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Examination of wetlands system using ecological network analysis：A case study of Baiyangdian Basin, China

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Abstract

Understanding the integrality and organization of wetlands system (WS) is important for system-level water resources management and ecological protection. Yet too little research delved into to the whole status assessment of these connected aquatic systems. In this paper, ecological network analysis (ENA) is introduced as a powerful methodology to develop insights into the integrality of Baiyangdian WS. A 23-components steady-state WS model is built on basin macrohydrology in 1962. We investigate how 18 ENA indicators that characterize ecosystem growth, development, and condition are affected by 8 scenarios including (1) increased boundary input, (2) decreased boundary input, (3) increased boundary output, (4) decreased boundary output, (5) addition of new pathway, (6) removal of component, (7) addition of new component and (8) addition of both new pathway and new component. Furthermore, we use coefficient of variation (CV) to compare system indicators' robustness to network changes. Scenario analyses demonstrate that following results regarding current network indicators: I. System indicators will response differently to different scenarios in different extent; II. Whole-indicators, such as Ascendency (A), are generally sensitive to network flow and topology changes; III. Ratio-based indicators and average mutual information (AMI) are basically with lower variability than non-ratio indicator. IV. Most of indictors present high sensitive to network topology changes even if there are few changes in total system throughput (TST). We hypothesize that WS are self-organized into a selective structure that exhibit certain criterion under favorable natural condition. This paper can promote the understanding of integrality of wetlands system and can be served as evidence supporting the need for wetlands policies that go beyond conservation of individual wetland sites.

Keyword: Wetlands System；Ecological network analysis；Baiyangdian Basin

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1. Introduction

Wetlands are not isolated spaces but, on the contrary, dynamic, complex habitats with biotic and abiotic connections all around [1]. Among the abiotic connections, those related to the flow and quality of water is, perhaps, the most important ones. Once individual wetlands are hydraulically connected, these connected wetlands present a specific network structure and present holistic characteristics [2]. All too often, wetland is considered as a single hydraulic unit, regardless of the extent of networking between individual wetland.

The sustainable use of wetlands and water resources requires management approaches that incorporate explicitly the spatial and temporal interconnections among different aquatic ecosystems [3-5]. Some studies have revealed the importance of system integrity that incorporate river with complex, interrelated multiple-component wetlands in achieving effective water resources and ecological restoration [6-8]. An improved understanding of whole-level organization and complexity of river and its associated wetlands linked through an intricate network of energy, matter and information interaction is the first step for achieving above goals. However, it is impossible to understand how these associated wetlands functions by examining the component relationships in isolation, and related research is far from enough. Current difficulty is how to depict the whole system's inherent organization in holistic way, and there is urgent need for a method to deal with the system-level interaction to explore system holistic properties.

To obviate such problem, Ecological network analysis (ENA) is introduced here as a new way. It is a methodology developed to holistically assess the complex interactions within an ecosystem [9]. The approach can quantitatively analyze the direction of ecological flows and the interactions among them in an ecological network, and can thus reveal the integrity and complexity of ecosystem behaviors. It could be applied numerically to any system to illustrate organization for evaluation of budges of energy, nutrients, metals, toxin, water or other conservative components flowing within the environment. Thus, ENA is not only successful served in specific ecological systems, e.g., the Chesapeake Bay [10], Mondego estuary [11, 12] and Neuse River Estuary [13-16], but also extended into other realms, such as social and economic systems [17,18] and urban system [19]. There were also some applications of ENA in water resources field. Patten and Matis [20] once performed environ analysis to flow, storage, intercompartmental transfer and residence time for hydrologic components in Okefenokee Swamp watershed. Bodini and Bondavalli [21] described water exchanges in the municipality of Sarmato in Italy and probed into different types of flows to evaluate the sustainability of water use with network analysis. The latest studies are the application of ENA in water use systems to analyze the sustainability issue [22, 23]. Their successful applications have proved that ENA is a potential approach for integral study to river and its associated wetlands.

In recent decades, Baiyangdian Lake-the largest remaining freshwater the in northern China-is facing great ecological degradation with water scarcity, flood risk, sedimentation, and severely pollution. The relatively recent acceptance of the socio-economic and ecological importance of the lake has not yet succeeded in reversing this trend. The most important reason caused above situation is the poor planning in the use and allocation of the basin's water resources with limited understanding of its integral role. Thus, it is extremely important to exam the integrity and organization of local aquatic ecosystems network in whole-level system perspective. In this paper, we consider 'wetlands' to be defined as in the Ramsar Convention: "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 suits our discussion below as it dealing with wetlands from a broader point of view. According to the definition given above, we considered different aquatic ecosystems within Baiyangdian basin as Wetlands System (WS) and presented a 23-component steady-state network models. Using ENA with 18 information indices, we hope to probe into the organization and integrity of Baiyangdian WS as evidence supporting the need for wetlands policies that go beyond conservation of individual wetland sites.

The rest of the paper is organized as follows: Section 2 presents the material and method employed to measure the holistic organization of WS. Section 3 reports and interprets the studied results and Section 4 discusses some considerations with current study. Section 5 concludes with a simple retrospect to the entire paper and the insights evoking from an ecological network perspective.

2. Study area

Baiyangdian drainage basin is located in the middle of North China Plain with a surface area of 31199km2 (39.4 °-40.4° N, 113.39°-116.11° E) (Fig.1). Its name originates from the Baiyang Lake, which is the largest remaining semi-closed freshwater lake in the northern China. The lake serves as a sink of nine rivers including Ci, Gao, Sha, Xiaoyi, Tang, Fu, Cao, Pu and Ping River. Six large and middle-scale reservoirs including Hengshanling, Koutou, Wangkuai, West Dayang, Longmen and Pu were constructed in 1950s, which have played significant roles in local water resources allocation.

Fig.3. Baiyangdian Lake served as a sink of upstream rivers in the basin (Dotted lines correspond to network topology changes caused by anthropic activities).

3. Methods

3.1. Wetland system network model

We developed a 23-compartment steady-state network model and quantified it by the hydrological data in 1962. As illustrated in Fig. 2, nine rivers, six large or middle scale reservoirs and Baiyang Lake were considered as main components in the network model. Six rivers, including Ci, Gao, Sha, Tang, Cao and Pu, were further divided into upstream components and downstream components as there are reservoirs constructed on it.

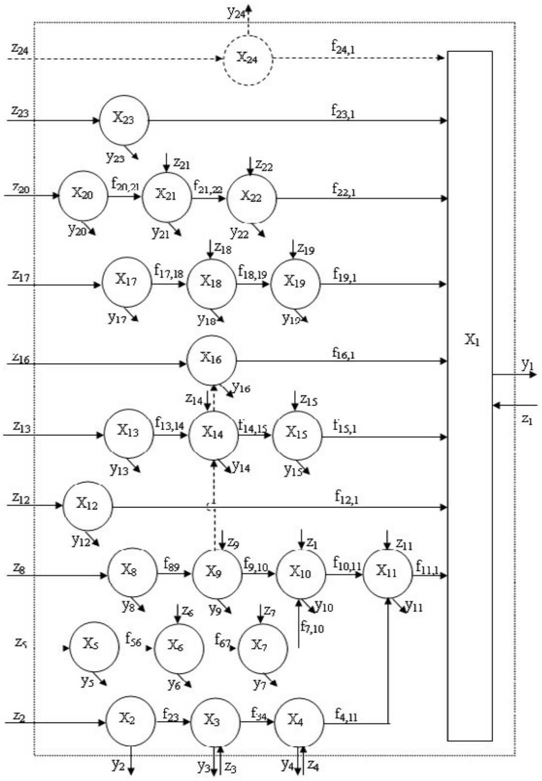

Fig. 2. Diagram of Baiyangdian WS network model(Dotted lines correspond to network topology changes caused by anthropic activities; 1-Baiyangdian Lake; 2-Upstream of Ci River; 3-Hengshanling Reservoir; 4-Downsream of Ci River; 5-Upstream of Gao River; 6-Koutou Reservoir; 7-Downstream of Gao River; 8-Upstream of Sha River; 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-Fu River; 17-Upstream of Cao River; 18-Longmen Reservoir; 19-Downsream of Cao River; 20- Upstream of Pu River; 21- Pu River Reservoir; 22- Downstream of Pu River; 23-Ping River; 24-Baigou River).

In Fig. 2, f_{ij} represent statistic flows (m^{3}year^{-1}) of water from compartment i to compartment j; z_k and y_k are boundary input (m^3 year^{-1}) and boundary output (m^3 year^{-1}) of the kth compartment, respectively; X_k denotes storage of component k. z_k is consists of precipitation, surface and ground runoff from system boundary to system components. y_k includes: (I) natural loss due to evaportranspiration, deep seepage and lateral leakage; (II) stream flow out of boundary through watercourse; (III) water withdrawal by anthropic activities. The changed volume of reservoir water is included in z_k or y_k of corresponding components. As the storage volume is not involved in the current analysis, the related data are not listed in this paper.

Since 1956, hydrological and weather monitor have been started in more than 40 monitor stations of Baiyangdian basin, so the quantified data including precipitation, runoff and evaportranspiration can be obtained from the hydrologic yearbooks issued by Water Resources Department of Hebei province. For the absent data, water mass balance method is used to help quantifying reference networks. A detailed data is listed in Table 1.

Table 1. Flows of WS model in 1962(Unit:10^8m^{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	0.771	0.303	0.083	0.451
Comp	13	14	15	16	17	18	19	20	21	22	23	-
Inputs	z_{13}	z_{14}	z_{15}	z_{16}	z_{17}	z_{18}	z_{19}	z_{20}	z_{21}	z_{22}	z_{23}	-
data	3.437	0.826	0.225	0.707	0.875	0.238	0.097	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	7.871	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	-
Output	y_{13}	y_{14}	y_{15}	y_{16}	y_{17}	y_{18}	y_{19}	y_{20}	y_{21}	y_{22}	y_{23}	-
data	0.437	1.416	1.308	0.271	0.065	0.278	0.167	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	-
Interflow	$f_{13,14}$	$f_{14,15}$	$f_{15,1}$	$f_{16,1}$	$f_{17,18}$	$f_{18,19}$	$f_{19,1}$	$f_{20,21}$	$f_{21,22}$	$f_{22,1}$	$f_{23,1}$	-
data	2.964	2.374	1.291	0.436	0.815	0.775	0.705	0.291	0.214	0.192	0.271	-

3.2. Ascendency analysis for network organization

Ascendency theory, as one branch of ENA, is used to quantify ecosystem behaviors as a whole [24, 25]. It deals with the joint quantification of overall system activity with the organization of component processes and could be used specifically to assess function of system [12]. It has wide applicability and can be used as well to provide a measure of the overall degree of organization inherent in a purely physical flow field, such as carbon, nitrogen, and phosphorus but can also be applied to any currency that is exchanged in a network, which can also be useful in investigating wetlands network topology.

We focused on 18 ENA indicators in Table 2. These indicators are divided into three categories: whole-system indicators, component system indicators and ratio-based indicators. Whole-system indicators describe the whole system, including Total System Throughput (TST), Average Mutual Information (AMI), Ascendency (A), Overhead (Ø), and Development Capacity (C). TST reflects the level of activity which is measured by the sum of the magnitudes of all the flow exchanges occurring in the system. The AMI represents the organization inherent in a system because it capture the average amount of constraint exerted upon an arbitrary amount of mass as it flows from any one compartment to the next [25]. Ascendency is the production of TST and AMI that quantifies both the level of system activity and the degree of the organization [24]. Development Capacity is functions as a mathematical upper bound on the ascendency. It represents the scope of the system for further development. Overhead represents multiplicity of pathways; consequently, when it is high, it is said to reflect a system under rigorous environmental conditions [26], so it is generated by structural ambiguities deriving from multiplicities in system inputs, exports, dissipations and internal exchanges [27, 12].

Table 2. Ecosystem network analysis indicator name, symbol and algorithms

NO	Name	Symbol	Algorithms
1	Total System Throughput	TST	$=\sum_{i=1}^{n+2}\sum_{j=1}^{n+2}T_{ij}$
2	Average Mutual Information	AMI	$=\sum_{i,j}\frac{T_{ij}}{T_{..}}\log_2\left[\frac{T_{ij}T_{..}}{T_{i\cdot}T_{\cdot j}}\right]$
3	Ascendency	A	$=\sum_{ij}T_{ij}\log_2\left[\frac{T_{ij}T_{..}}{T_{i\cdot}T_{\cdot j}}\right]$
4	Import Ascendency	A_0	$=\sum_{j=1}^{n}T_{n+1,j}\log_2\left[\frac{T_{n+1,j}T_{..}}{T_{n+1\cdot}T_{\cdot j}}\right]$
5	Internal Ascendency	A_i	$=\sum_{ij=1}^{n}T_{ij}\log_2\left[\frac{T_{ij}T_{..}}{T_{i\cdot}T_{\cdot j}}\right]$
6	Export Ascendency	A_e	$=\sum_{j=1}^{n}T_{j,n+2}\log_2\left[\frac{T_{j,n+2}T_{..}}{T_{\cdot n+2}T_{j\cdot}}\right]$
7	Overhead	Ø	$=\sum_{ij}T_{ij}\log_2\left[\frac{T_{ij}^{2}}{T_{i\cdot}T_{\cdot j}}\right]$
8	Overhead from Import	Ø$_0$	$=-\sum_{j=1}^{n}T_{n+1,j}\log_2\left[\frac{T_{n+1,j}^{2}}{T_{n+1\cdot}T_{\cdot j}}\right]$
9	Redundancy	R	$=-\sum_{ij=1}^{n}T_{ij}\log_2\left[\frac{T_{ij}^{2}}{T_{i\cdot}T_{\cdot j}}\right]$
10	Overhead from Export	Ø$_e$	$=-\sum_{j=1}^{n}T_{j,n+2}\log_2\left[\frac{T_{j,n+2}^{2}}{T_{\cdot n+2}T_{j\cdot}}\right]$
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	H	C/TST	=C/TST

Component system indicators are the decomposed Ascendency (A_0, A_i, A_e, A_s), Overhead ($Ø_0$, Redundancy(R), $Ø_e$, $Ø_s$) and Capacity (C_0, C_i, C_e, C_s) measures could provide more detailed information of network in four quarters of the network: import, internal and export, dissipation [26]. A_0, $Ø_0$ and C_0 are import Ascendency, Overhead from import and import Capacity, respectively. A_i, R and C_i are internal Ascendency, internal Overhead and internal Capacity, respectively. A_e, $Ø_e$ and C_e describe the Export Ascendency, Overhead from Export and Export Capacity, respectively. A_s, $Ø_s$ and C_s correspond to dissipative Ascendency, dissipative Overhead and dissipative capacity, respectively. In our study, we make no difference between export and dissipation. Dissipative Ascendency, Dissipative overhead and Dissipative capacity equals to zero and not considered further.

Ratio-based indicators could be used to quantify ecosystem health and condition [24,28]. For example, the Ascendency over Capacity (A/C) would describe the network efficiency and optimized at system maturity while the internal ascendency to internal capacity ratio A_i/C_i describes the internal network efficiency. The Overhead over Capacity (Ø/C) might show how the Capacity is limited by the Overhead, and H= C/TST describes the diversity of flows in the system.

3.3 Model examinations

We applied eight different scenarios to the baseline model to observe the impacts from changed boundary input, boundary output and internal flow as well as flow topology (Table 3). Since component 1 serves as the sink of upstream components, the balance of models are finally adjusted by the boundary output of component 1. It is worth to note that each scenario is specially designed to represent changes caused by realistic situations. For example, boundary input and output changes may be caused by climate fluctuation, water abstraction changes and so on. Two new pathways are under construction projects according to local water resources planning.

Table 3. Network modification to baseline model

NO	WS	Modification	Scenario analysis	TST
0	WS_0	Baseline model	Baseline model	60.33
1	WS_1	Boundary input increased by 10%	Precipitation increase	69.11
2	WS_2	Decreasing boundary input by 10%	Precipitation decrease	53.29
3	WS_3	Increasing boundary output by 10%	Water abstraction increase	59.42
4	WS_4	Decreasing boundary output by 10%	Water abstraction decrease	63.01
5	WS_5	Adding new pathways from components 9 to 14 and from components 14 to16	Aqueduct construction	60.13
6	WS_6	Adding component 24	Canal	61.91
7	WS_7	Removing component 12	Dried up due to natural or artificial causes	59.09
8	WS_8	Modifying according modification 5 and 6	Aqueduct r construction	61.71

The indicator changes between baseline model and modified models were calculated by percent difference: $(WS_i-WS_0)/WS_0\times 100\%$. *TST* is chosen to be the benchmark for the other indicators because it most simply describes the system flows, exports, respiration and imports [29]. Through the percent difference, we could understand how and what extent are these changes impact different ENA indicators. Besides, since each indicator suffered from the same series of changes, we used coefficient of variation (*CV*) to detect the robust of each indicator to these network changes.

4. Results

As shown in Table 4, the ENA generated 162 values for total nine models. The A/C for our baseline model is about 0.443, and the A_i/C_i value is 0.752. The A_i =101.74 ($10^8 m^3 y^{-1}$) makes as large as 74.8% of A=135.96 in baseline model. We also see that the Ø/C is 0.557, and about 80.3% of the Capacity is explained by the remaining overhead due to boundary imports and exports. Percent differences in indicators between baseline model and modified models are shown in Fig. 3 (a)-(h).

Table 4. Network modification to baseline model

Symbol	WS_0	WS_1	WS_2	WS_3	WS_4	WS_5	WS_6	WS_7	WS_8
TST	60.33	69.11	53.29	59.42	63.01	60.13	61.91	59.76	61.71
AMI	2.254	2.297	2.199	2.205	2.303	2.154	2.248	2.26	2.152
A	135.96	158.79	117.24	131.0	145.16	129.56	139.21	133.72	132.81
A_0	18.21	20.57	16.28	18.12	18.70	17.43	18.88	17.66	18.10
A_i	101.74	119.56	86.68	97.01	109.42	96.60	103.60	100.47	98.48
A_e	16.018	18.64	14.27	15.89	17.03	15.52	16.71	15.56	16.22
Ø	170.50	187.90	154.99	172.24	170.62	181.52	177.84	163.75	188.83
$Ø_0$	73.72	81.64	66.05	73.44	74.29	74.42	77.38	70.61	78.08
R	33.472	39.17	28.70	32.14	35.63	43.38	36.08	31.47	45.95
$Ø_e$	63.29	67.08	60.23	66.65	60.68	63.71	64.37	61.67	64.79
C	306.49	346.70	272.23	303.27	315.78	311.08	317.05	297.45	321.64
C_0	91.94	102.22	82.33	91.57	93.01	91.86	96.26	88.26	96.18
C_i	135.21	158.73	115.38	129.15	145.06	139.99	139.69	131.95	144.44
C_e	79.31	85.73	74.50	82.55	77.72	79.23	81.09	77.23	81.01
A/C	0.443	0.458	0.430	0.432	0.459	0.416	0.439	0.449	0.412
A_i/C_i	0.752	0.753	0.751	0.751	0.754	0.690	0.741	0.761	0.681
A/C	0.557	0.542	0.570	0.568	0.541	0.584	0.561	0.551	0.588
H	5.080	5.016	5.108	5.103	5.011	5.175	5.121	4.977	5.212

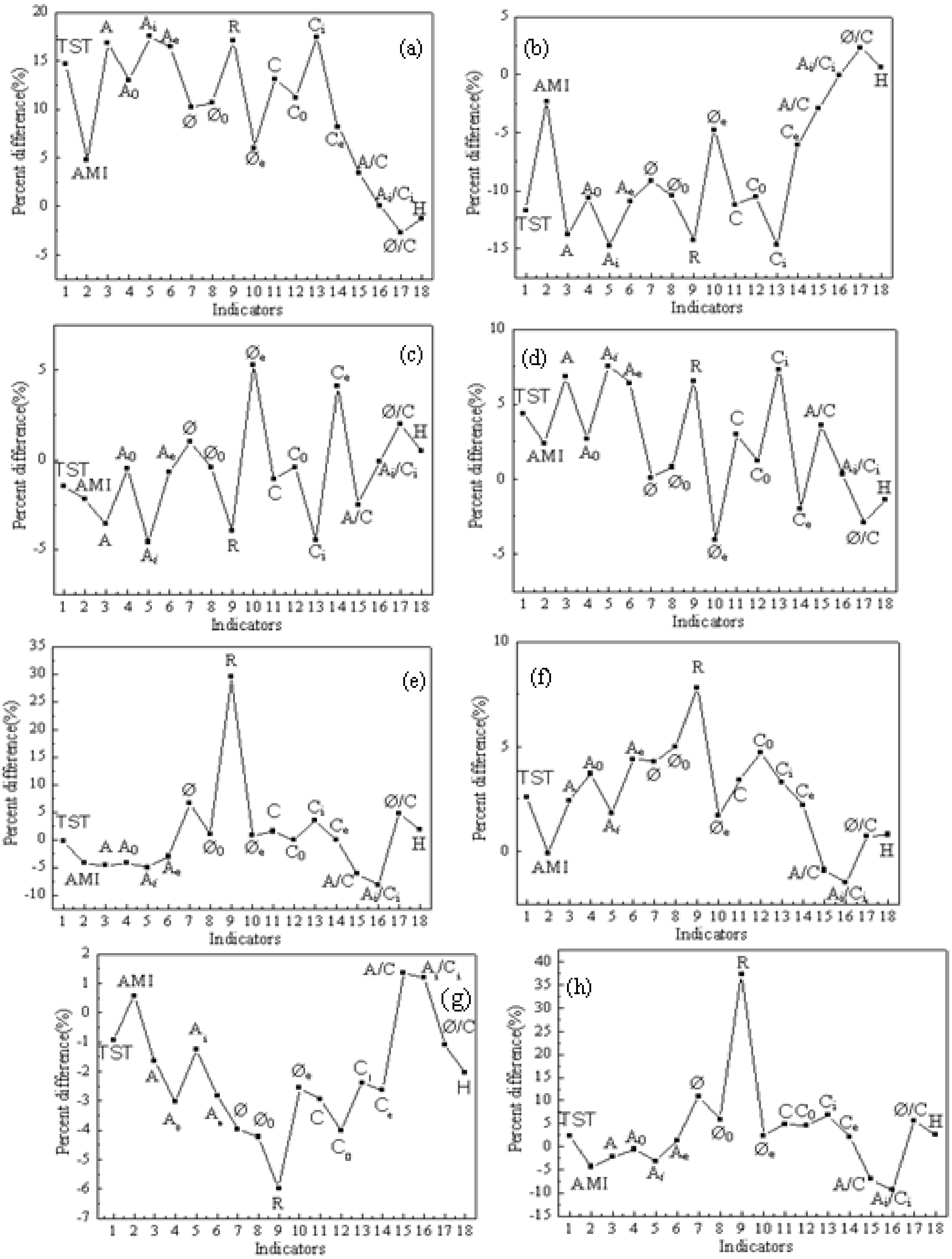

Fig.3. (a)-(h). Percent differences in indicators between baseline model and modified models.

As we can see form Fig. 3 (a)-(h), network indicators present different change tendency in eight scenarios. Related results are described as follows:

(1) Increased boundary input indicates more flows from upstream components to downstream components and more outflows from component 1. As a result, it gives increase to all indicators except for Ø/C and H (Notice that

Ø/C and A/C will always vary in opposite direction). The increases of A, A_i, C_i and R are obviously larger than the increases of TST (about 15%). On the contrary, AMI, $Ø_e$, C_e, A_i/C_i, Ø/C and H are obviously less changed than TST.

(2) Decreased boundary input indicates fewer flows from upstream components to downstream components and less outflows from component 1. It gives decrease to all indicators except for Ø/C and H. The decrease of A, A_i R and C_i are obviously larger than the decrease of TST (about 12%). The other indicators including AMI, $Ø_e$, C_e, A_i/C_i, Ø/C and H are less changed than TST.

(3) Increase boundary output brings with obvious rise in $Ø_e$ and C_e. Contrarily, A_i and C_i decreased obviously because increase boundary output will result in less interflow between system components. Compared with the results of scenario 1 and 2, system indicators in this scenario are obviously less variable. We contribute this to the balance process because the system balance was fulfilled by the boundary output of component one, which cancel part changes in this scenario.

(4) Decreased boundary output gives increase to all indicators except for $Ø_e$, C_e, Ø/C and H. The increase of A, A_i, A_e, R and C_i are obviously larger than the increase of TST (about 4.4%). This tendency is the same as scenario 1 since decreased boundary output also indicates more flow from upstream components to downstream components and more outflows from component 1.

(5) It seems that network organization measured by A/C and A_i/C_i became worse after involving additional links even if the TST varies little. For example, the percent change of TST is about -0.3% while A/C and A_i/C_i reduced more than 6%. The reason may be that both the C and Ø increased greatly due to additions of new pathways, which enhance the structural ambiguities.

(6) Adding component 24 yields an increase in TST (about 2.6%) and brings increases to most of indicators. However, it also offers more enhancements to C than A and still yields an overall decrease in A_i/C_i and A/C.

(7) Removing component 12 corresponds to decrease in most of system indicators. Percent differences of some indicators, such as Ø (4%) and R (6%), are obviously larger than TST (1.8%). The decreases of A and C_i is smaller than the decrease of C_i and C, which still results in an overall decrease in A/C and A_i/C_i.

(8) The change tendency of scenario 8 is extremely similar with scenario 5, which indicates system indicators are very sensitive to changes in flow topology.

The CV values of the variability of each indicator are shown in Fig.4. As little changes were set to baseline model, the CV varies in a relative small range from 0.02-0.16. Indicator A, A_i and R have larger CV_S than TST, while $Ø_e$, C_e, AMI and ratio-based indicators exhibit lower variability than TST. Remaining indicators have equivalent CV_S with TST. Thus, these more variable indicators can be served to detect the system dynamic evolvement and these less variable indicators can be used in comparing different system characteristics.

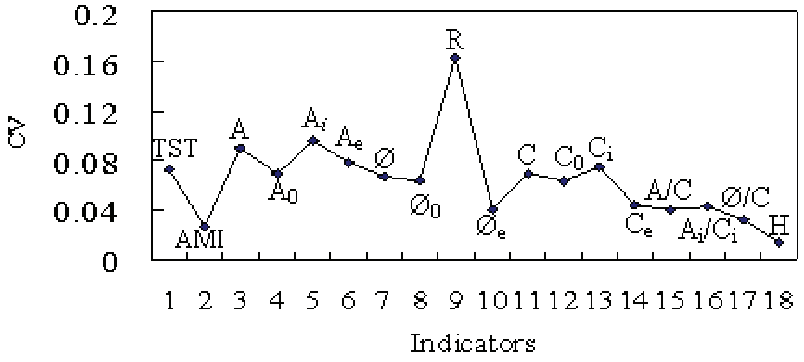

Fig.4. The CVs for system indicators

5. Discussion

River basin is a large, coordinated dissipative and self-organized system [30]. The structure of its drainage network (termed wetlands network as aforementioned) reflects the general properties of the soil and vegetation system that, when linked to a particular climate, yield the basin runoff and the sediment load that the network collects and transports to the outlet of the basin. Like ecological network participants, each of components in wetlands network take in water, transform or alter it in some ways (e.g., evaporation, seepage, and water withdrawal), and pass it on to another network actor. Also similar to ecological network, each compartment uses water and causes fluxes of water in the transformation process it performs. Therefore, it is analogous to metabolism, albeit a form of "wetland metabolism" that differs significantly from biological metabolism. The water not actually ingested in wetland components and is not transformed into another life form via true metabolism. The components defined and quantified in this paper are associated with particular properties of each component, such as soil, vegetation, and climate as so on. Besides, anthropogenic activities will affect the "metabolism" since more and more water abstraction from different wetland components.

Ascendency theory has wide applicability and can be used as well to provide a measure of the overall degree of organization inherent in a purely physical flow field, such as carbon, nitrogen, and phosphorus but can also be applied to any currency that is exchanged in a network. This technique for estimating both the extent of shared information and the direction of information flow can also be useful in investigating wetlands network topology. The wetlands network transport information through water transfer between a message source (upstream wetland) and a message receiver (downstream wetland component). Thus, the wetlands network can be interpreted as the results of information transmission between different system components by units of water flow. The topological structure of wetlands network comes from the general operating criteria in which WS works. The topological structure of wetlands network comes from the general operating criteria in which WS works. TST captures the system activity of WS and AMI captures topographical constraint based upon the pattern of flow in the network.

Network indicators in ENA are not just the sum of different water flows within network; it was calculated through an information-based calculated method that delves deeply into the inner operation mechanism of WS. Results indicate these 18 ENA indicators show different sensitivities to the model changes. Whole-indicators are generally more sensitive than ratio-based indicators and AMI. However, ratio-based indicators and AMI exhibit high sensitive to network topology changes. Taking modification 5 as an example, percent differences of A_i/C_i and R approach -8.2% and 29.6%, respectively, while the percent differences of TST are only about -0.3%. Slimily tendency could also be found in scenario 8. The A_i/C_i decreased by 9.4% in spite of the TST increased only by 2.3%. Related results indicated that food webs buffer the effects of perturbation, while food chains, probably exhibiting an elevated AMI over web structures, were sensitive to network changes [31]. We consider increased internal redundancy (increasing internal overhead) is equivalent to a decrease in the AMI, which result in an overall decrease in A_i/C_i. Besides, decomposed indicators, such as A_i, R and C_i, can also reflect the corresponding changes in network interflow flows.

In this case, Baiyang Lake is a focal node. While its connections with other rivers as well as upstream reservoirs can not be ignored as they are actually a whole one. It is reported that artificial regulation to wetlands is projected to increase to an astounding 70% by 2025 [32]. Extreme natural events, including floods and droughts, may also disrupt WS. Understanding how the WS reacts to those natural and artificial changes is critical for sustainable water resources use and management. Besides, there is growing demand to conserve or restore the ecological health and functioning of rivers and their associated wetlands for the benefit of people and biodiversity [33]. Understanding the integrity and organization of WS is the first step to achieve system-based basin water resources management and ecological restoration.

It is also important to note the difference in topology and especially recycling links between natural ecological network and wetlands network. In the latter, from upstream to downstream, all flows are linear and no recycling occurs. Besides, WS is quite different from ecosystem and we should be caution about the explanation to these results. Ulanowicz [24,25,27] has stated that as systems grow and develop, the ascendency index should increase. However, we can not easily draw the conclusion that a WS with A/C=0.443 is more mature than a WS with lower Ascendency value. The magnitude of network indicators depends on many factors, such as particular climate, landform and human activities, etc. However, the overall natural characteristics of WS can be reflected in dynamic Ascendency or other system indicators. For example, an untouched river should have higher A_i/A than human-controlled river since less water is lost from the "metabolism" process.

6. Conclusion

The present study intends to apply ENA to the WS network model as a case study of the Baiyangdian Basin in northern China. We made two primary contributions to the system-level network analysis to WS. First, we provided a quantified method to investigate and assess WS organization and condition. Secondly, we investigate the ENA indicators' sensitivity to the changes of network flow and topology. We believe that the understanding of organization of WS is important for better water resources management and could serve as a potential framework for predicting the evolution of WS in light of anthropogenic activities and environmental changes.

Although the considerable time required for data acquisition and network analysis, the current quantified network model is still relative simple and coarse. The reality situation will be more complicated than current model and eight modifications are also far from sufficient to get generally rules about the change tendency of system indicators. Further studies of empirical systems are needed to assess the overall rules of network indicators.

Nevertheless, the case study on Baiyangdian Basin in China serves as an attempt to determine system-level characteristics of WS with the promising ENA methodology. The results provide new insight in holistic and systemic study to rivers and its related wetlands in basins, which can be useful for the management toward basin wetlands. Besides, since network is developed with respect to water, the method could also used to assess the whole-based environmental flow requirements (EFRs) of WS in the perspective of wetlands network.

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