indicators of the Baiyangdian WS are, respectively, 13%, 75% and 12%.

4. Discussion

Connectivity is a major concern for the maintenance of wildlife populations, ecological flows, and many other functions (Saura and Pascual-Hortal, 2007). Hydrological connectivity is especially critical for the long-term persistence and diversity of fish populations and assemblages, and fragmentation of aquatic ecosystems (Erős et al., 2011). There is an increasing need for an integrated wetland management that recognizes patterns of flow form, hydrologic function, and biotic response within the context of watershed characteristics and wetlands network location (Shaw and Cooper, 2008). The Baiyangdian Lake is a focal node of the Baiyangdian WS while its connections with upstream network components should not be ignored. It is impossible to restore the ecological function of the lake if we cast our eyes only on the lake itself. In a similar vein, the connections between different hydrological nodes are also important for maintaining the integrality and basic function of the Okefenokee WS. If vertical and horizontal connections among four subsystems were destroyed, the swamp cannot survive long.

With increasing water withdrawals and hydrological modifications, more and more hydrological connections (includes longitudinal, horizontal and vertical) among wetlands will be destroyed, and increasing wetlands are facing the challenge in maintaining their hydrological integrity. Holistic assessment to those interconnected wetlands can highlight the importance of hydrological connections. Integrating information from different methods (e.g., ecological networks) is challenging, but can be fruitful in uniting research areas (Cumming et al., 2010; Cai et al., 2009a, b). ENA method can be served as a potential framework for predicting the evolution of a WS influenced by anthropogenic activities and environmental changes (Mao et al., 2010). These network indicators are not just the sum of different water flows within the network but calculated through an information-based method that combines numerous environmental factors into a single value (Ulanowicz, 1980, 1986, 1997). With it one can identify numerous indices of WS functioning (e.g., A, $TSTP$, A_i/A) and relate them to environmental phenomena (e.g., ecological degradation, disturbance) (Ulanowicz and Norden, 1990). A potential use of the wetland network analysis may be the comparative studies on system dynamics. For example, a less modified WS should have higher A_i or A_i/A than those of the same but largely modified WS because less water was consumed in the 'metabolism' processes, which is mostly affected by water withdrawal for anthropogenic purposes (Mao et al., 2010).

Wetland network and food network are different but with some similarities. Each wetland node in the network transports 'information' through water transfer between a message source (e.g., upstream wetland) and a message receiver (e.g., downstream wetland component). A wetland network can be interpreted as the result of information transmission between different system components. The topological structure of a WS reflects the general operating criteria, which depend largely on a particular climate, land use of soil and vegetation systems (Rodríguez-Iturbe and Rinaldo, 1997). In the light of the above results, we believe that these network indicators can depict the system attributes of a WS and provide a basis for system comparisons. For instances, the A/C of two WSs are 0.44 and 0.46, respectively. Comparing with the A/C of other networks, these values are intermediate between nitrogen network (0.52) of the U.S. beef supply chain (Fiscus, 2009) and the full Chesapeake Bay nitrogen (N) network (0.43) (Ulanowicz and Baird, 1999) and Florida Everglades cypress swamp carbon (C) network(0.33) (Ulanowicz et al., 1997). Baird et al. (1991) identified several problems with comparing ENA indicators across models with different topologies, however, the ratio indicators are considered to be the most comparable indicators (Heymans and Baird, 2000).

It is important to note the difference in topology, and especially recycling links, between a natural ecological network and a wetland network. For example, all interflows in the Baiyangdian WS are linear and no recycling flow occurs. Besides, WSs are different from ecosystems and we should be cautious about the interpretation of analysis results. Ulanowicz (1980, 1986, 1997) has stated that as systems grow and develop, the ascendency index should increase. We cannot readily draw the conclusion that a WS with higher ascendency is more mature than a WS with lower ascendency. The magnitude of network indicators depends on many factors, such as climate, landform and human activities. It is difficult to draw conclusions about a relationship between Ascendency and maturity in each system's development (Mageau et al., 1998). Scientific conclusions can be drawn only after the incorporation of network indicators and biotic response of the ecosystem. Specially, time series analysis is necessary for dynamic studies in WSs.

5. Conclusions

The present study intends to apply ENA to detect the whole network characteristics of two WSs. We compared the Baiyangdian WS to the Okefenokee WS to show how ENA captures system attributes and provides a holistic comparison between two WSs. Results show there is a large difference, from system activity to inner organization, between two WSs. We are not going to compare two WSs to find which one is better but to introduce a new method for holistic information of a WS.

Although considerable time required for data acquisition and network analysis, the current network models are relative simple and coarse. The reality situation should be more complicated than the current models. Nevertheless, the above network models explained some essential problems with respect to a wetland network, such as hydrologic organization, holistic characteristics, and so on. We believe the understandings of hydrologic organization and holistic characteristics of a WS are important for better water resources management and wetland restoration. The current case study can be served as an attempt to system-level wetland research with the promising ENA methodology, which stimulates development of more definitive information from systemic research.

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References

Amezaga, J.M., Santamaría, L., and Green, A.J. (2000). Wetland connectedness and policy fragmentation: steps towards a sustainable European wetland policy, *Phys. Chem. Earth (B)*, 25(7-8), 635-640. http://dx.doi.org/10.1016/S1464-1909(00)00077-0

Amezaga, J.M., Santamaría, L., and Green, A.J. (2002). Biotic wetland connectivity- supporting a new approach for wetland policy. Acta Oecol. 23, 213-222. http://dx.doi.org/10.1016/S1146-609X(02)01152-9

Baird, D., McGlade, J.M., and Ulanowicz, R.E. (1991). The comparative ecology of six marine ecosystems, *Philos. Trans. R. Soc. Lond., Ser. B: Biol. Sci.*, 333, 15-29. http://dx.doi.org/10.1098/rstb.1991.0058

Cai, Y.P., Huang, G.H., Tan, Q., and Chen, B. (2010). Identification of optimal strategies for improving eco-resilience to floods in ecologically vulnerable regions of a wetland, *Ecol. Model*, 222, 360-369. http://dx.doi.org/10.1016/j.ecolmodel.2009.12.012

Cai, Y.P., Huang, G.H., Wang, X., Li, G., and Tan, Q. (2011). An inexact programming approach for supporting ecologically sustainable water supply with the consideration of uncertain water demand by ecosystems, *Stoch. Env. Res. Risk. Assess. (in press)*. http://dx.doi.org/10.1007/s00477-011-0477-5

Cai, Y.P., Huang, G.H., Yang, Z.F., Lin, Q.G., and Tan, Q. (2009a). Community-scale renewable energy systems planning under uncertainty - An interval chance-constrained programming approach, *Renew. Sust. Energ. Rev.*, 13(4), 721-735. http://dx.doi.org/10.1016/j.rser.2008.01.008

Cai, Y.P., Huang, G.H., Yang, Z.F., Sun, W., and Chen, B. (2009b). Investigation of public's perception towards rural sustainable development based on a two-level expert system, *Expert Syst. Appl.*, 36(5), 8910-8924. http://dx.doi.org/10.1016/j.eswa.2008.11.032

Chen, H., and Zhao, Y.W. (2011). Evaluating the environmental flows of China's Wolonghu wetland and land use changes using a hydrological model, a water balance model, and remote sensing, *Ecol. Model*, 222, 253-260 http://dx.doi.org/10.1016/j.ecolmodel.2009.12.020

Christiana, R.R., Brinsona, M.M., Damea, J.K., Johnsonb, G., Peterson, C.H., and Baird, D. (2009). Ecological network analyses and their use for establishing reference domain in functional assessment of an estuary, *Ecol. Model*, 20, 3113-3122. http://dx.doi.org/10.1016/j.ecolmodel.2009.07.012

Cohen, M.J., and Brown, M.T. (2007). A model examining hierarchical wetland networks for watershed stormwater management, *Ecol. Model,* 201, 179-193. http://dx.doi.org/10.1016/j.ecolmodel.2006.09.029

Cumming, G.S., Bodin, Ö., Ernston, H., and Elmqvist, T. (2010). Network analysis in conservation biogeography: challenges and opportunities, *Divers Distrib.,* 16, 414-425. http://dx.doi.org/10.1111/j.1472- 4642.2010.00651.x

Davis, T.J. (ed.). (1993). *Towards the Wise Use of Wetlands. Wise Use Project*, Ramsar Convention Bureau, Gland, Switzerland.

Dong, N. (2009). Analysis of ecological drought and supplementing water to Baiyangdian Wetland from two reservoirs linking system. Agriculture University of Hebei. pp.21-26 (in Chinese).

Erős, T., Schmera, D., and Schick, R.S. (2011). Network thinking in riverscape conservation- A graph-based approach. *Biol. Conserv.* 144(1), 184-192. http://dx.doi.org/10.1016/j.biocon.2010.08.013.

Fath, B.D., and Patten, B.C. (1999). Review of the foundations of network environ analysis, *Ecosystems*, 2, 167-179. http://dx.doi.org/10.1007/s100219900067

Fath, B.D., and Borreet, S.R. (2006). A MATLAB® function for Network Environ Analysis. *Environ Modell Softw.* 21, 375-405. http://dx.doi.org/10.1016/j.envsoft.2004.11.007

Fiscus, D.A. (2009). Comparative network analysis toward characterization of systemic organization for human-environmental sustainability. *Ecol. Model.* 220, 3123-3132. http://dx.doi.org/10.1016/j.ecolmodel.2009.05.006

Heymans, J.J., and Baird, D. (2000). A carbon flow model and network analysis of the northern Benguela upwelling system, Namibia, *Ecol. Model*, 126, 9-32. http://dx.doi.org/10.1016/S0304-3800(99)00192-1

Krause, A.E., Frank, K.A., Mason, D.M., Ulanowicz, R.E., and Taylor, W.W. (2003). Compartments revealed in food-web structure, *Nature*, 426, 282. http://dx.doi.org/10.1038/nature02115

Latham, L.G. (2006). Network flow analysis algorithms, *Ecol. Model.,* 192, 586-600. http://dx.doi.org/10.1016/j.ecolmodel.2005.07.029

Li, Y., Chen, B., and Yang, Z.F. (2009). Ecological network analysis for water use systems-A case study of the Yellow River Basin, *Ecol. Model.,* 220(22), 3167-3173. http://dx.doi.org/10.1016/j.ecolmodel. 2009.08.007

Loftin, C.S. (1997). Okefenokee Swamp Hydrology. *Proceedings of the 1997 Georgia Water Resource Conference*, March. University of Gerogia, Athens, Georgia.

Mageau, M.T., Costanza, R. and Ulanowicz, R.E. (1998). Quantifying the trends expected in developing ecosystems, *Ecol. Model.*, 112, 1-22. http://dx.doi.org/10.1016/S0304-3800(98)00092-1

Mao, X.F., Yang, Z.F., Chen, B., and Chen, H. (2010). Examination of wetland system using ecological network analysis: A case study of Baiyangdian Basin, China. Procedia Engineering Science. *International Society for Environmental Information Sciences 2010 Annual Conference (ISEIS)*, 1, 433-445.

Mao, X.F., and Yang, Z.F. (2011). Ecological network analysis for a virtual water trade system: A case study for the Baiyangdian Basin in Northern China, *Ecol. Inform*., http://dx.doi.org/10.1016/j.ecoinf.2011.05.006

Mitsch, W.J., and Wang, N.M. (2000). Large-scale coastal wetland restoration on the Laurentian Great Lakes: Determining the potential for water quality improvement, *Ecol. Eng.*, 15, 267-282. http:// dx. doi.org/10.1016/S0925-8574(00)00081-1

Pahl-Wostl, C. (1992). Information theoretical analysis of functional temporal and spatial organization in flow networks, *Math. Comput. Model.*, 16, 35-52. http://dx.doi.org/10.1016/0895-7177(92)90044-L

Pahl-Wostl, C. (1995). *The Dynamic Nature of Ecosystems: Chaos and Order Entwined*. John Wiley and Sons, Chichester.

Patrícioa, J., Ulanowicz, R.E., Pardal, M.A., and Marques, J.C. (2004). Ascendency as an ecological indicator: a case study of estuarine pulse eutrophication, *Estuar, Coast Shelf. S.,* 60, 23-35. http://dx.doi.org/10.1016/j.ecss.2003.11.017

Patrícioa, J., Ulanowicz, R.E., Pardala, M.A., and Marques, J.C. (2006). Ascendency as an ecological indicator for environmental quality assessment at the ecosystem level: a case study, *Hydrobiologia*, 555, 19-30. http://dx.doi.org/10.1007/s10750-005-1102-8

Patten, B.C., and Matis, J.H. (1982). The water envions of Okefenokee Swamp: An application of static liner environ analysis*, Ecol. Model.,* 16, 1-50. http://dx.doi.org/10.1016/0304-3800(82)90 071-0

Rodríguez-Iturbe, I., and Rinaldo, A. (1997). *Fractal river basins: chance and self-organization.* Cambridge University Press.

Rykiel, E.J. (1977). *The Okefenokee Swamp watershed: water balance and nutrient budgets*. Ph.D. Dissertation, University of Georgia, Athens, GA.

Rykiel, E.J. (1982). *Okefenokee Swamp watershed: water balance, nutrient budgets, and modeling*. In: H.T. Odum and K.C. Ewell, Cypress Swamps.

Saura, S., and Pascual-Hortal, L. (2007). A new habitat availability index to integrate connectivity in landscape conservation planning: Comparison with existing indices and application to a case study, *Landscape Urban Plan*, 83(2-3), 91-103. http://dx.doi.org/10.10 16/j.landurb plan. 2007.03.005

Seilheimer, T.S., Mahoney, T.P., and Chow-Fraser, P. (2009). Comparative study of ecological indices for assessing human-induced disturbance in coastal wetlands of the Laurentian Great Lakes, *Ecolo. indic.*, 9, 81-91. http://dx.doi.org/10.1016/j.ecolind.2008.02.001.

Shaw, J.R., and Cooper, D.J. (2008). Linkages among watersheds, stream reaches, and riparian vegetation in dryland ephemeral stream networks, *J. Hydrol.,* 350, 68-82. http://dx.doi.org/10.1016 /j.jhydrol.2007.11.030

Sun, T., Yang, Z.F., Shen, Z.Y., and Zhao. R. (2009). Environmental flows for the Yangtze Estuary based on salinity objectives, *Commun. Nonlinear Numer. Simul.,* 14, 959-971. http://dx.doi.org/10. 1016 /j. cnsns. 2007.10.006.

Tilley, D.R., and Brown, M.T. (1998). Wetland networks for stormwater management in subtropical urban watersheds, *Ecol. Eng.,* 10, 131-158. http://dx.doi.org/10.1016/S0925-8574(98)00010-X

Ulanowicz, R.E. (1980). A hypothesis on the development of natural communities, *J. Theor. Biol.,* 85, 223-245. http://dx.doi.org/10.10 16/00 22- 5193(80)90019-3

Ulanowicz, R.E. (1986). *Growth and Development: Ecosystems Phenomenology*, Springer-Verlag, NY, pp. 203.

Ulanowicz, R.E. (1997). *Ecology, the Ascendent Perspective*. Columbia University Press, New York, pp.201.

Ulanowicz, R.E. (2002). The balance between adaptability and adaptation, *BioSystems*, 64, 13-22. http://dx.doi.org/10.1234/1234 5678

Ulanowicz, R.E., and Baird, D. (1999). Nutrient controls on eco-system dynamics: the Chesapeake mesohaline community, *J. Mar. Syst.*, 19, 159-172. http://dx.doi.org/10.1016/S0924-7963(98)90017-3

Ulanowicz, R.E., and Norden, J.S. (1990). Symmetrical overhead in flow networks, *Int. J. Syst. Sci.,* 21, 429-437.http://dx.doi.org /10. 1080/00207729008910372

Ulanowicz, R.E., and Tuttle, J.H. (1992). The trophic consequences of oyster stock rehabilitation in Chesapeake Bay, *Estuar.*, 15, 298-306. http://dx.doi.org/10.2307/1352778

U.S. Fish and Wildlife Service. (2009). National Wildlife Refuge System Profiles, Okefenokee National Wildlife Refuge. U.S. Fish and Wildlife Service, URL: http://www.fws.gov/refuges/profiles /index.cfm?id=41590.

Wang, H.G. and Jawitz, J.W. (2006). Hydraulic analysis of cell-network treatment wetlands, *J. Hydrol.*, 330, 721-734. http://dx.doi. org/10.1016/j.jhydrol.2006.05.005

Xu, F., Yang, Z.F., Chen, B., and Zhao, Y.W. (2011). Ecosystem health assessment of the plant-dominated Baiyangdian Lake based on eco-exergy, *Ecol. Model.,* 222, 201-209. http://dx.doi.org/10.10 16/j.ecolmodel.2010.09.027

Yang, Z.F., Cui, B.S., and Liu, J.L. (2005). Estimation methods of eco-environmental water requirements: Case study, *Sci. China. Ser. D*, 48(8), 1280-1292. http://dx.doi.org/10.1360/02yd0495

Yang, Z.F., Sun, T., Cui, B.S., Chen, B., and Chen, G.Q. (2009). Environmental flow requirements for integrated water resources allocation in the Yellow River Basin, China, *Commun. Nonlinear Numer. Simul.*, 14, 2469-2481. http://dx.doi.org/10.1016/j.cnsns.2007. 12.015

Yang, Z.F., and Mao, X.F. (2011). Wetland system network analysis for environmental flow allocations in the Baiyangdian Basin, China, *Ecol. Model*., 222, 3785-3794. http://dx.doi.org/10.1016/j.eco lmodel.2011.09.013

Zhong, P., Yang, Z.F., Cui, B.S., and Liu, J.L. (2008). Eco-environmental water demands for the Baiyangdian Wetland, *Front. Environ. Sci. Eng. China.,* 2, 73-80. http://dx.doi.org/10.1007/s11783-008-0015-y