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Influence of human-water interactions on the water resources and environment in the Yangtze River Basin from the perspective of multiplex networks

Xi-Yin Zhou [a], [*], Kun Lei [b], [**]

[a] School of Systems Science, Beijing Normal University, Beijing, 100875, PR China
[b] Chinese Research Academy of Environmental Sciences, Beijing, 100012, PR China

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A B S T R A C T

Coupled human and natural system research is an urgent issue in the Anthropocene. However, this has not yet been conducted from the perspective of multiplex networks, which are a powerful tool to elucidate the interactions in human-natural systems. This paper establishes a framework of human-water multiplex networks (HWMNs) to explain the combined effects of human-water interactions in the Yangtze River basin. The spatial linkages and the status of each province in the Yangtze River basin can be characterized through the index of network flow and topology. Research demonstrated that the highest import flow of the virtual water environment capacity flow in the Yangtze River Basin is to Jiangsu Province, at 16.2 thousand t. The highest export flow in the Yangtze River Basin is from Shanghai city, at 33.2 thousand t. The control power of Shanghai city over Sichuan Province accounts for 56.59% of the water resources, which is the highest value and can be recognized as one type of telecoupling of water resources. The provinces in the delta of the Yangtze River basin, including Shanghai city, Jiangsu Province and Zhejiang Province, benefit the most from economic trade. The community structure of the virtual water environment capacity flow is highly consistent with the geographical distribution of the Yangtze River basin. Comprehensive research methods combined with network flow analysis and network topology analysis provide more general results. The microenvironmental effect of indirect pollutant discharge is uncovered through HWMNs. This research can provide a more connected view of integrated water management.

1. Introduction

Continuous and intense human activities have caused various environmental changes, including atmospheric composition change, soil and water environmental degradation, and ecological function loss (Lewis and Maslin, 2015; Ma et al., 2020). They have even induced a new human-dominated epoch, named the Anthropocene epoch (Coen, 2020; Crutzen and Stoermer, 2000; Crutzen, 2002; Zalasiewicz et al., 2010). To realize the sustainability of humans and nature in the Anthropocene, interdisciplinary research on coupled human and natural systems (CHANS) has been proposed over the past decade, including similar concepts such as social-ecological systems and human-environment systems (Liu et al., 2007, 2020).

In recent decades, notable progress has been attained in research on CHANS from both theoretical and methodological perspectives (Binder et al., 2013). Various approaches have been developed for CHANS research in certain domains. Mckey et al. (2010) analyzed the interactions between people and crop manioc to reveal the CHANS interactions in the field of chemical ecology and global impacts. Li et al. (2017) proposed an assessment framework in combination with a coupled human−natural system behavioral model and evaluated its weather and climate services value for farmer decisions. O'Donnell and O'Connell (2013) simulated human flood protection decisions in CHANS, especially hydrological and climate systems. Iwamura et al. (2016) examined the environmental degradation of demarcated indigenous lands in the Amazon considering human livelihood, forest dynamics, and animal metapopulations. The interaction mechanism of internal

* Corresponding author.
** Corresponding author.
E-mail addresses: zhouxiyin@bnu.edu.cn (X.-Y. Zhou), watereconomy@163.com, leikun@craes.org.cn (K. Lei).

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CHANS has been researched regarding different natural elements, such as water, atmosphere, land, and ecosystems. The agent-based model (ABM) has been a typical tool in CHANS research (Monticino et al., 2007; An, 2012; Zvoleff, 2014; Rovere et al., 2017). Integrated models based on the ABM have also been developed to improve the simulation performance (Pope and Gimblett., 2017). The research scale varies according to the specific requirements from the global scale to the local scale (Currie et al., 2016; Holdschlag and Ratter, 2013). Compared to the real coupling framework at particular geographic locations, Liu proposed a telecoupling framework to analyze CHANS in which interactions occur across long distances (Liu et al., 2013, 2016).

The characteristics of CHANS have also been studied, such as the threshold, vulnerability, resilience, and nonlinearity. Stevenson (2011) analyzed threshold features among the various elements in CHANS and proposed that threshold propagation is a significant driver of policy development. Elshafei et al. (2015) identified the characteristics of threshold behavior, time scale and lag, and adaptive learning based on the observed isolated feedback between CHANS was implemented. Srinivasan et al. (2013) revealed that water vulnerability is dynamic, spatially variable and scale dependent in urban areas from the perspective of CHANS. Turner et al. (2003) established a vulnerability framework and demonstrated that vulnerability reduction to environmental hazards should be achieved through a comprehensive vulnerability assessment accounting for CHANS complexity. Cumming et al. (2013) found that enhancing landscape resilience requires tests of diverse approaches. Sanderson (2018) examined social issues, including social stratification, inequality, and power, from the perspective of CHANS. Wang et al. (2018) explained the structure, function, and dynamic mechanisms of CHANS and stated that the nested hierarchy is a structural characteristic of CHANS, and sustainability realization requires integrated regime efforts of markets, governments, and human needs. Ferraro et al. (2019) summarized the two traditional causal analysis approaches (predictive inference and causal inference) and proposed that causal inference requires various disciplines of knowledge and multicooperation.

CHANS are typical complex systems. The complex systems theory is widely recognized as having been established by scientists from the Santa Fe Institute in the 1980s (Waldrop, 1993). Adaptability, intelligence, nonlinearity, and emergence are the key characteristics of complex systems. Complex systems widely exist in physical, biological, and social systems (Wu and David, 2002). A complex network is a natural tool to accurately describe complex systems to capture their internal intricate interactions (Strogatz, 2001; Tumminello et al., 2005; Palla et al., 2005). Each element is regarded as a node, and the interactions between nodes are regarded as a link. The vast numbers of nodes and links form a complex network. The two typical complex network properties called small-world networks and scale-free networks, which were proposed by Watts and Strogatz, 1998 and Barabási and Albert (1999), have accelerated the research on complex networks. Complex networks in the real world have been investigated, including neural networks, internet networks, scientific coauthorship networks, and transportation networks (Boccaletti et al., 2006). Currently, the key concerns of complex network research are the characteristics of the topological structure and its dynamics and their impact on the function, robustness and vulnerability of complex networks (Barrat et al., 2004). Linyuan et al., 2016 reviewed the methods of vital node identification in complex networks to trigger interdisciplinary solutions. Other indicators for network structure measurement include the node degree, betweenness, centrality, and PageRank. In addition to the reality requirements, more different types of complex networks have been proposed to better explain complex systems such as directed networks, weighted networks, and interdependent networks (Rosvall and Bergstrom, 2008). In the field of CHANS, certain significant advancements have been attained in network research on ecological systems and social systems. Ecological network analysis is a common tool in network research on ecosystems (Ulanowicz et al., 2014), virtual water trade (Fang and Chen, 2015), carbon emissions (Lu et al., 2015), energy systems (Chen and Chen, 2015), and their coupled systems, especially focusing on the indirect influence between different nodes. It is an ecological application of the input-output table, which was proposed by Leontief (Fath and Patten, 1999). The method mainly concerns the environmental impact of human activities. Social network analysis is another useful tool to elucidate the network characteristics of social systems (Borgatti et al., 2009).

However, the current research on complex networks is mainly implemented in social systems or environmental systems, and there is still a lack of an integrated complex network for CHANS research. On the other hand, the single-layer network has commonly been adopted in the current research on complex networks, in which all components are treated on an equivalent footing (Boccaletti et al., 2014). Actually, in the real world, especially in CHANS, social-economic systems have special network structures and dynamic features, as do natural systems. We propose that the single-layer network does not represent the complex interactions among CHANS suitably. Multilayer network research is urgent for a better description of CHANS because each subsystem of CHANS can be recognized as a one-layer network, and the interactions between different subsystems can be described with edges between the nodes from different layers. Multilayer networks can also be called multiplex networks (Gomez et al., 2013), interdependent networks (Parshani et al., 2010), hypergraphs, network of networks, etc.

Only in the last few years, along with the production of vast data amounts and hardware improvements, has multiplex network research become possible for scientists in various fields. Boccaletti et al. (2014) reviewed the main structure and dynamics characteristics of multilayer networks and the typical types of multiplex networks in the fields of economy, technology, society, ecology, psychology, etc. Battiston et al. (2014) also proposed certain measurements for the structure of multiplex networks, such as the node degree, edge overlap and reinforcement, clustering coefficient, transitivity, and navigability of the multiplex across the different layers. Research on ecological multilayer networks has also been proposed in the field of ecology to examine high-dimensional, heterogeneous and complex characteristics (Pilosof et al., 2015). Pilosof et al. (2017) stated that the maximum community and extinction cascades are two key aspects of ecological multilayer network analysis. Timóteo et al. (2018) reported the mutualistic structure features of habitats and identified species importance through ecological multilayer networks across Great Rift landscapes.

There is still a lack of network analysis of CHANS, in addition to the absence of the multilayer network perspective. In fact, network analysis could provide new insights into CHANS from the perspectives of topology and dynamics. Furthermore, the multilayer network theory could naturally explain the complex multiple interactions among the various subsystems of CHANS and their complexity. It could also offer a great potential for new phenomenon interpretations of CHANS. In the current research, the common concerns about CHANS are the scale, spatial pattern and internal structure (Zhou et al., 2020). Researchers have analyzed CHANS from the large scale to the fine scale, such as the global scale, country scale and regional scale (Maria et al., 2018; Zhao et al., 2018). Researchers have attempted to explain the flow characteristics in a single system of CHANS. Tamee et al. (2018) developed methods for water-food-energy nexus research in social systems. Sohn et al. (2019) uncovered the atmospheric circulation characteristics of natural systems. CHANS research from the network perspective has been little reported in regard to both the characteristics of network flow and network topology. In fact, complex interactions and feedbacks occur between human systems and natural systems through network linkages (Shabanzadeh-Khoshrody et al., 2016). The network change in the human system would directly influence the natural process, and vice versa. It is urgent to connect the human system with the natural system through multiple networks. The research method of multiplex networks can reveal more structures and interactions that cannot be exploited through a single network (Heaney, 2014). The water flow layers in the human system and the natural system form a multiplex network, in which the same nodes exist in the two layers and interact differently in terms of the economic flow and natural flow. Multiplex networks can uncover more interaction processes that cannot be explained by one single network. Based on the multiplex network, the self-coupling relationship can be researched whereby the same node can be connected to two different networks (Zeng and Battiston, 2016).

Herein, our objectives are twofold. First, we aim to establish an integrated framework of human-water multiplex networks (HWMNs) for CHANS research from the perspective of multiplex networks to gain new insights. The multiplex networks are established by combining the economic transfer layer, water pollutant transfer and water resource transfer in the Yangtze River basin. Then, we investigate how the multiplex network is structured across the HWMN. The key regions for sustainable cycling across the river basin are identified through the centrality of the nodes, multilayer communities, and connectivity between the layers, especially for multilayer networks. We will evaluate the extent to which this multilayer approach improves the currently used monolayer analysis methods. We will also examine the potential of the multilayer network approach through a comparison with traditional CHANS analysis approaches. The network flow and topology analysis related to HWMNs can reveal the spatial linkages between each province and their status in coupled human-water systems. Specific improvement measures considering both economic and environmental benefits can be proposed for a certain region from the perspective of a systematic network according to the indicator values of the HWMN flow and topology.

2. Characteristics of human-natural multiplex networks

In the literature, there are typical examples of multiplex networks to describe the different systems that can be encountered (Boccaletti et al., 2014). The characteristics of multiplex networks include the centrality and ranking of nodes, clustering, shortest path and distance, and modular structure. These are also the basic characteristics of HNMNs. The main difference between HNMNs and other multiplex networks is the internal generation process. The existing multiplex networks are always formed through classification. For example, a transportation multiplex network is formed according to different traffic means, such as air and train transportation networks (Yao et al., 2015), or an air transport multiplex network is established according to different airlines (Zanin and Lillo, 2013). A trade multiplex network is formed through commodity imports and exports based on different types of commodities (Barigozzi et al., 2011). For climate systems, a multiplex network could be established according to different geographic heights (Donges et al., 2011). For HWMWs, each layer represents a subsystem of CHANS. For example, an economic network could indicate an economic subsystem, and a population network could indicate a population subsystem. An energy network could indicate an energy subsystem, and a water network could indicate a water subsystem. The economic network is the key subnetwork of HWMWs from the perspective of sustainability. Human networks can directly influence natural processes and network structures. Therefore, it has been recognized that other natural subnetworks are predominantly influenced by human subnetworks. HWMWs can be considered independent non-equilibrium directed weighted multilayer networks. HWMNs are a typical type of complex system. HWMNs have the characteristics of emergence, nonlinearity, dynamics and spatial heterogeneity, which are also a characteristic of most complex systems (Fig. 1).

3. Methods

The research consists of four main steps to complete HNMN analysis (Fig. 2). First, the required data should be prepared and processed for further multiplex network construction. During network construction, the virtual water flow and the physical water flow should be established, and then, multiplex networks can be formed according to the same nodes in the different networks. The characteristics of multiplex networks can be analyzed through network flow analysis and network topology analysis. The corresponding results can thus be obtained, including the cost-benefits of water resources and water environment and the key provinces that influence the network structure in the Yangtze River basin. The research results can support integrated water management considering economic development, water resource usage and water environment protection.

3.1. Network construction

The steady-state network of the virtual water resources and water environment capacity flow is developed to illustrate the interprovincial flows and indirect effects across the Yangtze River basin based on the basic economic input-output model of China by incorporating statistical data on the water consumption and pollutant discharge of each province. The intermediate input/use matrix of water resources and water pollutant input-output model reveal the patterns of the virtual water resources and water environment trade, respectively.

The total inputs of each province in the Yangtze River basin equal the total outputs, including both the interprovincial flows with the provinces outside the Yangtze River basin and the flows to other countries (Fath and Patten, 1999). The equation is shown below:

$$\sum_{i=1}^{n} vp_{ij} + opo_j + oco_j = \sum_{i=1}^{n} vp_{ji} + OPI_j + OCI_j \quad (1)$$

where p_{ij} is the virtual water resource flow or the virtual water environment capacity flow produced by province i and consumed by province j, OPO_j are the outputs of the water resources or the water environment capacity to the provinces outside the Yangtze River basin in China, OCO_j are the outputs of the water resources or the water environment capacity to other countries, OPI_j are the inputs of the water resources or the water environment capacity from the provinces outside the Yangtze River basin in China, and OCI_j are the inputs of the water resources or the water environment capacity from other countries.

The local water resource amount, real water resources and water pollutant flow are determined based on the provincial water flow relationship from upstream to downstream according to the

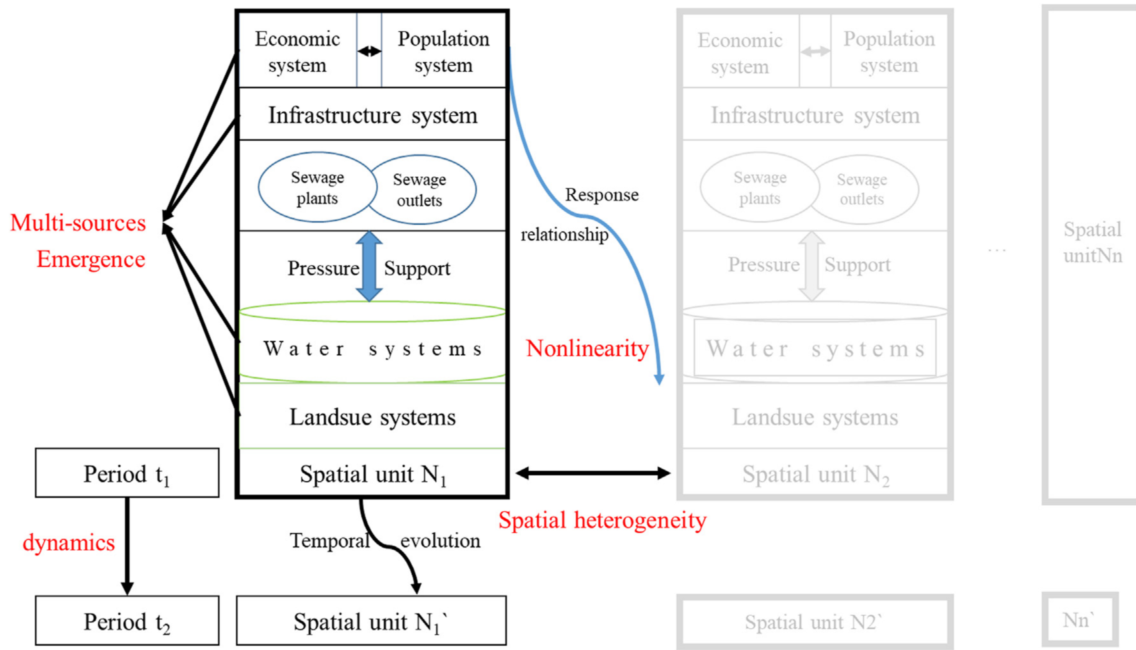

Fig. 1. Sketch map of human-water multiplex networks.

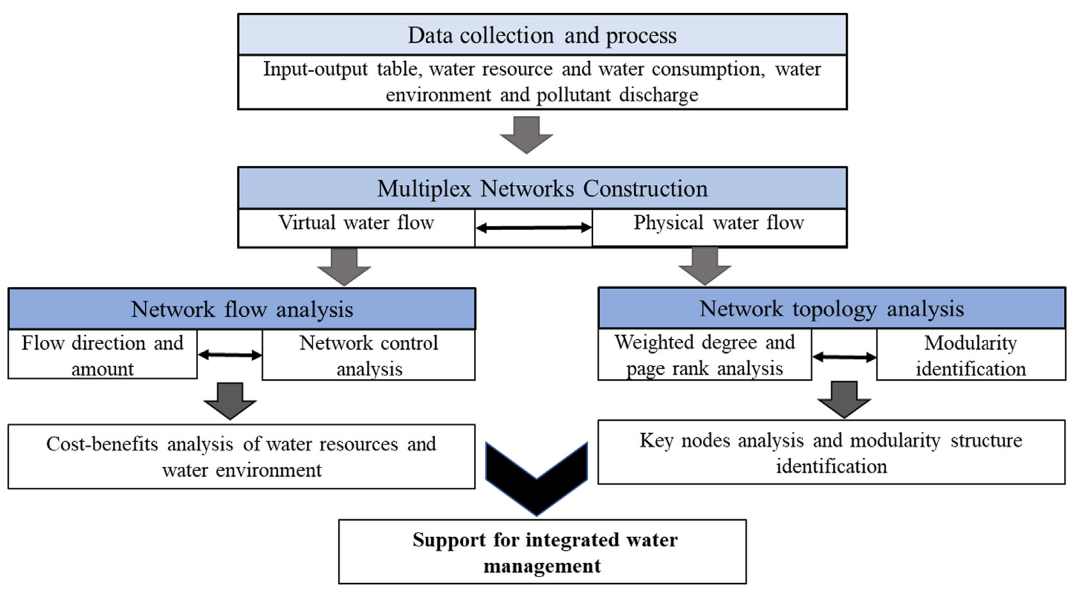

Fig. 2. Research design of HWMN analysis.

Water Resource Bulletin, Water Environmental Bulletin and real measured data. The water environment capacity is obtained according to a water quality model (Yicheng et al., 2010). Each province has outflow and inflow values of their water resources and water pollution level.

3.2. Network control analysis

Network control analysis can determine the control/dependence relationship of one province over another via pairwise analysis. Network control analysis is represented by the index of the ratio (p_{ij}/p'_{ji}) between the integral flow from provinces j to i (p_{ij}) and the integral flow from provinces i to j (p'_{ji}). The integral flow consists of the direct flow and the indirect flow from the other provinces in the Yangtze River basin, from the provinces outside the Yangtze River basin (OP) and from other countries (OC), while the control matrix can explain the relationship from the perspectives of the overall system configuration and the integral flow. The calculation equation of the network control analysis index is shown below (Yang et al., 2012).

$$IPNCI_i = \sum_{j=1}^{m} (P-I)_{ij} \Bigg/ \sum_{i=1}^{m} \sum_{j=1}^{m} (P-I)_{ij} \ (\mathrm{i},\ \mathrm{j} = 1\ \&\ \mathrm{m}) \quad (2)$$

$$OPNCI_j = \sum_{i=1}^{m} (P^{'} - I)_{ij} \Big/ \sum_{j=1}^{m} \sum_{i=1}^{m} (P^{'} - I)_{ij} \ (\mathrm{i},\ \mathrm{j} = 1 \ \& \ \mathrm{m}) \qquad (3)$$

where $IPNCI_i$ is the influence strength of province i on the whole Yangtze River basin through the virtual input of water resources and environment, $OPNCI_j$ is the influence strength of province j on the whole Yangtze River basin through the virtual output of water resources and environment, $\sum_{j=1}^{m} (P - I)_{ij}$ is the integration of the ith row elements in matrix $(P - I)$, and $\sum_{i=1}^{m} (P^{'} - I)_{ij}$ is the integration of the jth column elements in matrix $(P^{'} - I)$. Matrices $(P - I)$ and $(P^{'} - I)$ are the integral input and output flow matrices, respectively, with regard to the direct and indirect flows, respectively.

The control ratio (CR) matrix obtained through network control analysis can explain the relationship by considering both the direct and indirect effects. The CR value ranges from 0 to 1. The closer the value is to 1, the stronger the control relationship between two provinces is.

3.3. Network topology analysis

Network topology analysis including weighted degree analysis and page rank analysis of HWMNs is conducted with R software 3.5.2, specifically the muxViz package.

3.4. Study area and data sources

The Yangtze River is the largest river in China and the third longest river in the world. Its basin covers 20% of the land area and supports more than 40% of people and accounts for 40% of the GDP of China. It consists of three parts: the upper reach, the middle reach and the lower reach (Fig. 3). It is a region with high-intensity interactions between humans and water along with a thousand years of development, especially the rapid economic development after the reform and opening up of China. Therefore, in this study, the related 15 provinces in the Yangtze River basin are studied to reveal the characteristics of HWMNs. Most culture worldwide has developed in river basins. The high-intensity interactions of the HWMNs in the Yangtze River Basin produce certain notable phenomena, which provides certain indications for other similar river basins.

The data sources include the Water Resources Bulletins, Water Environment Bulletins, and Statistical Yearbooks of the 15 provinces in the Yangtze River basin. The monthly water quality data of each province are collected at the inlet and outlet of the Yangtze River basin. The input-output table, which is retrieved from the World Input-Output Database (www.wiod.org/database/wiots16), is applied to establish the expanded water resources and water environment input-output table of the 15 provinces in the Yangtze River basin for 2014.

There are various types of pollutants that are discharged into the water bodies of the Yangtze River basin. To focus on the key water environment problem and to reveal the multiplex networks, according to the environmental statistical bulletin and monitoring data of the water quality, the most prevalent pollutant, NH4, is adopted as the pollutant index in the case study of the Yangtze River basin.

4. Results and discussion

4.1. Economic influence on HWMNs

Economic activities cause water resource consumption and water pollutant discharge. Product trade is the reason for virtual

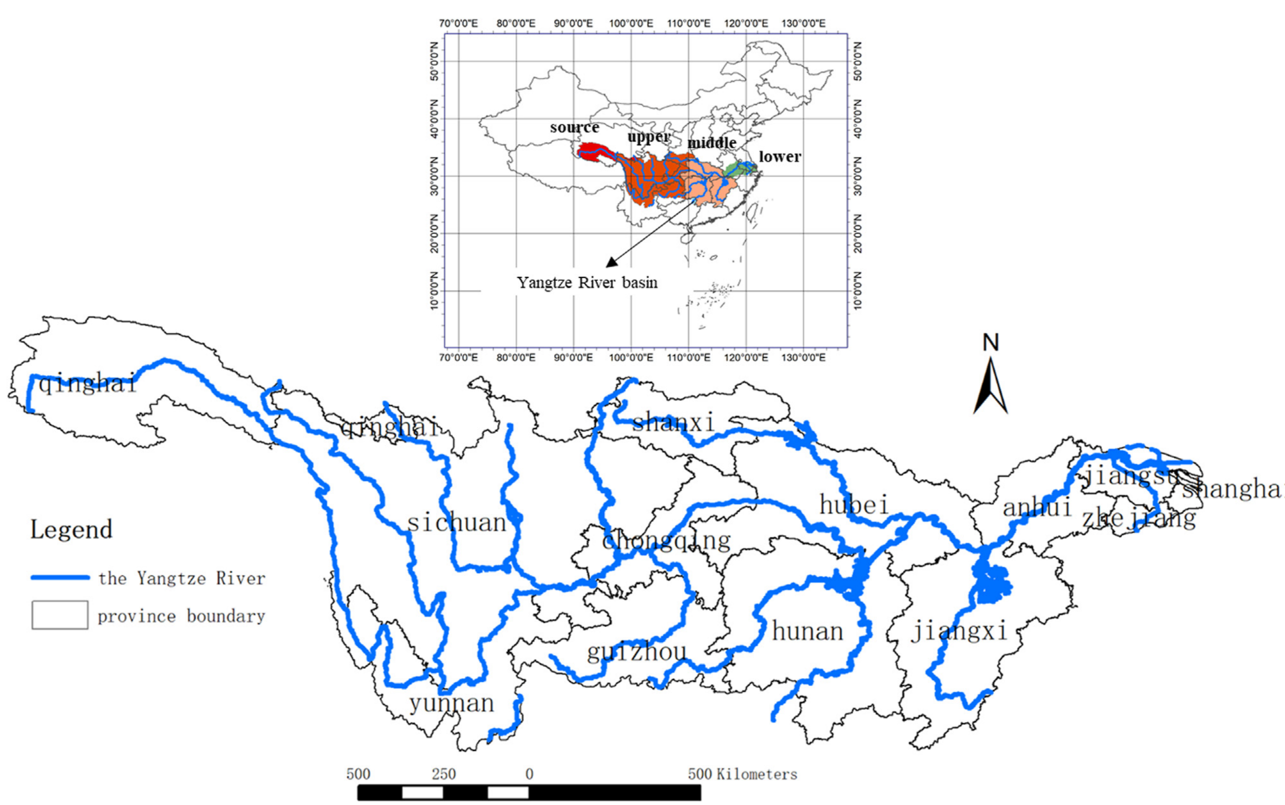

Fig. 3. Location of the Yangtze River basin and the sample points in this study.

water resources and gray virtual flow. Local activities, including industrial production, water resource consumption and pollutant discharge, are the preconditions of teleconnection among provinces. Therefore, the local scale of the economy, water resource consumption and pollutant discharge amount are analyzed first in this section. It is observed that in total, positive correlations occur among any two of the above aspects.

It is clear that in addition to river flow from upstream to downstream, the economic scale is becoming more developed (Table 1). The provinces in the Yangtze River Delta with the largest economic scale, i.e., Jiangsu Province, Zhejiang Province and Shanghai City. Qinghai Province, Guizhou Province and Gansu Province have the smallest economic scale. Jiangsu Province, Hunan Province and Anhui Province have the largest water resource consumption amounts, while Qinghai Province, Chongqing city and Shaanxi Province have the smallest water resource consumption amounts. Through analysis of the relationship between the economic scale and water resource consumption amount, it is found that Shanghai city, Zhejiang Province and Shaanxi Province have the highest water utilization efficiency, while Gansu Province, Jiangxi Province and Anhui Province have the lowest water utilization efficiency. The water utilization efficiency is related to many factors, such as the industrial structure, water usage intensity, and wastewater reuse level. Compared to the other provinces in the Yangtze River Basin, the economic scale and water resource consumption amount are the largest in Jiangsu Province, and the water utilization efficiency is slightly lower than that of the other two provinces in the Yangtze River Basin. The possible reason is the higher ratio of heavy industry.

Hunan Province, Jiangsu Province and Henan Province have the largest pollutant discharge amounts, while Qinghai Province, Guizhou Province and Gansu Province have the smallest discharge amounts. From the perspective of the pollutant discharge intensity per GDP, Shanghai city, Jiangsu Province and Zhejiang Province have the lowest pollutant discharge levels, while Hunan Province, Gansu Province and Jiangxi Province have the highest levels. The pollutant discharge intensity is also influenced by many factors, such as the industrial structure, cleaner-production level, and wastewater treatment level.

In total, the provinces in the delta of the Yangtze River basin can maintain a larger economic scale, higher water utilization efficiency and lower pollutant discharge intensity, and the provinces along the midstream of the Yangtze River can maintain a moderate economic scale, relatively lower water utilization efficiency and higher pollutant discharge intensity. The provinces in the upstream area of the Yangtze River basin maintain the smallest economic scale and moderate water utilization efficiency and pollutant discharge intensity.

4.2. *Water flow characteristics of the HWMN*

The direct water resource consumption of the 13 provinces in the Yangtze River basin accounted for 50.09% of the total direct water resource consumption of China. The results of the virtual water resource flow analysis of the Yangtze River basin are shown in Fig. 4a. The internal water resource consumption of the Yangtze River basin is 280.82 billion m^3, while that of the other provinces in China is 253.48 billion m^3. The water resource consumption of the Yangtze River basin is slightly higher than that of the other provinces in China. The highest internal flow of the Yangtze River basin is 2.14 billion m^3 from Jiangsu Province to Anhui Province. The virtual water resource flow amount from the Yangtze River basin to the other provinces in China is 27.46 billion m^3, while in the opposite direction, the virtual water resource flow amount is 31.28 billion m^3. This indicates that the economic activities in the Yangtze River basin require a higher net water resource input than the other provinces in China. The highest flow from the Yangtze River basin to the other provinces in China is 4.9 billion m^3 from Jiangsu Province. The virtual water resource import amount of the Yangtze River basin is 26.03 billion m^3, while that of the other provinces in China is 37.33 billion m^3. The virtual water resource export amount of the Yangtze River basin is 44.06 billion m^3, while that of the other provinces in China is 46.9 billion m^3. This indicates that China exhibits a net virtual water resource export. The import and export amounts of the virtual water resources in the Yangtze River basin are both smaller than those of the other provinces in China. The highest import and export flows are both from Jiangsu Province, at 8.57 and 17.5 billion m^3, respectively.

The direct water pollutant discharge of the 13 provinces in the Yangtze River basin accounted for 56.04% of the total direct water pollutant discharge of China. The results of the water environment capacity flow analysis of the Yangtze River basin are shown in Fig. 4b. The internal water pollutant discharge of the Yangtze River Basin is 726.3 thousand t, while that of the other provinces in China is 548.7 thousand t. The water resource consumption of the Yangtze River Basin is higher than that of the other provinces in China. The highest internal flow of the Yangtze River basin is 4.15 thousand t from Jiangsu Province to Anhui Province. The water environment capacity flow amount from the Yangtze River basin to the other provinces in China is 51.11 thousand t, while the water environment capacity flow amount is 81.41 billion thousand t in the opposite direction. This indicates that the economic activities in the Yangtze River basin required a higher water environment capacity than that of the other provinces in China. The highest flow from the Yangtze River basin to the other provinces in China is 9.26 thousand t from Jiangsu Province. The water environment capacity import amount

Table 1
The GDP, water resource consumption and pollutant discharge amount of each province in the Yangtze River Basin.

Province	GDP (billion yuan)	Water resource consumption (billion m^3)	Pollutant discharge (thousand tons)
Shanghai	2356.09	10.59	44.60
Jiangsu	6510.00	59.13	142.50
Zhejiang	4015.30	19.29	103.20
Anhui	2084.88	27.21	100.50
Jiangxi	1570.86	25.93	86.00
Henan	3493.94	20.93	139.00
Hubei	2736.70	28.83	120.40
Hunan	2704.85	33.24	154.40
Chongqing	1426.54	8.05	51.30
Sichuan	2853.67	23.69	134.70
Guizhou	925.10	9.53	38.00
Yunnan	1281.46	14.94	56.50
Shaanxi	1768.99	8.98	58.20
Gansu	683.53	12.06	38.10
Qinghai	230.11	2.63	9.80

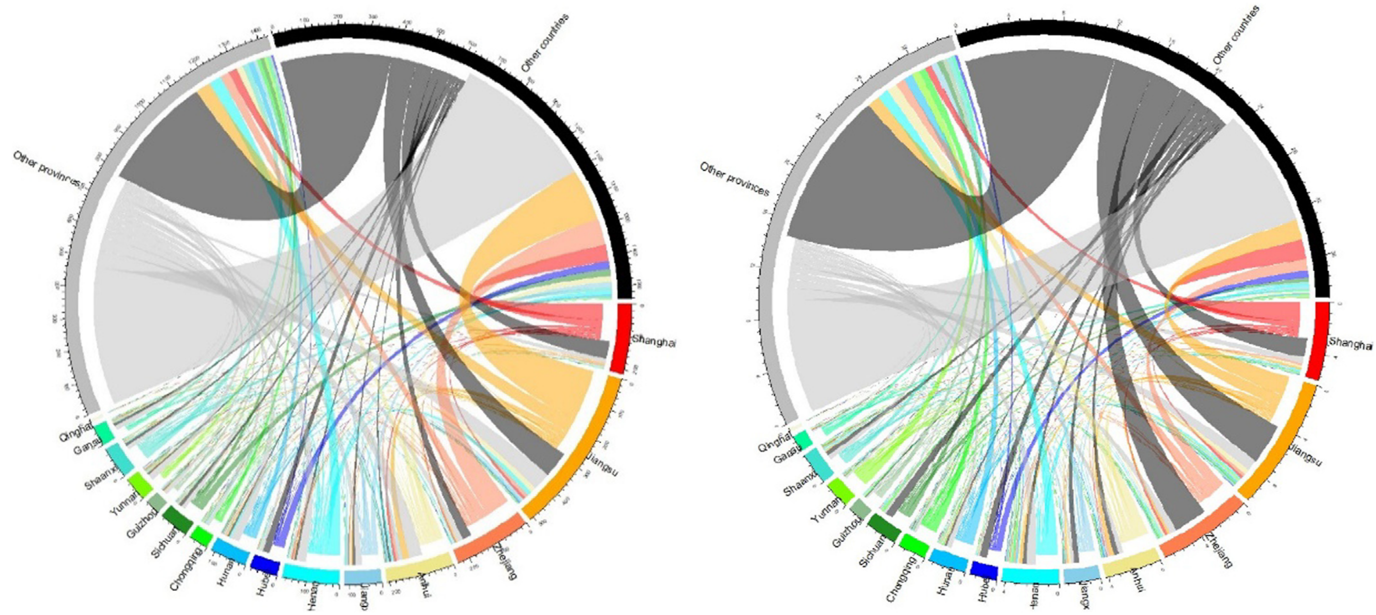

Fig. 4. Virtual water resource flow (a) and virtual water environment capacity flow (b) in the Yangtze River basin.

of the Yangtze River basin is 63.63 thousand t, while that of the other provinces in China is 96.41 billion m^3. The water environment capacity export amount of the Yangtze River basin is 107.3 thousand t, while that of the other provinces in China is 124.7 thousand t. This indicates that China exhibits a net water environment capacity export. The import and export amounts of the water environment capacity in the Yangtze River basin are both smaller than those of the other provinces in China. The highest import flow in the Yangtze River basin is to Jiangsu Province, at 16.2 thousand t. The highest export flow in the Yangtze River basin is from Shanghai city, at 33.2 thousand t.

The pairwise control relationship is shown in Fig. 5. In terms of both the virtual water resource flow and virtual water environment capacity flow, Shanghai city and Henan Province are the two dominant regions. The control power between each pair of provinces is less than 0.6 regarding the virtual water resource flow, while it is less than 0.5 regarding the virtual water pollution flow. This indicates that economic activities mainly consume local water resources and water environment capacity, rather than input and output from other provinces. Among them, Shanghai exerts the main control power over Jiangxi Province, Sichuan Province, Anhui Province, Jiangsu Province, and Guizhou Province. Even though Shanghai city is located in the Yangtze River Delta and Sichuan Province is located in the upstream area of the Yangtze River basin, the control power of Shanghai city over Sichuan Province is 56.59%, which is the highest value. One type of telecoupling of water resources can thus be recognized. The reliance of Jiangsu Province on Shanghai city, Henan Province and Hubei Province is 47.47%, 49.42% and 50.02%, respectively, indicating that the water environment capacity consumption of Jiangsu Province relies on input from other provinces to a certain extent, but it rarely provides output to the other provinces. In terms of the virtual water environment capacity flow, Henan Province is the main control power, and its control power over Sichuan Province, Zhejiang Province, Jiangsu Province, Guizhou Province and Qinghai Province is 47.49%, 46.68%, 42.29%, 39.30% and 41.04%, respectively. The telecoupling effect of the water environment is more diverse compared to that of the virtual water resource flow.

In contrast to the complicated flow relationship, the actual water resource and pollutant flows are relatively simple from upstream to downstream under the effect of gravity. The water resource flow quantity of the Yangtze River basin is quite large compared to the virtual water resource flow quantity, which ranks fourth among all the river basins globally. The real water resource flow in the Yangtze River basin is shown in Fig. 6a. The source and delta of the Yangtze River basin exhibit relatively low water flows between the provinces. The lowest water flow is 0.89 billion m^3 from Zhejiang Province to Anhui Province. The water flow amount between the provinces in the middle of the Yangtze River basin is large, ranging from 300 to 600 billion m^3. The cause of the vast water resource flow amount from upstream to midstream is the accumulation effect of the water flow. The pollutant loads produced from human activities are discharged into the rivers and are transported by the water flow, and the pollutant amount decreases due to physical settlement, chemical reactions and biological degradation (Fig. 6b). Therefore, the water pollutant flow amount is much smaller than the pollutant discharge amount from the human system due to the natural degradation process. Only the excess pollutant amount not degraded by the local water environment capacity flows to the other provinces downstream. The total water pollutant flow amount between the different provinces along the natural river is 266.1 thousand t, while the total discharge pollutant amount is 792.9 thousand t. The smallest flow amount is 0.73 thousand t from Zhejiang Province to Jiangxi Province, and the largest flow amount is 25.1 thousand t from Jiangsu Province to Zhejiang Province. In contrast to the accumulation effect of the water resource flow, due to natural degradation, the pollutant amount in the river gradually decreases along the flow direction.

4.3. The combined effects of HWMNs

The provinces can be divided into three classes through commercial trade (Fig. 7). One class includes the water resource and water environment benefitting provinces whose direct water resource consumption and water pollutant discharge amount are smaller than their water resource consumption and water pollutant discharge, including Shanghai city, Zhejiang Province, Jiangsu Province, Chongqing city and Shaanxi Province. Another class comprises the water resource- and water environment-deficient

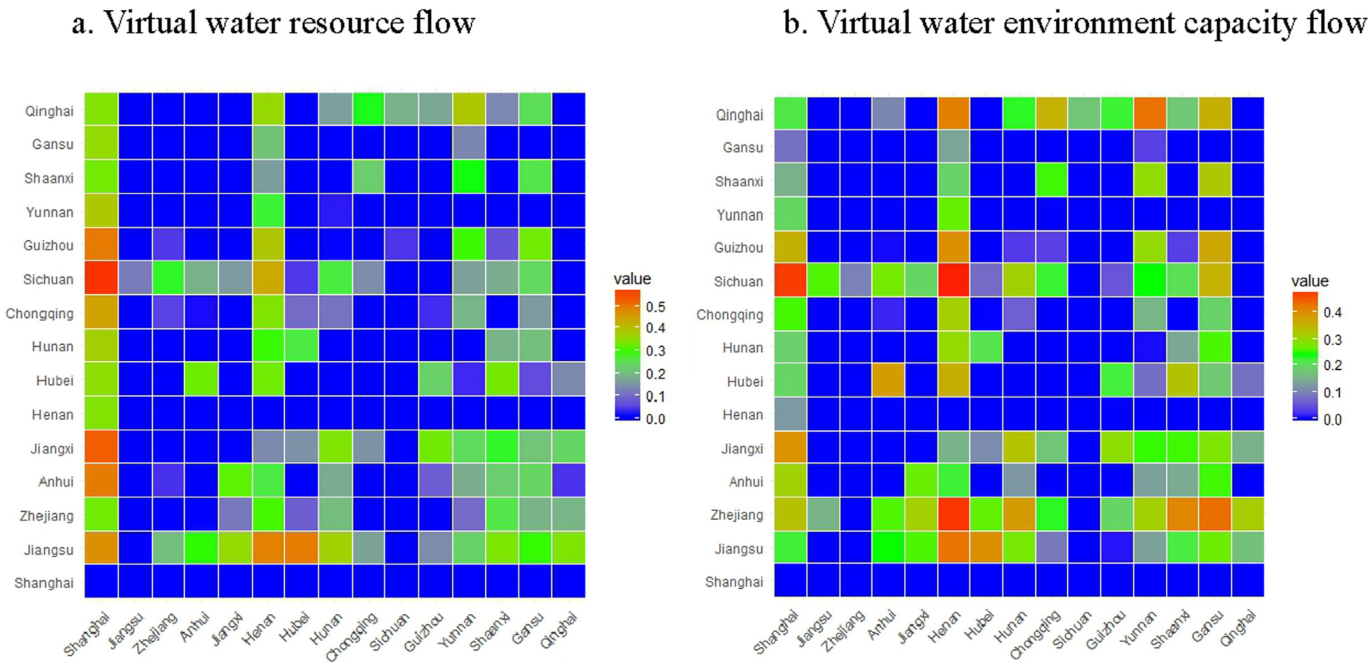

Fig. 5. Pairwise control relationships between all provinces in the Yangtze River basin derived from the results of the control ratio (CR) matrix. Notes: The control/dependence relationships between the provinces are presented. from the production side (matrix row) to the consumption side (matrix column).

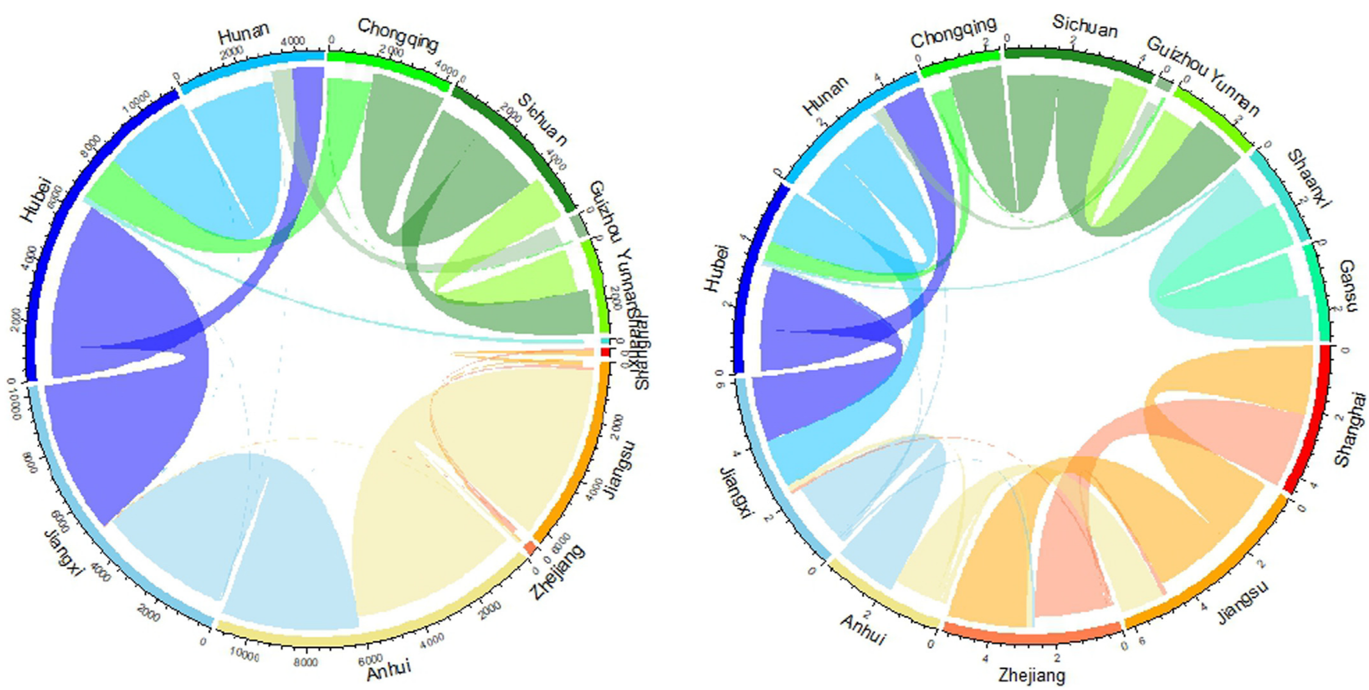

Fig. 6. Virtual water resource flow (a) and virtual water environment capacity flow (b) in the Yangtze River basin.

provinces, whose direct water resource consumption and water pollutant discharge amount are larger than their water resource consumption and water pollutant discharge, including Yunnan Province, Hubei Province, Hunan Province, Gansu Province, Qinghai Province, Guizhou Province, Anhui Province and Jiangxi Province. The last class consists of the water resource benefitting and water environment-deficient provinces, and their direct water resource consumption is lower than their water resource consumption, while their water pollutant discharge amount is larger than their water pollutant discharge amount, including Henan Province and Sichuan Province. This indicates that the provinces of the first class benefit from the two aspects of water resources and water environment through commercial trade. The provinces that benefited the most were the three most advanced provinces in the Yangtze River Delta: Shanghai city, Zhejiang Province and Jiangsu Province. The provinces that were the most deficient were Jiangxi Province,

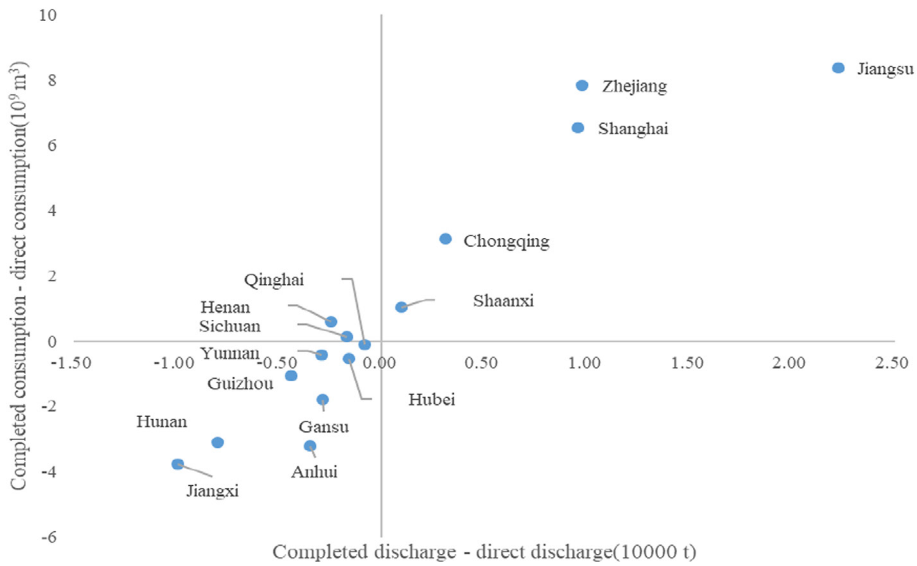

Fig. 7. Province classification according to the cost-benefit analysis of the water resources and the water environment through economic trade.

Hunan Province, Anhui Province, etc. in the middle of the Yangtze River basin.

Most of the provinces in the Yangtze River basin possess adequate water resources to support local economic development, except Shanghai city and Jiangsu Province, due to the very high water flow (Fig. 8a). The water supply gaps of Shanghai city and Jiangsu Province can be satisfied through water extraction from the Yangtze River basin. However, the local water environment capacity is limited and highly influenced by upstream economic activities (Fig. 8b). The ideal water environment capacity without the influence of water pollutants from the upstream economic activities is the completed capacity. Compared to the current water environment capacity, the completed capacity of the provinces, especially the downstream provinces, notably increases. For example, the current water environment capacity is 2440 t, while the completed capacity is 47.9 thousand t. The provinces where the water pollutant discharge amount substantially exceeded the local current water environment capacity are Shanghai city, Jiangsu Province, and Henan Province. This indicates that the completed environmental capacity of Shanghai city could support the direct discharge of water pollutants and even the complete discharge of water pollutants.

The environmental effects of commercial trade may be different once combined with the real local water resources and environmental conditions. Shanghai city and Jiangsu Province benefited in the two aspects of the water resources and the water environment through commercial trade. They are still provinces with a deficient water quantity and poor water quality due to the very high pressure from economic development. Jiangxi Province, Hunan Province and Anhui Province were deficient in the two aspects of the water resources and the environment through commercial trade. However, they are provinces with adequate water resources and water environment capacity due to their excellent water resources and environmental conditions. Henan Province is slightly deficient in terms of its water environment through commercial trade, but its water environment status is clearly diminished due to its limited water environment capacity.

There are two direct ways to realize water environment quality improvement. One is to reduce economic activities to reduce the local water environment pressure, but this is not a feasible way to achieve the mutual development of environmental protection and economic development. The other way is to realize pollutant transfer through industrial transfer. However, this requires a comprehensive view of both the natural processes and economic activities in the Yangtze River basin as a whole. The provinces would interact with each other through river and pollutant flow from upstream to downstream. They would also interact through commercial trade via industrial chains. The pollutants from the economic activities in Jiangxi Province, Anhui Province and Hunan Province, which are located in the middle of the Yangtze River basin, influence the environmental capacity of Shanghai City, Jiangsu Province and Zhejiang Province, which are located in the delta of the Yangtze River basin. Thus, it is clear that industrial transfer from the provinces in the delta to the provinces in the middle of the Yangtze River basin would not improve the water environmental quality of the delta, while this phenomenon would normally occur between two provinces without upstream and downstream river linkages. For example, the indirect water pollutant discharge amount from Jiangsu Province to Anhui Province is 3.11 thousand t. The reduced pollutant amount of Jiangsu Province through the industrial transfer from Jiangsu Province to Anhui Province was not observed. However, due to the upstream and downstream linkages between Anhui Province and Jiangsu Province, it occupied 11 t of the water environment capacity of Jiangsu Province. Compared to the complicated commercial trade and large amount of local pollutant discharge at the scale province, this has a microscale influence and has commonly been ignored. This can be described as the indirect environmental effect of the indirect pollutant discharge. Fig. 9 shows the process between the different pollutant flows in economic systems and natural systems.

4.4. Topology characteristics of HWMNs

Despite the notable water quantity differences between the virtual water resource flow and real water resource flow, research on the topological characteristics of water resource flow systems is lacking. Only the topological characteristics of the water pollutant flow in HWMNs are studied. The combined water environment endowment input between the virtual water environment capacity system and the real water environment system of each province is indicated by its weighted in-degree properties, while the water environment endowment output is indicated by its weighted out-

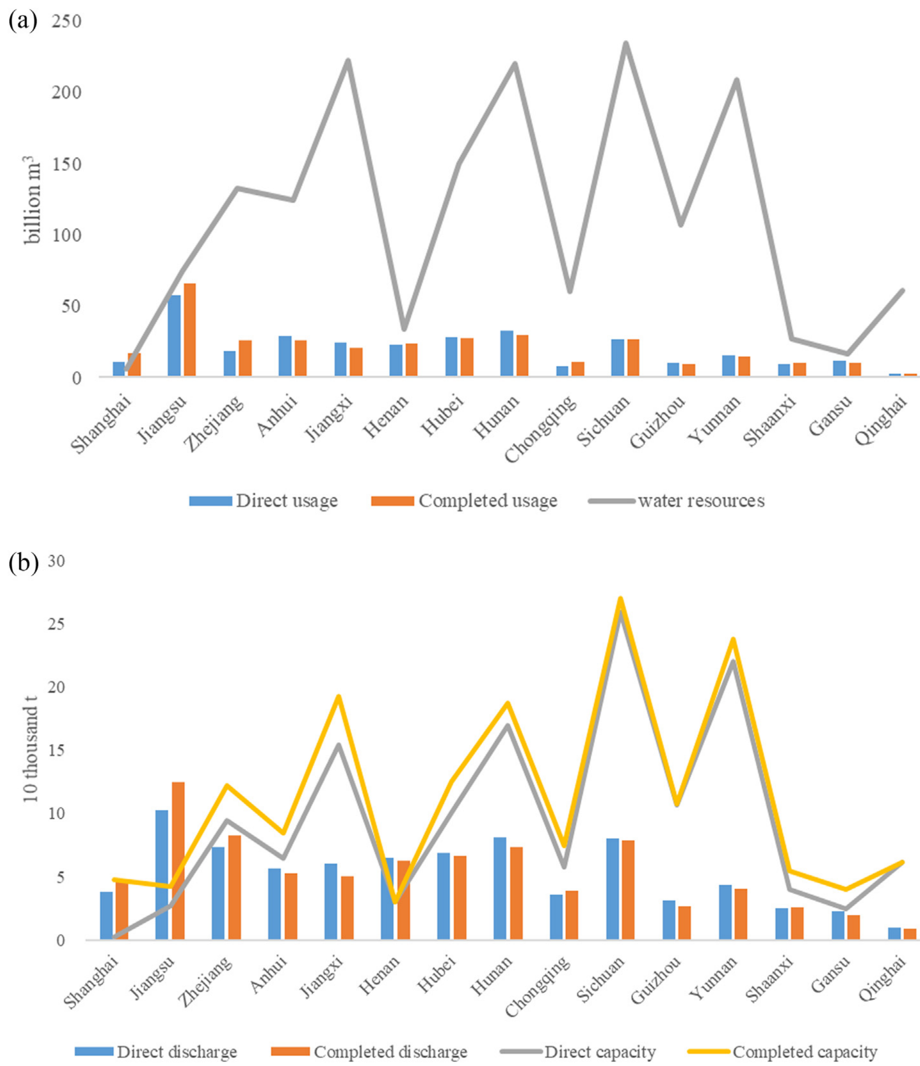

Fig. 8. The combined effects of the water resources (a) and water environment (b) considering the human-water coupled process.

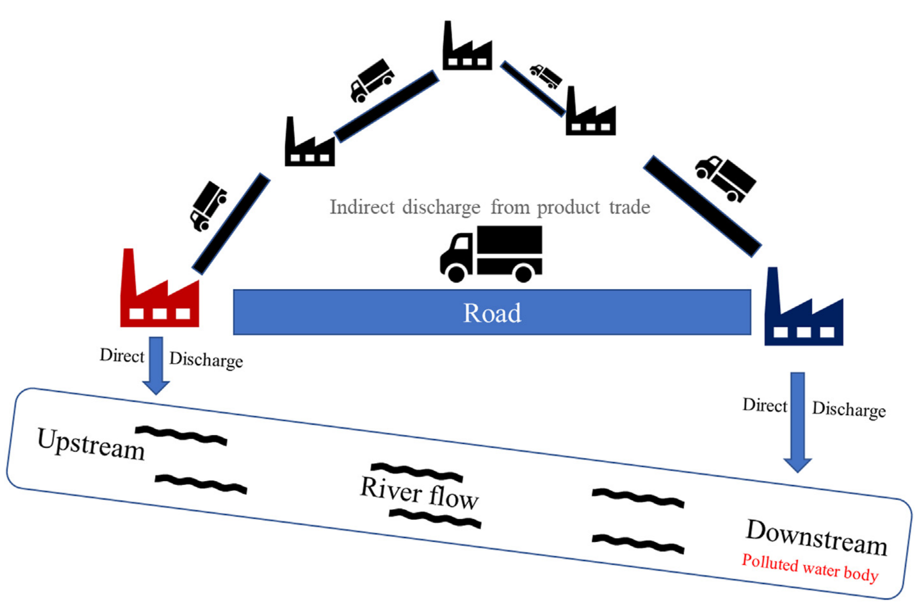

Fig. 9. The environmental effect of the indirect discharge in HWMNs.

degree properties (Fig. 10). This indicates that Jiangsu Province obtained most of its water environmental benefits through social-natural cycling and contributed most of the water environmental benefits to the other provinces. Sichuan Province, Hunan Province, Hubei Province and Zhejiang Province also received water environmental benefits. Jiangsu Province, Zhejiang Province, Shanghai Province and Hubei Province contributed the most to the water environment benefits through social-natural cycling.

The page rank provides an indication of the relative importance of provinces in terms of the water environment endowment transfer in the economic system. The page rank of a province depends on the number and weight of all provinces that are connected to it. The provinces highlighted by their page rank include Jiangsu Province, Hunan Province, Sichuan Province and Yunnan Province.

Community identification in the water environment endowment flow in social-natural systems could help to reveal the important provinces influencing the water environment (Fig. 11). The pattern of the community structure in the real water environment system almost reflects the natural river flow of the Yangtze River basin except Qinghai Province and Henan Province. The reason is that all the pollutants produced by local economic activities have been degraded by the local water environment capacity in Qinghai Province and Henan Province. There are five communities in the water environment system. Shanghai city, Jiangsu Province, Zhejiang Province, and Anhui Province belong to the same community due to their close river flow linkages and very high economic pressure. The provinces along the midstream of the Yangtze River mainly belong to another community. In the economic systems, there are three main communities in the virtual water environment systems. This is highly consistent with the geographical distribution of the upstream, midstream and downstream areas. Shanghai city, Zhejiang Province, Jiangsu Province, Anhui Province and Jiangxi Province belong to the first community, which is also located in the downstream area of the Yangtze River basin. Shanxi Province, Hunan Province, Hubei Province and Henan Province belong to the second community, which is located in the midstream area of the Yangtze River basin. Sichuan Province, Chongqing Province etc. belong to the third community, which is located in the upstream area of the Yangtze River basin. Thus, the community structures in the virtual water environment system and real water environment system are nearly the same, especially in the downstream provinces of the Yangtze River basin.

4.5. Integrated insights through network flow analysis and topology analysis

Flow analysis and topology analysis could provide more integrated insights and a new foundation for HWMN research. Through water flow analysis of the HWMN, it was observed that the provinces in the delta of the Yangtze River basin contributed a large proportion of the virtual water environment capacity flow. Network control analysis revealed the control power of Henan Province and Shanghai city over the other provinces, such as Sichuan Province, Jiangsu Province and Zhejiang Province, due to their economic position. The downstream provinces in the Yangtze River basin obtained their water environment benefits primarily through economic trade. However, the environmental status of Shanghai city and Jiangsu Province has diminished due to their limited water environment endowment. Moreover, the water environment effect of the indirect discharge between two provinces with upstream and downstream linkages has been uncovered through coupled flow analysis of the HWMN. Via network topology analysis of the HWMN, the effect of each province on the water environment has been revealed in the HWMN. Jiangsu Province is the most active province obtaining and contributing water environmental benefits through economic trade. The community structure of the virtual water environment capacity flow in the economic system is highly consistent with the geographical distributions of the upstream, midstream and downstream areas of the Yangtze River basin through community identification.

4.6. Comparison of HWMNs research

Virtual water research has been a topic of increased interest ever since it was proposed by Allan (1997). The virtual water flow pattern has been analyzed at different scales, including the global scale (Dalin et al., 2012), country scale (Zhao et al., 2019), river basin level (Feng et al., 2012) and city scale (Cheng et al., 2019). Researchers have analyzed the combined effects of virtual water flow patterns and physical hydrological cycles or physical water transfer projects at the global scale or country scale (D'Odorico et al., 2019;

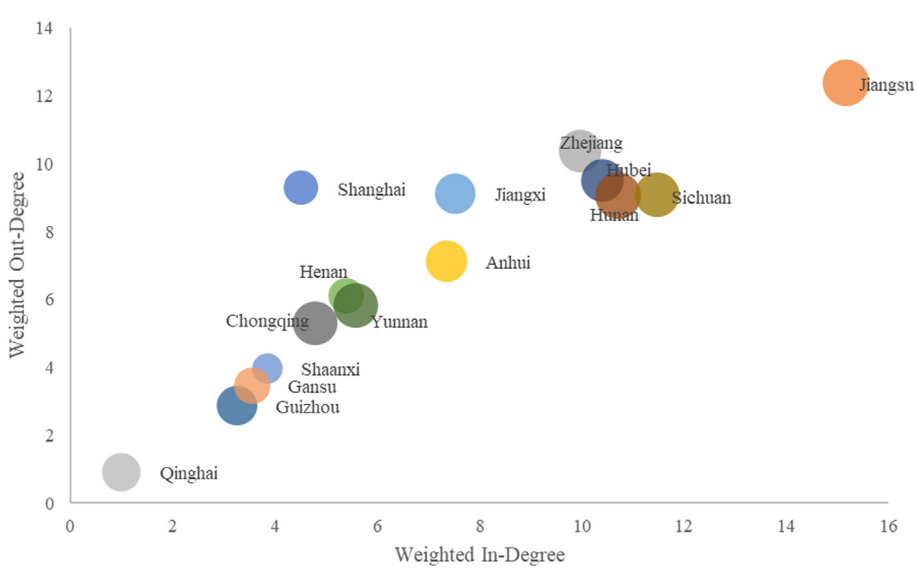

Fig. 10. Weighted in-degree, weighted out-degree and page rank (bubble size) of the water environment capacity flow in the HWMN of the Yangtze River basin.

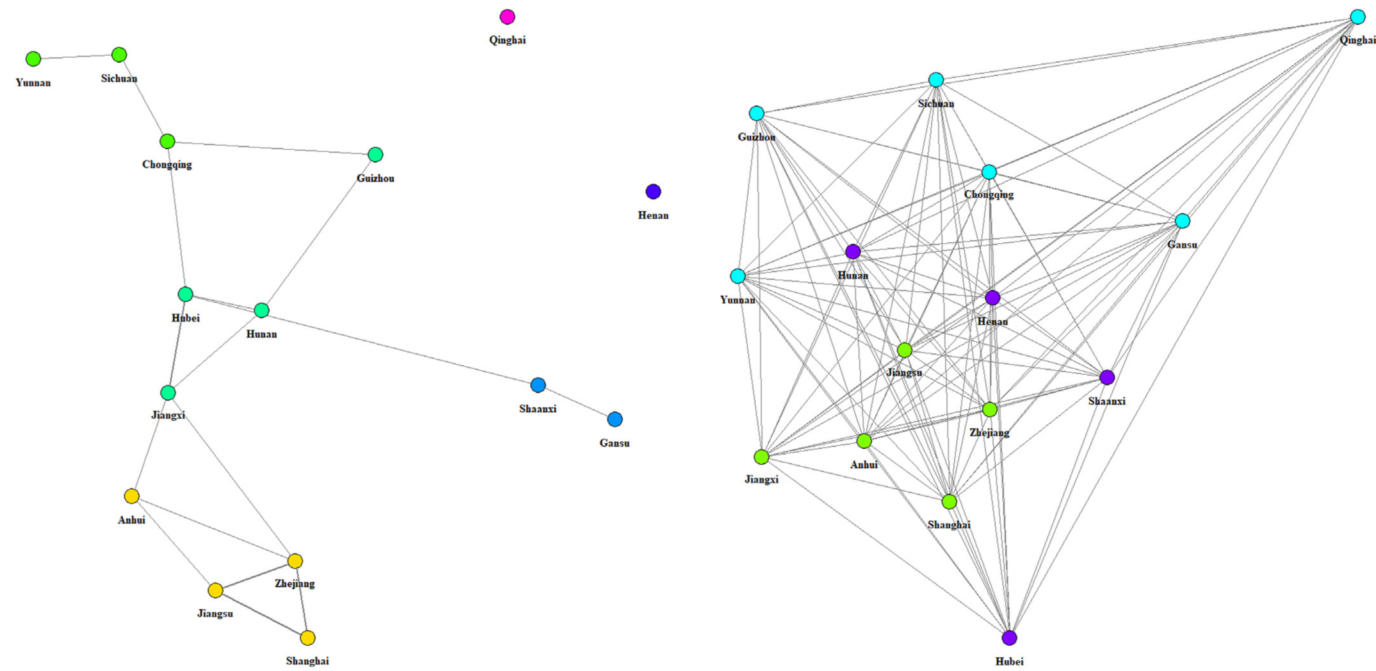

Fig. 11. Community identification of the real water environment system (a) and virtual water environment capacity flow system (b) in the Yangtze River basin.

Zhao et al., 2015). For the water environment system, the pollutant flow in physical rivers has attracted a large amount of attention in water quality model research (Fu et al., 2019). Compared to water resource research, gray virtual water research is lacking. Liao et al. (2019) analyzed the flow pattern in China. Integrated research on the combination of physical rivers and gray virtual water in water environment systems is even less common. Overall, most of the current research focuses on network flow analysis, and less network topology research is less conducted, which is a common method in network science. Topology research can reveal the key nodes that influence the network structure, which can be recognized as important regions in the virtual water trade. Thus, integrated research combining network flow and network topology from the perspective of multiplex networks can uncover the important regions that influence the networks of water resources and water environment (Table 2).

5. Conclusions

The characteristics of human-water systems in the Yangtze River basin are revealed through network flow analysis and the network topology characteristics of multiplex networks. The impact of each province on the water environment of the Yangtze River basin can be determined considering the combined effects of economic activities and natural river flow. This study can also provide further enlightenment for broader CHANS research.

5.1. Policy implications for water management

The integrated research of human-water systems from the perspective of HWMNs indicates that the Yangtze River basin is a highly active economic region with intense influence and response effects between human systems and water systems. The virtual flow of the water resource environment accounts for approximately 50% of the total flow in China. The telecoupling relationship can be determined through network control index analysis between Shanghai city and Sichuan Province in terms of the virtual water resource flow, as well as between Henan Province and the other provinces in terms of the virtual water environment capacity flow.

The analysis from the perspective of network flow and network topology provides a new foundation for HWMN research. The downstream provinces in the Yangtze River basin obtained water environment benefits primarily through economic trade. However, the environmental status of Shanghai city and Jiangsu Province has diminished due to their limited water environment endowment. Through network topology analysis of the HWMN, the impact of each province on the water environment is identified in the HWMN. The community structure of the virtual water environment capacity flow in the economic system is highly consistent with the geographical distribution of the upstream, midstream and downstream areas of the Yangtze River basin through community identification.

The research methods can be used in research on other river basins worldwide. Most culture has developed in river basins

Table 2
Comparison of HWMN research.

Comparison	Research
Scale	Global scale (Dalin et al., 2012), country scale (Zhao et al., 2019), river basin level (Feng et al., 2012) and city scale (Cheng et al., 2019)
Network flow of virtual water	Cai et al. (2019)
Network flow of virtual water and physical water	D'Odorico et al. (2019); Zhao et al. (2015)
Network flow of pollutants in physical rivers	Fu et al. (2019)
Network flow of gray virtual water	Liao et al. (2019)
Network topology of multiplex networks	Current research

globally. This indicates that the proposed method has a large application range. The HWMN research results indicate that water management is an interdisciplinary problem and requires adequate knowledge of the economy, environment, and resources. The research results can provide basic support for integrated water management in both economic systems and water systems. This indicates that a connected view of the river basin should be adopted for integrated water management.

5.2. Human-water multiplex network prospects

This study recognizes human-water systems as HWMNs to identify the water resources and environmental effects of economic activities accounting for the natural water flow and endowment. Network flow and topology analysis related to HWMNs reveals the spatial linkages between each province and their status in the coupled human-water system. Specific improvement measures can be proposed for a certain region from the perspective of a systematic network according to the indicator values of the HWMN flow and topology. The proposed research method can also be applied in other coupled human-natural systems from the aspect of multiplex networks.

Due to the limitations of the data, only the annual and provincial relationships in HWMNs are considered in the current research. More accurate spatial-temporal data are required for a better identification of water problems at finer space and time scales. Data fusion for multisource and multiscale data is also a challenge for a better presentation of HWMNs. The current algorithm for the topology structure of multiplex networks is mainly adopted from the single-layer network. A more suitable algorithm should be developed for topology analysis of multiplex networks.

To support enhanced water management utilizing the knowledge of complex networks, more work should be conducted in future research. Machine learning technology, especially the technology of graph neural networks, should be adopted to elucidate the network relationship of HWMNs with large amounts of input network data. A graph neural network is also a suitable platform for multisource and multiscale data fusion.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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