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Ecological network analysis for urban physical-virtual water cycle: A case study of Beijing

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ABSTRACT

Growing water demands have increasingly challenged the urban water cycle resilience. In contrast to conventional evaluations, which concentrate primarily on the physical water cycle, this study presents a methodological framework considering both physical and virtual components and chooses Beijing as a case study. We constructed an urban physical-virtual water cycle (PVWC) network model to investigate water cycle resilience through structural and functional analysis based on ecological network analysis (ENA). The PVWC model covers multiple water suppliers (surface water, groundwater, transferred water, and reclaimed water), multiple water users (production water use, domestic water use, and ecological water use), water leakage, and wastewater treatment, as well as physical links and virtual flows driven by trade among these nodes. This study analyzed the system's robustness and the contributions of individual components to overall resilience from structural dimension, as well as revealed dominant sectors and interrelationships between components that sustain the system's resilience from functional dimension. The case study of Beijing in 2017 demonstrates that its network is moderately robust and synergistic. The external water transfer subsystem mainly has more remarkable mutualistic pair-wise relationships with secondary industry, tertiary industry, and household consumption. Moreover, water distribution subsystem is the dominant controller of PVWC, while the through flows of water leakage and wastewater treatment rely on the operation of whole system. The ecological environment, which has strong connections with reclaimed water and ecological water flows, played an important role in the entire system promoting more mutualistic relationships. We found that increasing the proportions of transferred water and reclaimed water supply and promoting mutualistic interactions between water users are critical to improving urban water cycle resilience.

1. Introduction

Fast socioeconomic growth and large-scale urbanization have significantly intensified the water resources demand (Flörke et al., 2018; He et al., 2021; Liu et al., 2022). Human interventions such as underground water extraction and water transfer project, which have been implemented to address such growing water demands. Yet they have escalated water exploitation and depletion, impacting the physical processes of natural water cycle, further aggravating urban water scarcity and straining the balance between supply, consumption, and drainage (Duan et al., 2023; Haddeland et al., 2014; Long et al., 2020). Additionally, they have increased the city's dependence on groundwater and external water transfers, which could impact the urban water system resilience if their supplies are insufficient.

Emerging studies investigate water scarcity issues through the lens of water cycle resilience. Traditional urban water cycle resilience assessment studies have focused on isolated subsystems of the physical water cycle process in engineering dimension, such as water supply (Bata et al., 2022; Li et al., 2022; Liu et al., 2021; Sweya et al., 2020) or water drainage systems (Dong et al., 2017; Meng et al., 2018; Zhang et al., 2021). Some studies analyzed the entire physical water cycle process and set up an indicator system considering water quantity and quality to evaluate water cycle performance (He et al., 2023; Jeong and Park, 2020; Renouf et al., 2018, 2017; Renouf and Kenway, 2017; S. S. Zhang et al., 2020; Zhang et al., 2017). Furthermore, the resilience indicators of urban water systems were developed to measure technical and

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economic, environmental, as well as social and institutional aspects (Jemmali and Matoussi, 2013; Polonenko et al., 2020). In addition, a few studies explored water flow structure and interactions among various components to investigate the water cycle resilience (Kharrazi et al., 2016; Li et al., 2009; Zhang et al., 2010). While these studies provide valuable insights, they overlooked the interactions of water flows between different socioeconomic sectors via commodity trading activities on water cycle resilience. Such water flows embodied in the products through economic trade can be manifested by virtual water (Cheng et al., 2023; Ji et al., 2022), which was proposed by Allan (Allan, 1998, 1996) to expand the boundary and scope of physical water cycle (Fang et al., 2014; Fang and Chen, 2015), and provide a feasible way to integrate direct physical water flow and indirect virtual water flow.

Recently, the effects of transferred physical and virtual water on water stress have been addressed at different scales (Karandish et al., 2021; Zhao et al., 2015, 2020), including the optimal allocation of physical and virtual water resources (Ye et al., 2018). For example, a physical and virtual water cycle efficiency assessment was conducted based on material flow analysis (Huang et al., 2013), and networks of physical and virtual water resources were set up to assess their vulnerabilities (Zhang et al., 2020). Meanwhile, researchers have identified the main causes and critical components influencing urban water cycle (Cui et al., 2021). Furthermore, key components such as ecological water use and water leakage, which are essential for a holistic understanding of urban water consumption, remain underexplored (Ai et al., 2022; Hu et al., 2021). Likewise, the interrelationships between various suppliers and users, which can significantly impact water cycle resilience, are yet to be fully identified.

To address these gaps, this study proposed an integrated approach combing physical and virtual water perspectives to assess urban water cycle resilience. By utilizing ecological network analysis (ENA) proposed originally by Hannon (1973), we aimed to uncover the hidden dependencies and interactions within the urban water cycle. ENA conceptualizes a system as network of nodes and connections (flows, links, etc.) between them (Fath, 2007), and is applied to uncover the hidden effects and interactions among nodes within different materials networks through its detailed pathway-focused analysis capability (Chen and Chen, 2015; Lu et al., 2015; Qi et al., 2021; Wu et al., 2016; Zhai et al., 2019; Zheng et al., 2019). ENA provides a dual perspective: structurally, it analyzes the system's robustness and the contributions of individual components to overall resilience (Fang and Chen, 2015; Fu et al., 2021); functionally, it reveals dominant sectors and interrelationships between components that sustain the system's resilience (Chen and Mei, 2021; Xu et al., 2021). This approach allows us to go beyond traditional water cycle analysis by integrating both direct physical flows and indirect virtual flows, thus providing a more comprehensive understanding of urban water systems.

This study primarily proposed a methodological framework and chose Beijing as an example case study. We constructed an urban physical-virtual water cycle (PVWC) network model that captures integral connections between multi-source water suppliers (e.g., surface water, groundwater, transferred water, and reclaimed water) and multiple water users (e.g., households, industries, construction, agriculture, services, and ecological environment). We defined resilience in the context of PVWC as the capacity of the integrated water system to maintain its core functions, such as water supply, ecological balance, and service provision, despite facing disturbances such as resource depletion, environmental stress, and socio-economic shifts. This resilience is characterized by the system's ability to absorb shocks, recover from disruptions, and adapt through structural reorganization and the rebalancing of water flows, both physical and virtual. To assess this water cycle resilience, we applied ENA and proposed a modified framework from structure-function dimension integrating properties such as robustness and efficiency, as well as properties like utility and control incorporating to evaluate how components within the system interact to maintain resilience through functional and organizational adjustments.

2. Material and methods

2.1. Study area and data

Beijing is one of the largest water-intensive cities in the world. Since the South-to-North Water Diversion Project (SNWD) has finished in 2014, a pattern of joint water-supply including surface water, groundwater, transferred water, and reclaimed water has been formed in Beijing (Huang et al., 2022; Wang et al., 2019; Ye et al., 2018). Transferred water is fresh water that transfers from Yangtze River in southern China to northern China through eastern, central and western routes, which has significantly alleviated the over-exploitation of Beijing local water resources and increased water availability (Long et al., 2020; Zhao et al., 2020). However, heavy reliance on transferred water will lead to potential water supply risks due to possible emergencies (such as earthquake, heavy rainfall, insufficient upstream water supply). To relieve water scarcity, it is critical to promote water utilization efficiency, improve water quality, and increase reclaimed water recycling. Recently, ecological water, defined as the water volume necessary to maintain a healthy and stable eco-environment (Zhen et al., 2023), has come to constitute a significant portion of urban water consumption in Beijing with 1.22 billion m^3, which accounted for 30.81 % of its total water consumption. Furthermore, the Beijing Water Conservation Regulation (BWCR, 2023) demonstrate to control the level of the water leakage in water supply system in order to improve the stability of water system. Therefore, besides traditional water supply and consumption sector, this study includes transferred water, ecological water use, and water leakage to construct the water network. The water for daily use in all households includes water use for urban residents and rural residents.

The data of physical water flows are derived from Beijing Water Resources Bulletin (BWRB, 2018) , Beijing Statistical Yearbook (BSY, 2018), Beijing Water Statistical Yearbook (BWSY, 2018), China Urban Construction Statistical Yearbook (CUCSY, 2018), the first National Pollution Source Census in China (NPSC, 2010). The virtual water flows are calculated based on trade activities via the input–output models. The input-output table is derived from the Beijing Bureau of Statistics (IOTB, 2015), which showed in supplementary material. The specific details of the data sources are provided in Table S1. The original 42 sectors in the input-output table in Beijing 2017 merged into 4 sectors as shown in Table S2.

2.2. Construction of PVWC model

The water flow structure of an urban PVWC could be divided into three processes (Fig. 1a). First, the physical water flow process includes the main process of water supply, use, discharge, reuse, as well as water leakage. Second, physical water is utilized from certain water bodies and transformed into virtual water when physical water is incorporated into products or services. Third, the virtual water flow process is reflected in the virtual water transfer within various sectors via commodity trade.

We identified four node types of the network (water supply, water use, water leakage, and wastewater treatment) and the direct links among them considering multiple water suppliers and users (Fig. 1b, Table 1). Nodes of water supply side include the natural environment subsystem (Nat), the water transfer subsystem (WT), the water distribution subsystem (WD), and the reused water subsystem (Reu). Nat means the local water supply subsystem that directly provides surface water or groundwater to meet the demand of water users, while WT means the external water supply subsystem indirectly providing fresh water. WD obtains water from Nat or WT and then further allocates water resources to water users, while Reu provides treated wastewater for water users. Nodes of water use side are corresponding with various water users in socioeconomic system including the primary industrial sector (Pri), secondary industrial sector (Sec), construction sector

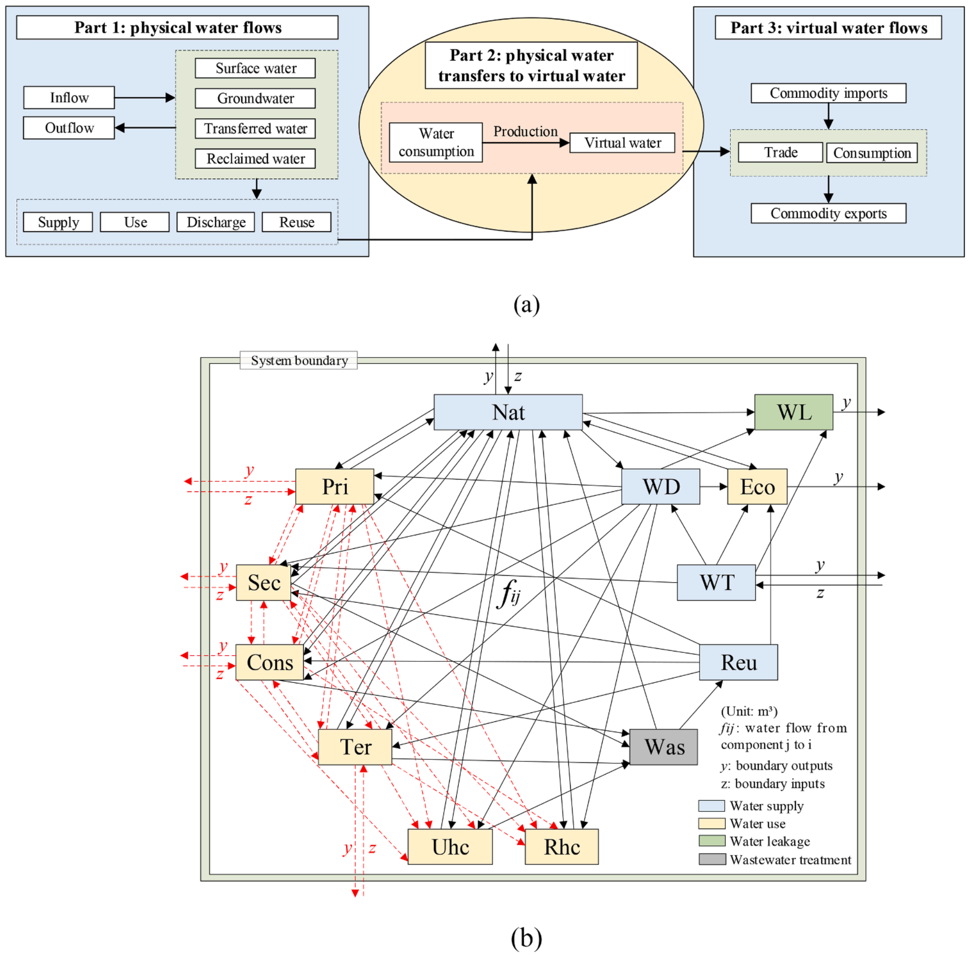

Fig. 1. The ecological network model of PVWC.
Notes: (a) Water flow structure of the PVWC; (b) Ecological network with physical water flows (shown by solid black arrows) and virtual water flows (shown by dotted red arrows).

(Cons), tertiary industrial sector (Ter), urban household consumption sector (Uhc), rural household consumption sector (Rhc), and ecological environment (Eco). Water leakage subsystem (WL) is the third node type, which means water lost by water conservancy projects or public water supply pipes network. Wastewater treatment subsystem (Was) is the last node type, which collects and treats the wastewater discharged by water users and then transfers the treated wastewater into natural environment or water recycling facilities. The direct links among these nodes are divided into two types: (1) physical water flows among four types of nodes; (2) virtual water flows among various water users. Since the completion of the SNWD in 2014, transferred water has become an important replenishment for Beijing (Long et al., 2020; Zhao et al., 2017). Ultimately, there are 13 components and 74 direct paths in 2017. The specific technical framework and structure for this study are shown in Fig. 2. The system boundary inputs and outputs include the physical water flows of natural environment subsystem, water transfer subsystem, water leakage subsystem, and ecological environment, as well as the virtual water flows embodied in trade with other regions.

In the ecological network, paths are channels connecting different components by water flows. A steady-state system meets the requirement that, for each component of a system, the total inputs equal the total outputs, including both intersectoral flows and boundary flows (Fath and Patten, 1999a, 1999b), that is:

$$F = \left(f_{ij}\right) \tag{1}$$

$$\sum_{i=1}^{n} f_{ij} + y_i = \sum_{i=1}^{n} f_{ji} + z_i \tag{2}$$

$$T_j = \sum_{i=1}^{n+1} f_{ij} = T_j^{out} = \sum_{i=1}^{n+1} f_{ji} = T_j^{in} \tag{3}$$

$$TST = \sum_{j=1}^{n} T_j \tag{4}$$

where F represents the dimensional direct flow matrix, f_{ij} stands for the flow originating from component j to i, which only contains the direct physical or virtual water flows among components with direction from the production side (matrix column) to receivers on the consumption side (matrix row), and y_i and z_i refer to the boundary outputs and boundary inputs of component i (Fang and Chen, 2015). T_j^{in} and T_j^{out} represent the input-oriented throughflow and output-oriented throughflow of component j, T_j is the throughflow of component j when the system is at a steady state, and TST is the total system throughput that indicates the dimensional direct throughflow of the system (Cao et al., 2021).

2.3. Assessment of PVWC resilience

Resilience concerning system elements and how these elements are connected to each other was originated in ecology during the 1970s

Table 1
The names and abbreviations of each component in the PVWC.

Node type	Abbreviation	Full name	Detailed description
Water supply	**Nat**	Natural environment subsystem	Provides fresh water to water users and water distribution subsystem
	WT	Water transfer subsystem	Provides fresh water to water users and water distribution subsystem
	WD	Water distribution subsystem	Provides tap-water
	Reu	Reclaimed water subsystem	Provides reclaimed water
Water use	**Pri**	Primary industrial sector	Includes agriculture, forestry, animal husbandry and fishery
	Sec	Secondary industrial sector	Includes mining, manufacturing, and the supply of electricity, gas, etc
	Cons	Construction sector	Includes the construction sector
	Ter	Tertiary industrial sector	Includes other industries except for primary and secondary industries, such as transport and storage, wholesale and retail trades, hotels and catering services, municipal service, information service, etc
	Uhc	Urban household consumption sector	Refers to urban residents
	Rhc	Rural household consumption sector	Refers to rural residents
	Eco	Ecological environment	Includes rivers, lakes, wetlands, landscaping and environmental sanitation
Water leakage	**WL**	Water leakage subsystem	Includes water lost by water conservancy projects or public water supply pipes network
Wastewater treatment	**Was**	Wastewater treatment subsystem	Includes sewage collection and treatment

(Folke, 2006; Holling, 1973) and has evolved into a useful metric for promoting the urban water systems security in context of stable structure and function to adapt with internal and external interferences (Makropoulos et al., 2018; Pizzol, 2015). Here, we propose a framework from structure-function dimension to assess the resilience of PVWC. From structural dimension, we investigate the robustness of PVWC utilizing information-based ENA as well as the contribution of each sector based on network structure analysis. From functional dimension, we identify the dominant sectors and strong linkages applying network control analysis, and evaluate the mutual relationships between sectors based on network utility analysis.

2.4. Information-based network analysis

Achieving a balance between efficiency and redundancy is critical for maintaining the long-term sustainable development of PVWC (Cao et al., 2021; Chen et al., 2010; Fang and Chen, 2015). Thus, information-based network analysis is used to investigate the

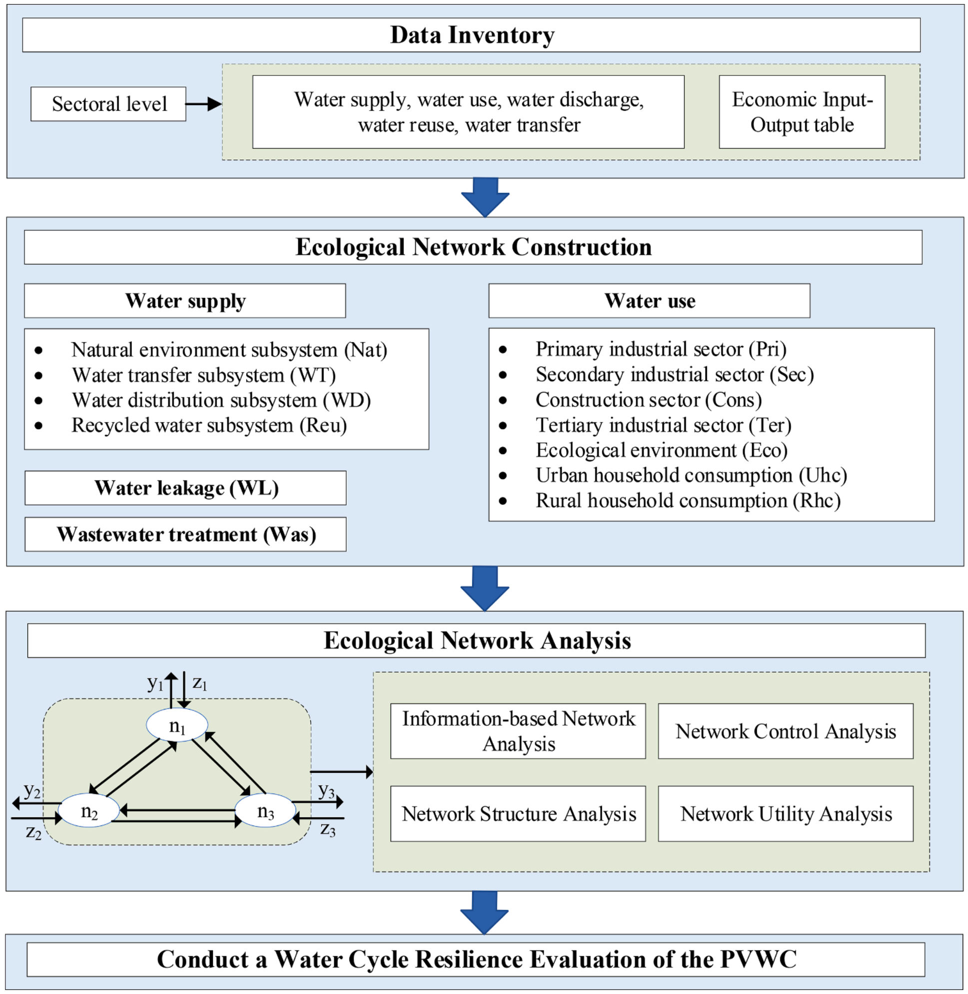

Fig. 2. The technical framework and structure of the PVWC.

characteristics of PVWC, including efficiency, redundancy, and robustness. The ascendency can represent the efficiency of PVWC, which shows how well organized these water flows are. For instance, a PVWC with larger water flows along fewer paths has a higher ascendency. Redundancy stands for the ability of PVWC to withstand perturbations. The combination of efficiency and redundancy constitutes the robustness of PVWC, which is used to identify the balance between the system's efficiency and its redundancy. A brief explanation of this method follows.

2.4.1. Efficiency

The scale average mutual constraint of a system is referred to as the system ascendency or system efficiency. Ascendency describes the degree to which a system efficiently distributes flows among its nodes (Kharrazi et al., 2013). The average mutual information (AMI) of a system shows the network's capacity to perform in an efficient and well-organized way to maintain its integrity over the long term. For a PVWC, AMI can reflect its efficiency and indicate the degree of organization of water flows from a structural perspective, which is calculated as follows (Cao et al., 2021; Kharrazi et al., 2013):

$$AMI = k\sum_{i,j}\left(\frac{f_{ij}}{TST}\right)log\left(\frac{f_{ij}TST}{T_i^{in}T_i^{out}}\right) \tag{5}$$

where k is the scale coefficient.

In this study, the nonscale AMI (i.e., $k = 1$) stands for the authentic network efficiency of PVWC only from the structural perspective, which is not correlated with the size of PVWC. A higher AMI indicates that the water flows within PVWC are more concentrated with fewer dispersion pathways, and the water flow structure is highly organized, corresponding to higher network efficiency.

2.4.2. Redundancy

The scaled conditional entropy (H_c) of a system is called the system "overhead" or system redundancy. H_c describes the flexibility that a system maintains for overcoming disruptions and shocks to its network (Kharrazi et al., 2013). H_c represents the amount of residual uncertainty pertaining to both the inputs and outputs of an average component in the network. H_c is calculated as follows (Cui et al., 2021; Kharrazi et al., 2013):

$$H_c = -k\sum_{i,j}\left(\frac{f_{ij}}{TST}\right)log\left(\frac{f_{ij}^{\ 2}}{T_i^{in}T_i^{out}}\right) \tag{6}$$

Similar to AMI, in this study, the nonscaled H_c (i.e., $k = 1$) reveals the authentic residual uncertainty of PVWC only from the structural perspective. A higher H_c indicates less organization of the water flow structure of PVWC, that is, the existence of more alternative pathways to contain unidentified flows, which corresponds to higher network redundancy. An appropriate redundancy benefits the stability maintenance of PVWC and helps to reduce the risk of collapse when facing unfavorable changes, while an overly redundant network is disadvantageous for the long-term sustainable development of PVWC.

2.4.3. Robustness

Robustness (R) is regarded as a balance between efficiency and redundancy of a system, and is used to measure the possibility that alternate flow paths can cope with internal and external changes (Cao et al., 2021; Ulanowicz et al., 2009). To help determine where such a balance between system constraint and system flexibility might lie, the relative order degree (i.e., relative efficiency) of the system is introduced as α. α is affected by a combination of the ascendency and the capability of a system and is used to measure the organized power flowing within the PVWC (Kharrazi et al., 2013). Robustness shows the degree of constraint and degree of freedom, which depends on both the order and disorder of the system. α and R can be calculated as follows (Cao et al., 2021; Fang and Chen, 2015):

$$\alpha = \frac{AMI}{AMI + H_c},\ 0 \le \alpha < 1 \tag{7}$$

$$R = -\alpha \log(\alpha) \tag{8}$$

The relationship between α and R can be described by an inverted U-shaped curve (Cui et al., 2021). Achieving balance between efficiency and redundancy is critical for achieving a sustainable PVWC. If the indicator is close to the peak value, the PVWC demonstrates a balance between efficiency and redundancy that is needed to achieve long-term sustainable development while maintaining integrity and stability. However, if the indicator lies on the left or right of curve, the PVWC is stagnant with less efficiency or too much efficiency leading to an imbalance.

2.5. Network structure analysis

Based on the network structure analysis (NSA), combining the upstream and downstream relationships through the weight coefficients (W_i and W_j), the contribution made by each sector to the PVWC and the support provided to each sector from the water flows can be determined. The contribution weight factors can be calculated as follows (Fu et al., 2021):

$$F_n = (\lambda_{ij}) = N^* diag(T_j) \tag{9}$$

$$W_i = \sum_{j=1}^{n} \lambda_{ij} \Big/ \sum_{i=1}^{n} \sum_{j=1}^{n} \lambda_{ij} \tag{10}$$

$$W_j = \sum_{i=1}^{n} \lambda_{ij} \Big/ \sum_{i=1}^{n} \sum_{j=1}^{n} \lambda_{ij} \tag{11}$$

where F_n is the dimensional integral flow matrix. $\sum_{j=1}^{n} \lambda_{ij}$ means that the water flows of the whole system contribute to sector *i*. $\sum_{i=1}^{n} \lambda_{ij}$ means that the water flows of sector *j* contributes to the whole system. W_i is called the "pulling force weight", reflecting the ability of sector *i* to receive water flows from the whole system, which represents the sector's "pull" on the other sectors through forward linkages (demand linkages). W_i stands for the degree of demand and the dependency of the sector on the system. W_j is called the "driving force weight", indicating the capacity of sector *j* to deliver water flows to other sectors, which represents the sector's ability to drive other sectors through backward linkages (supply linkages) and reveals the impact of component *j* on the system.

2.6. Network control analysis

Network control analysis (NCA) is utilized to quantitatively assess the dominance of one sector over another by examining pairwise interactions, specifically through the control and dependence relationships between sectors. (Xu et al., 2021). The distributed control matrix is featured by the integral flow, which can explain the influence that one sector exerts on another within the overall system configuration (Schramski et al., 2007, 2006). The integral flow matrix is defined as N and N', which include both the direct and indirect flow contributions through the system and is found by summing the infinite power series of the direct interaction matrix (Fath and Patten, 1999a, 1999b):

$$N = I + G + G^2 + G^3 + G^4 + \ldots \tag{12}$$

$$N' = I + G' + G'^2 + G'^3 + G'^4 + \ldots \tag{13}$$

This infinite power series can be rewritten as:

$$N = (n_{ij}) = (I - G)^{-1} \tag{14}$$

$$N' = (n'_{ij}) = (I - G')^{-1} \tag{15}$$

where $G = (g_{ij}) = f_{ij}/T_j^{out}; G' = (g'_{ij}) = f_{ij}/T_j^{in}$ (Fang and Chen, 2015). Based on these equations, the control difference matrix (CD) and dimensionless control ratio matrix (CR) can be defined as describing the pairwise individual comparisons of the fractional transfer water magnitude considering both direct and indirect effects, which can be calculated as follows (Cao et al., 2021):

$$CD = (cd_{ij}) = (n_{ij} - n_{ji}),\ i,\ j - 1,\ 2,\ \ldots n.\ 0 \le |cd_{ij}| < \infty \tag{16}$$

$$CR = (cr_{ij}) = \begin{cases} n_{ij} - n_{ji} > 0,\ cr_{ij} = \left[\dfrac{n_{ij} - n_{ji}}{max(n_{ij},\ n_{ji})}\right] \\ n_{ij} - n_{ji} \le 0,\ cr_{ij} = 0 \end{cases},\ i,\ j - 1,\ 2,\ \ldots n.\ 0 \le |cr_{ij}| \le 1 \tag{17}$$

where cd_{ij} and cr_{ij}(value between 0 and 1) indicate the control influence of component *j* on component *i* via integral system flows (Fang and Chen, 2015). If the value of cd_{ij} is positive, it represents the control intensity; otherwise, it represents the dependence intensity. If cr_{ij} is closer to 1, this pairwise relationship has a definite direction; otherwise, the control pairwise relationship is weaker. Specifically, if cr_{ij} is closer to 1, then the pairwise pathway can be defined as a stronger pathway with a definite direction, which means that component *j* strongly controls *i* with a magnitude of value cr_{ij}. In contrast, if cr_{ij} is closer to 0, then the pairwise pathway can be described as a weaker pathway with uncertain directions, as two directions have relatively equal strength. Moreover, the mean positive value of cr_{ij} can be adopted to identify the control power condition of a system under consideration:

$$CR_{mean} = \text{mean}(cr_{ij}),\ cr_{ij} > 0 \tag{18}$$

The system control vector (SC) represents the control difference relationship between a single component and the remaining components of an n-component system, which helps identify the dominant sectors and strong linkages as well as the dependent sectors and weaker linkages:

$$SC = (sc_j) = \sum_{k=1}^{n} cd_{kj},\ j = 1,\ 2,\ \ldots,\ n.\ 0 \le |sc_j| < \infty \tag{19}$$

where the subscript *j* represents the specific donor component, and the sum of all sc_j equals zero for total system balance. For $sc_j > 0$, focal sector *j* controls the remaining system with an integrated control intensity; otherwise, it is controlled by the remaining system, which means that the component is dependent on the system with an integrated dependence intensity.

2.7. Network utility analysis

Network utility analysis (NUA) is used to evaluate the mutual relationships (i.e., mutualistic or antagonistic relationship) between different sectors in a PVWC. The mutual benefit between components is evaluated via a mutualism matrix. A direct utility matrix D shows the relative strength of direct bottom-up and top-down control in the network, which is used to evaluate the direct relationship between components (Fath and Patten, 1998):

$$D = (d_{ij}) = \frac{f_{ij} - f_{ji}}{T_i} \tag{20}$$

where d_{ij} is the intercompartmental flow utility, and T_i is the sum of flows in or out of sector i when the system is at a steady state. Integral mutualism considers both the direct and indirect effects that encompass the integral effects hidden in the system, interpreted via the integral utility matrix U, which is used to show the strength of the bottom-up and top-down control of the entire network organization (Fath and Patten, 1998):

$$U = I + D^1 + D^2 + D^3 + D^4 + \ldots \tag{21}$$

where I stands for the initial flows, D^1 stands for the direct utility relation, and D^n stands for the direct utility relationships realized by the extended flow pathways. This infinite power series can be rewritten as:

$$U = (I - D)^{-1} \tag{22}$$

$$U = (u_{ij}) \tag{23}$$

where the U matrix is chosen to exhibit the system's mutual utility relationship. The signs of the elements of U are used to determine the qualitative integral relations in the system. The diagonal elements of U are all positive, indicating that each component is self-mutualistic. There are four types of possible utility relationships among the components of a PVWC. (+, +) indicates a mutualistic relationship, (+, -) indicates an exploitative relationship, (-, +) indicates an exploited relationship and (-, -) indicates a competitive relationship (Zhang et al., 2012).

From a systematic perspective, the network mutualism index (*NMI*) and network synergism index (*NSI*) can be used to determine the fitness of the current PVWC, which helps to reveal the over mutual condition of the entire water cycle system (Xu et al., 2021). *NMI* represents the ratio of the number of positive signs over the number of negative signs in *U*. *NSI* represents the summation of all elements of *U* used to assess the magnitude of the positive and negative relationships of a system. *NMI* and *NSI* are calculated as follows (Chen and Chen, 2012; Fath, 2007):

$$NMI = SignU(+)/SignU(-) \tag{24}$$

$$NSI = \sum_{i=1}^{n} \sum_{j=1}^{n} u_{ij} \tag{25}$$

where $SignU(+)$ and $SignU(-)$ indicate the number of positive and negative signs in *U*. *NMI* and *NSI* can be combined to determine the systematic relationship. In the direct utility matrix, the sum of all elements equals zero because the matrix is skew-symmetric. Therefore, if positive signs are in the dominant position, e.g., $NMI>1$ and $NSI>0$, the system is mutualistic; if not ($NMI<1$ or $NSI<0$), some negative or problematic pathways need to be modified or mitigated, which means that the system is antagonistic (Cao et al., 2021).

In general, this study mainly utilized Matlab software for the technical implementation, employing PVWC model and applying ENA method. Matlab was chosen due to its robust computational capabilities, allowing for precise analysis of interactions within the ecological network.

3. Results

3.1. Information-based network analysis for the PVWC

This study found that the value of *AMI* (0.797) is lower than *Hc* (1.776), meaning the less organization of water flow structure of PVWC. The relationship between α and R can be described by an inverted U-shaped curve showed in Fig. 3. The PVWC demonstrates a balance between efficiency and redundancy if the dot is close to the peak value. The result showed that the degree of order (α) and system robustness (R) of PVWC in Beijing were 0.310 and 0.363, respectively. The *R* dot scattered nearly close to the peak value on the left side of robustness curve, suggesting that the PVWC is generally maintaining balance between efficiency and redundancy. In comparison, previous research on the water metabolism network (WMN) of Pearl River Delta (PRD) found a slightly lower mean degree of order (0.293) and system robustness (0.349) in 2015 (Cao et al., 2021), with cities such as Shenzhen, Zhuhai, and Dongguan exhibiting a balance between efficiency and redundancy, while others, like Jiangmen and Guangzhou, were also marked by high redundancy but lacked efficiency. This contrast highlights that while the overall robustness of PVWC in Beijing is comparable to that of the WMN in PRD, its efficiency is still lagging behind, similar to Jiangmen and Guangzhou of the PRD.

3.2. NSA for the PVWC

For the driving force (Table S3), the water suppliers contributed the most to the integrated water cycle process, with *Wj* of 48.12 %. The water users contributed slightly less than the suppliers with *Wj* of 41.50 %. The wastewater treatment (Was) contributed with *Wj* of 9.82 %. The water leakage contributed the least, with *Wj* of 0.56 %. For pulling force (Table S3), the water users received the most from the integrated water cycle process with *Wi* of 42.00 %. The water suppliers received slightly less than users with *Wi* of 40.18 %. The wastewater treatment received with an average *Wi* of 15.40 %. The water leakage received the least with an average *Wi* of 2.42 %.

As Fig. 4 shown, the water transfer subsystem had both a weak driving force and pulling force, indicating that it does not actually play an important role in the whole system. The recycled water subsystem had a strong pulling force, which means treated wastewater is used intensively. Most water users had weak pulling and driving force except the ecological environment with high pulling force and primary industrial sector with high driving force. Although the *Wj* value of wastewater treatment (Was) was lower than 10 %, it had a strong pulling force because of a high sewage treatment capacity in Beijing.

3.3. NCA for the PVWC

The system control or dependence intensity of each component is shown in Table 2 based on the results of *SC* vector. For water suppliers, the *SC* values of the natural environment subsystem and recycled water

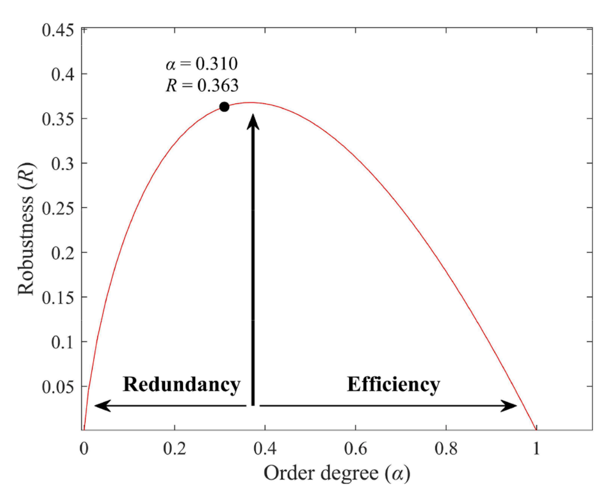

Fig. 3. Information-based network analysis of the PVWC.

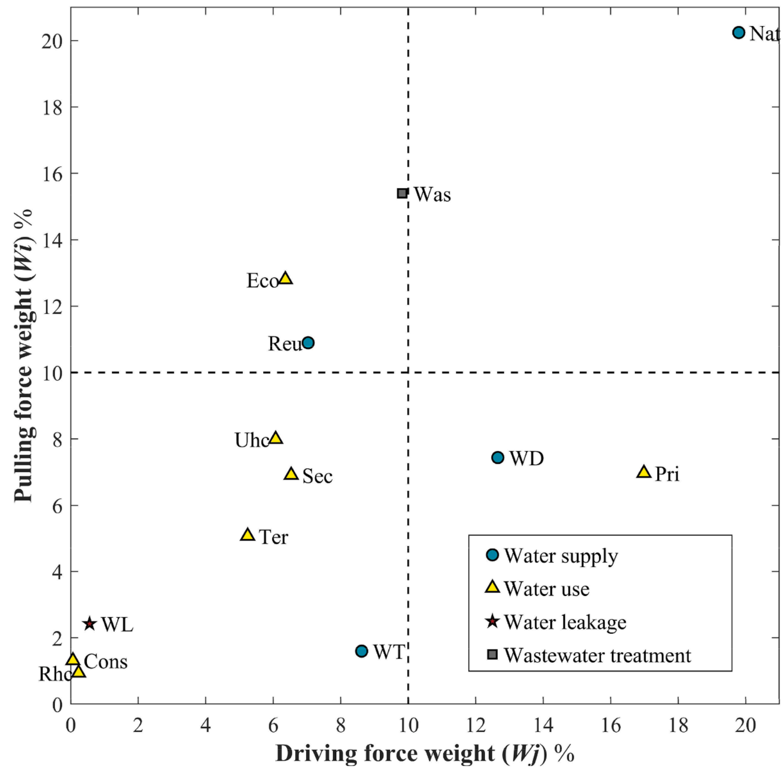

Fig. 4. Driving force and pulling force of components in the PVWC.

subsystem were lower than 0, showing that these components were dominated by the whole system. The water transfer subsystem and water distribution subsystem were the controllers of the entire system with the *SC* values higher than 0. For water users, the *SC* values of the secondary industrial sector and ecological environment were lower than 0, while those of other sectors were higher than 0. Meanwhile, the wastewater treatment subsystem and water leakage were dominated by the whole system. Specifically, the pairwise control relationships (Table S4) based on the *CR* matrix shown that the control of water transfer subsystem over other components was 100 %, while the natural environment subsystem and water leakage manifested a complete dependence of other components.

3.4. NUA for the PVWC

There were 13 sectors and 78 pairwise utility relationships in PVWC (Fig. 5). Exploitation and exploited relationships accounted for the largest proportion of the total, followed by competitive relationships and symbiotic relationships (Figure S1). However, the values of NMI and NSI were higher than 1 and 0, respectively, meaning the positive relationships are dominant and the system is mutualistic.

For water suppliers, the relationship between water transfer subsystem and natural environment subsystem showed competitive, while that between water transfer subsystem and water distribution subsystem showed exploitation, illustrating most water supply from water transfer subsystem and natural environment subsystem was concentrated in water distribution subsystem and then distributed to water users. For water users, the relationships between the primary industrial sector and other water users (Sec, Cons, Uhc, and Rhc) were exploitation relationships, while relationship between the primary industrial sector and the tertiary industrial sector was exploited relationship. Specifically, the primary industrial sector exploits embodied water from the tertiary industrial sector but always is exploited by other water use sectors. Additionally, the competitive relationships mainly occurred between the production water users (the primary industrial, secondary industrial, tertiary industrial and construction sectors) and household water users (urban and rural household consumption sectors).

The relationships between water users and suppliers are complicated. The primary industrial sector and the recycled water subsystem revealed an exploited relationship, where water-using components can serve both as consumers and as sources of reclaimed water. Meanwhile, ecological environment and recycled water subsystem showed exploitation relationship due to most of reclaimed water used for ecological environment. On the contrary, the relationship between ecological environment and natural environment showed exploited relationship indicating water used for ecological environment feeds back into local natural environment. For relationships between different water users, the construction sector and primary industrial sector, the tertiary industrial sector and secondary industrial sector showed exploitation relationships, which indicates complex virtual water flows embedded in products or services transferred between different production sectors and consumption sectors via the path of trade. In addition, the relationships between ecological environment and construction sector or primary industrial sector showed mutualistic, which means ecological environment played an important role in the entire system that promoted more symbiotic relationships.

4. Discussion

This study proposed a methodological framework that assess urban water cycle resilience by developing the PVWC network model. This model accounts for multi-source water supply (surface water, groundwater, transferred water, and reclaimed water), multiple water use (production water use, domestic water use, and ecological water use), water leakage, and wastewater treatment, as well as direct and indirect links among these nodes. Utilizing ENA, we presented a modified assessment framework from structure-function dimension to investigate the PVWC performance in Beijing 2017.

As a steady-state system, PVWC contains two aspects of input-output flows, physical water and virtual water, in which total water flow inputs

Table 2
System control or dependence intensity of each component.

Abbreviation	Value
Rhc	4.79
WT	4.39
Ter	2.81
WD	2.14
Uhc	2.00
Pri	1.89
Cons	0.55
Sec	-0.58
WL	-0.95
Reu	-2.26
Eco	-4.22
Was	-4.26
Nat	-6.29

> 0 / < 0

Water supply; Water use; Water leakage; Wastewater treatment

Notes: *SC* values lower than 0 indicate the components are the controller of the system; otherwise, the components are dominated by the system.

equal the outputs. From the structural dimension, we found that the PVWC is generally robust despite a slight lack of structural cohesion. Specifically, the system's organization is somewhat fragmented, as the physical and virtual water flows are distributed across various pathways rather than being concentrated. This scattering of flows may hinder the system's ability to adapt efficiently. The *R* dot value lies on the left side of the ideal robustness curve reflecting this structural fragmentation. Compared to the other cities in previous research such as Shenzhen (Cao et al., 2021), the efficiency of PVWC in Beijing is still lagging behind that there is still room for improvement in terms of streamlining water flows

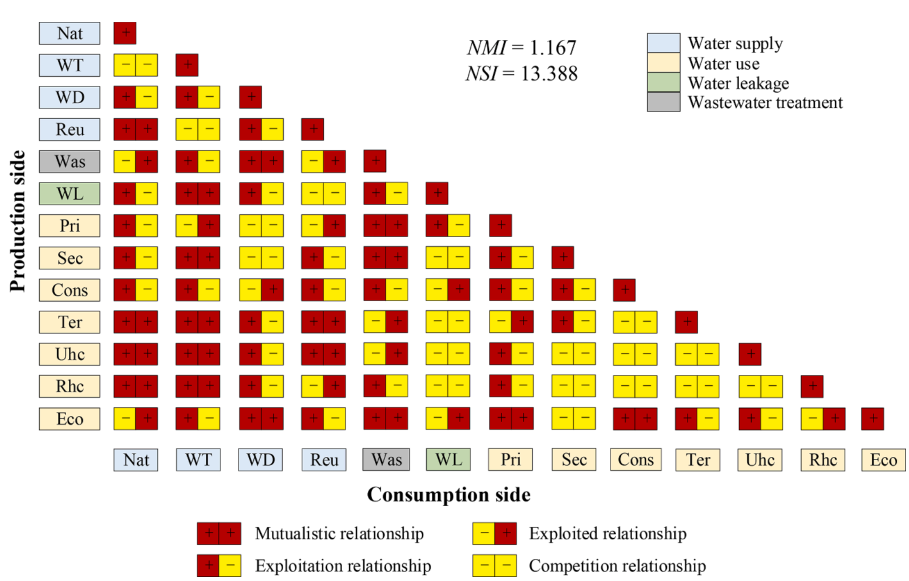

Fig. 5. Integral mutual relationships in the PVWC (in the integral utility sign matrix, *SignU*) between pairwise components.
Notes: The integral utility relationships among components are presented from the production side (matrix column) to the consumption side (matrix row).

to enhance system coherence and adaptability. However, Beijing's water supply and demand are generally balanced, as indicated by the higher *Wj* values for water users compared to suppliers, suggesting that users have access to sufficient water resources to meet their needs.

From functional dimension, the water transfer subsystem and most water use sectors function as key controllers within the entire system. Moreover, the positive relationships within the system are dominant, as indicated by NMI and NSI values that were higher than 1 and 0 respectively, signifying that the system is generally mutualistic. However, the presence of mutualistic relationships does not fully eliminate the antagonistic or exploitative interactions within the system. For example, the competitive relationships mainly occurred between the production water users (the primary industrial, secondary industrial, tertiary industrial and construction sectors) and household water users (urban and rural household consumption sectors). Additionally, the water transfer and natural environment subsystems exhibit competitive relationships, while the water transfer subsystem exploits the water distribution subsystem, which then distributes the water to various users. These exploitative interactions can resemble parasitic relationships, potentially leading to long-term sustainability challenges, particularly as resources become concentrated in dominant sectors, creating dependencies that strain weaker sectors. This dynamic is further complicated by the competitive relationships between production water users (e.g., primary, secondary, and tertiary industries) and household water users, as well as the complex virtual water flows embedded in products and services transferred between sectors. Such parasitic or competitive dynamics have been observed in other resource networks, where they contribute to resource imbalances and undermine system resilience by fostering unsustainable consumption patterns.

For water supply, natural environment subsystem is the main water supplier due to its strong driving force, while water transfer subsystem contributes less in water supply. However, water transfer subsystem was the second largest controller of PVWC and showed a more positive effect on the whole system than natural environment subsystem because of a larger number of mutualistic relationships between it and water users. Therefore, water transfer subsystem plays a positive role in the PVWC that not only alleviates local water stress but also contributes to a more resilient water cycle system. For water use, the primary industrial sector has a high ability to drive other components through supply linkages across the entire system, while other users have a weak driving force, making little contribution to PVWC from the water flow perspective. The construction sector, tertiary industrial sector, and household consumption sectors were the controllers of system, while secondary industrial sector and ecological environment were the dependency of system. Furthermore, the wastewater treatment subsystem showed a high dependency on the system and had a high value of pulling force. In addition, the active economic trade between economic sectors facilitates the transfer of virtual water, resulting in some exploitative relationships among water users (e.g., Cons-Pri, Ter-Sec). The ecological environment promotes mutualistic relationships with production water use sectors (e.g., Cons, Pri) meaning it plays an important role in the whole system.

Results demonstrated that the PVWC is in a relatively resilient status with a stable network structure and function to support the system's normal operation. These findings have important implications for water management policy that should consider the interconnectedness of water supply and use sectors when designing regulations and interventions. Addressing the structural fragmentation identified in this study could enhance system resilience, promoting policies that encourage collaboration among sectors to optimize water flows. We recommend that the conflict between water supply and demand could be mitigated by raising the water supply proportion of transferred and reclaimed water as well as strengthening water demand management through water conservation. Additionally, enhancing direct physical water distribution from the water transfer subsystem to users, and promoting intersectoral virtual water interactions through commodity trade, could streamline water flows and reduce pathway dispersion, thereby increasing network efficiency and strengthening symbiotic relationships across the system. It's critical to improve the system's internal capacity by advancing technical capabilities, which would effectively alleviate water scarcity. Significantly increasing the sewage treatment rate and recycling rates could also contribute to maintaining a sustainable system. Finally, expanding the use of transferred water for ecological replenishment will promote ecosystem stability, supporting a more resilient urban water cycle system in the long term. As for sustainability practitioners, recognizing the significance of resilience and synergistic systems is crucial to advocate integrated approaches for addressing competitive dynamics with water use sectors and fostering cooperative interactions, which support a sustainable and resilience system.

5. Conclusions

This study focused on multiple water suppliers and users, with particular consideration of ecological water use and water leakage, and anatomized the network structure and complicated relationships among different components in the PVWC to assess its resilience. A case study of Beijing provides empirical insights, offering scientific guidance for urban water management in this city. In addition, the network model proposed in this study is instructive and could be applied to other cities to improve local water management strategies in the future.

However, there are certain limitations to the findings of this study. Firstly, due to statistical restrictions such as the complex nonlinear relations inherent not accounted for in this model, the findings may not fully capture the intricate dynamics of the urban water cycle system resilience. Secondly, the limited availability of long-term, multiyear data restricts us to accurately identify the evolution of the PVWC network characteristics over time. This limitation hinders our understanding of how the system adapts and transforms under varying conditions. Thirdly, the model's ability to reflect real-world water management scenarios is constrained by the current data, which lacks sufficient detail to simulate the full range of socio-economic interactions and environmental factors that influence water flows and resilience.

Looking forward, further optimization of the ecological network model is necessary to provide more precise simulations and to better reveal the long-term evolution trends of urban water cycle systems. Incorporating multiyear water resource data and socio-economic data will enhance the accuracy of these simulations. Additionally, multi-scenario simulation studies based on the PVWC model would allow for deeper exploration of how different water flow patterns and policy interventions might impact the resilience of integrated water cycle systems.

Supplementary material

The supplementary material contains further details regarding the data sources for ecological network model of the PVWC, and the network structure, control, utility analysis results of the PVWC in Beijing.

CRediT authorship contribution statement

Qingnan Cai: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Delin Fang:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Bin Chen:** Project administration.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2024.110972.

Data availability

Data will be made available on request.

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