Cheng *et al. Heritage Science* (2024) 12:298
https://doi.org/10.1186/s40494-024-01412-0

Heritage Science

RESEARCH **Open Access**

Spatial distribution characteristics of relationship network of Beijing-Hangzhou Grand Canal water engineering facilities based on Gephi

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Abstract

The Beijing-Hangzhou Grand Canal, China's oldest and most crucial water transportation project, ensures smooth operation and efficient water transportation through interconnected water engineering facilities. Studying the connections among the water engineering facilities of the Beijing-Hangzhou Grand Canal is theoretically and practically significant for preserving and innovating canal heritage. Therefore, this study utilizes social network analysis to comprehensively examine the spatial connections and network status of water engineering facilities along the Beijing-Hangzhou Grand Canal across different channel structure. Gephi 0.10.1 was utilized in this study to construct a relational network of water engineering facilities along the Beijing-Hangzhou Grand Canal, with each facility considered as a network node. By applying network analysis indices such as degree, closeness centrality, and betweenness centrality, the correlation between water engineering facilities was thoroughly investigated. The study's findings reveal that: (1) the Beijing-Hangzhou Grand Canal possesses numerous overall network nodes with extensive coverage; however, its overall network density is relatively low, and the inter-node connection is weak. (2) Across the entire network, the spatial distribution of degree and betweenness centrality exhibits a clustered pattern. Their distribution patterns are centered on the Lake region section where Hongze Lake is located and the segment from Liucheng to Zhenjiang in the Lake region, the River transport confluence section, and the Nature river section, respectively. The spatial distribution characteristics of closeness centrality show a dispersed shape, with stronger areas mainly concentrated in the canal's tributaries, especially the Nature river section, which shows more prominence. (3) Analyzed from a channel structure perspective, water engineering facilities in different sections assume distinct linking roles within the network. Facilities in the Lake region section play the strongest overall linkage role, partly due to its highest node proportion. Conversely, in the Nature river section, facilities primarily serve transshipment and direct connection functions, whereas in the River transport confluence section, they act mainly as intermediaries or "bridges". Notably, water control facilities in the Nature river section and river engineering facilities in the River transport confluence section play pivotal driving roles in their respective sections, warranting special attention and protection as critical canal nodes.

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Keywords The Beijing-Hangzhou Grand Canal, Channel structure, Water engineering facilities, Relational network, Connecting features, Gephi

Introduction

The Beijing-Hangzhou Grand Canal, currently the world's longest man-made canal, traverses the eastern plains of China, stretching from Beijing in the north to Hangzhou in the south, covering a total distance of 1794 km and passing through eight provinces and centrally-administered municipalities. This invaluable linear cultural heritage and vital water transportation route, characterized by its rich historical and cultural significance and essential role in water transportation, stands as a remarkable testament to Chinese hydraulic engineering [1]. In 2014, during the 38th session of the World Heritage Committee, the Beijing-Hangzhou Grand Canal, a principal segment of the Grand Canal of China, was successfully inscribed on the World Heritage List. In 2022, after a century, the Beijing-Hangzhou Grand Canal achieved full water flow, leveraging the extensive advantages of the South-to-North Water Diversion Project, thus garnering increased attention from various sectors. In 2023, the Chinese government issued *the Outline of the National Water Network Construction Plan*, underscoring the urgency of expediting the construction of the national water network and enhancing water resource allocation. As an integral part of the national water transportation network, the water engineering facilities of the Beijing-Hangzhou Grand Canal bear significant responsibilities in water flow management within the network. Therefore, conducting a comprehensive and thorough investigation into the interconnections among the water engineering facilities of the Beijing-Hangzhou Grand Canal, identifying and prioritizing key links, lays the groundwork for future enhancements and restoration efforts, thus facilitating the canal system's scientific management.

Canal heritage stands as a crucial domain capturing the attention of international scholars. Its focal points revolve around the technical innovations and engineering feats of these waterways, underscoring their significance as water engineering facilities. Moreover, it delves into their contemporary roles in tourism, economy, and culture [2–4]. The scope of canal heritage research is broad, encompassing structures such as the Pontcysyllte Aqueduct in Wales, the Midi Canal in France, the Castilla Canal in Spain, and the Erie Canal in the United States [5–7]. These studies not only analyze the impact of canals on local societies and economies but also emphasize their potential as tourist attractions. They offer strategies and recommendations for preserving and passing down canal heritage [8, 9]. Additionally, Chinese scholars primarily focus on the classification, historical evolution, and study of both material and intangible cultural heritage along the Beijing-Hangzhou Grand Canal [10–13]. In recent years, scholars have turned their attention to researching the spatial distribution of urban settlements along canal routes, ecological environments, and the tourism value, thereby providing new perspectives and research directions for a comprehensive understanding of canal heritage [14–19].

The water engineering facilities of the Beijing-Hangzhou Grand Canal, as a significant component of canal heritage, have increasingly garnered attention in academic circles. While some monographs have delineated the development and evolution of canal water engineering facilities [20, 21], there remains a relative scarcity of specialized and systematic research on this topic. In recent years, some scholars have approached the study of water engineering facilities from the perspective of hydraulic engineering, delving into issues such as management systems and the natural and cultural landscapes [22, 23]. However, these studies predominantly focus on individual water engineering facilities or specific regions, without yet forming a widespread trend of comprehensive research on the entire water engineering system along the Beijing-Hangzhou Grand Canal.

Considering the research needs in the academic domain and the findings of previous scholars, our research team extensively explored the impact of natural and social factors on the spatial distribution of water engineering facilities. Regarding natural factors, we reconstructed the canal network distribution map during the Ming and Qing Dynasties, and assessed the influence of various natural factors on hydraulic facility placement using Amos26.0 software [24], introducing a novel research approach for studying world heritage canals. For social factors, the team analyzed the social driving forces behind the spatial distribution of Water engineering facilities during the Ming and Qing Dynasties. Additionally, we investigated the interplay between natural factors and water facility distribution. Some scholars advocate for a systematic approach to canal heritage, emphasizing functional, historical, and spatial connections [25]. Thus, adopting a relational network perspective, this paper thoroughly examines the interconnections among the water engineering facilities of the Beijing-Hangzhou Grand Canal, using channel structure as the fundamental unit.

Research aim

The study's focus is on water engineering facilities constructed along the entire route of the Beijing-Hangzhou Grand Canal during the Ming and Qing dynasties (1368–1912). Various water engineering facilities along different sections of the Beijing-Hangzhou Grand Canal exhibit unique engineering forms, spatial distributions, and functional roles, influenced by hydrological variations, water resource conditions, and system characteristics. Comprehending the connections among these facilities is vital for efficient water resource management and utilization. A thorough examination of these connections aids research organizations in grasping how water engineering facilities interact across various sections, facilitating improved maintenance, sustainable development, and efficient operation of the canal system. Thus, this study focuses on the channel structure and offers a comprehensive characterization of the connections among water engineering facilities.

Gephi 0.10.1 software is employed in this study to compute indicators reflecting the connectivity of water engineering facilities in the Beijing-Hangzhou Grand Canal. These data comprehensively illustrate the network architecture characteristics of the relationship network among water engineering facilities in the Beijing-Hangzhou Grand Canal. To enhance understanding of this data, the research team utilized a multi-step analysis method (Fig. 1). Initially, the calculation results were classified and filtered according to the channel structure to elucidate the dominant role of each channel structure in the overall network. Subsequently, the status of each indicator was represented through spatial distribution by overlaying the latitude and longitude of each water engineering facility, highlighting significant areas where nodes clustered under different metrics throughout the network. Ultimately, integrated analysis facilitated a comprehensive understanding of the structural features of the entire network, encompassing key nodes, high-value areas for each indicator, and the predominant impact of each channel structure. This research methodology furnishes a comprehensive and detailed data foundation for thoroughly analyzing and comprehending the relationship network of water engineering facilities in the Beijing-Hangzhou Grand Canal.

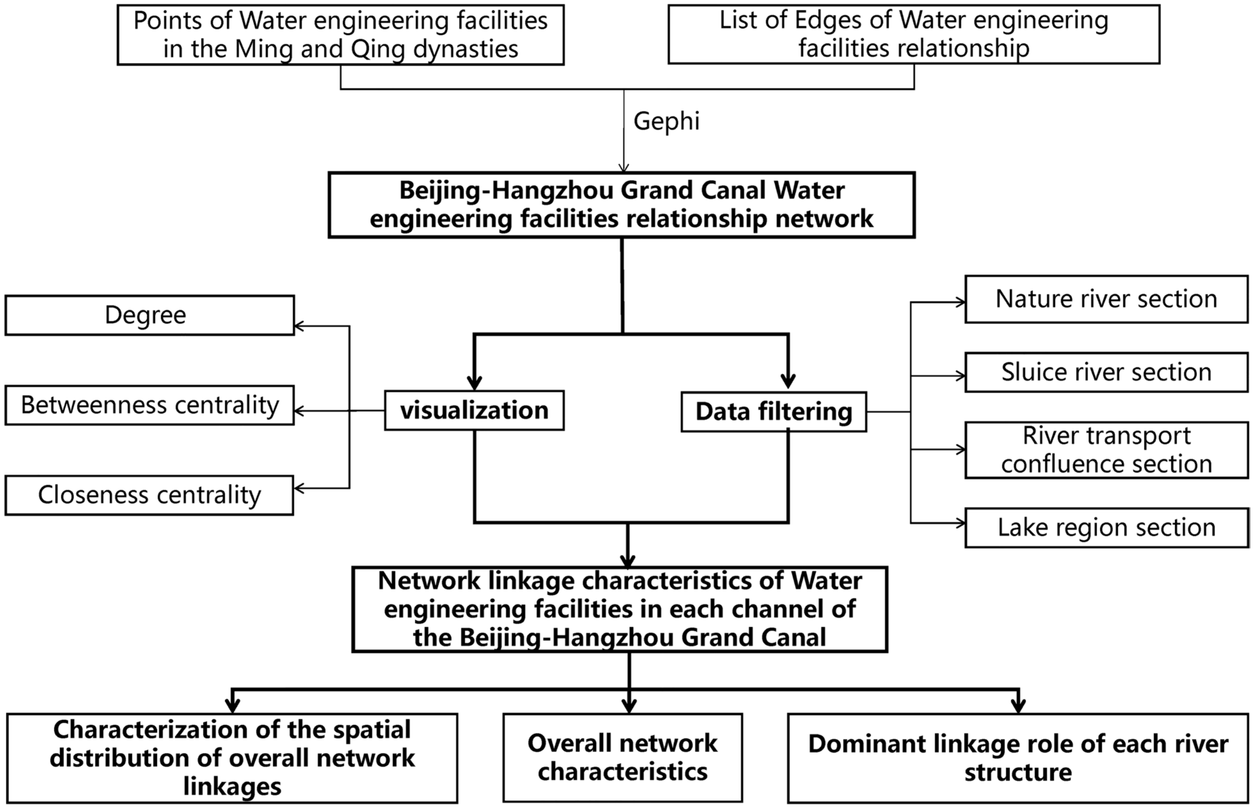

Fig. 1 Technical routes

Materials and methods

Research area

The Beijing-Hangzhou Grand Canal spans five major river systems, with varying terrain and significant differences in the hydrological and topographical conditions of each canal section. To address issues such as steep channel slopes and flood discharge, water engineering experts throughout history have designed various types of water engineering facilities. Consequently, researchers over the ages have classified the Beijing-Hangzhou Grand Canal into four types of channel structures based on geographical conditions: sluice river sections, lake region sections, nature river sections, and river transport confluence sections (Fig. 2, Table 1). This classification helps researchers develop specific water management and maintenance strategies tailored to the distinct geographical conditions of each section.

The various water engineering facilities constructed along the Beijing-Hangzhou Grand Canal can be categorized into seven main types based on their functions: water retention facilities (for preventing river floods), overflow facilities (for controlling peak flows and protecting downstream areas), water conveyance facilities (for diverting water to required areas), water storage facilities (for storing rainwater or importing external water sources), water control facilities (for regulating river water levels and flows), river engineering facilities (for protecting river channels, flood control, and dredging), and ancillary facilities (for providing spaces for cargo loading/unloading and passenger movement). Due to the varying geographical locations and water resource distributions of the four channel structures, the types and quantities of required water engineering facilities differ. Among these, the lake region sections contain the most water engineering facilities, accounting for 56% of the total along the entire Beijing-Hangzhou Grand Canal. The remaining sections are ranked by the number of facilities as follows: sluice river section (20%), nature river section (19%), and river transport confluence section (5%).

The Nature river section comprises naturally formed river channels within the Beijing-Hangzhou Grand Canal, encompassing the North Canal, the South Canal, and the Sishui River (which served as a vital waterway for 400 years during the Yuan, Ming, and early Qing dynasties) from Xuzhou to Huaiyin. These sections exhibit turbulent currents, necessitating the construction of numerous water retention facilities to strengthen and refurbish the river channels, ensuring safe navigation along the Beijing-Hangzhou Grand Canal [26].

The River transport confluence section denotes the locations where the Beijing-Hangzhou Grand Canal intersects with other watercourses, such as the Hai River, the Yellow River, the Huai River, and the Yangtze River. Infrastructure such as harbors and wharves is essential at these points to facilitate loading, unloading, and transshipment activities. Additionally, the construction and upkeep of water conservancy projects are necessary to maintain seamless navigation between the canal and other waterways.

The Sluice river section comprises the Tonghui River and Huitong River segments of the Beijing-Hangzhou Grand Canal, characterized by challenging engineering projects and water scarcity. This section derives its name from the abundance of locks present. The Tonghui River section features locks and dams, with seven sets located at intervals of approximately one mile, spanning from jWenmingmen to Tongzhou Gaoli Zhuang (Baihekou), including three additional sets above Wenmingmen, totaling 20 locks [27]. The Huitong River section spans approximately 200 km and includes 16 locks and around 100 km of embankments. With its gentle, slow-flowing currents, this section has a history of siltation and flooding issues [28].

The Lake region section encompasses the Huaiyang Canal segment of the Beijing-Hangzhou Grand Canal between Huai’an and Yangzhou, inclusive of Anshan Lake, Nanwang Lake, Zhaoyang Lake, and Luoma Lake. Wind and wave effects in the lake area have prompted the gradual construction of Embankments to mitigate their impact, with most Embankments and dams situated in the water, a characteristic and challenging endeavor. Moreover, aside from the lakes in the Nanwang area serving as reservoirs for the canal, no other water source projects exist. Flood discharge is the primary issue addressed by this section of the canal, resulting in a relatively high concentration of water retention and control facilities in the Lake region section.

Data sources

To gain a more comprehensive and detailed understanding of the distribution of water engineering facilities along the Beijing-Hangzhou Grand Canal, the research team extensively collected ancient documents, including over 500 historical texts such as official histories, local chronicles, and ancient maps. Major works include “Illustrated Treatise on the Transport River” and “Overview of River Defense”. From these ancient texts, the team extracted detailed information on 1,168 water engineering facilities along the Beijing-Hangzhou Grand Canal. The records included names, primary functions, associated river sections, channel structures, and geographic locations. After comparing multiple sources, 1146 valid points were selected to establish a preliminary basic information database for the water engineering facilities of the Beijing-Hangzhou Grand Canal.

Fig. 2 Distribution of the channel structure of the Beijing-Hangzhou Grand Canal

Table 1 Basic information on the four major channel structures of the grand canal (Table created by the research team)

Channel structure	Length	Terrain features	Hydrology	Cities	Historical significance
Sluice river section	Approximately 280 km	The sluice river section is mainly located in the northern and central areas of the canal. The terrain is undulating, and the water flow is relatively turbulent. Multiple sluices are set up to regulate water levels and control flow	There are significant differences in water levels, and the sluice system is used to control water volume and ensure navigability	Beijing, Tongzhou, Liaocheng, Jining	By setting up multiple sluices, the sluice river section solves the problem of water level differences between different terrains, ensuring the navigability of the canal
Lake region section	Approximately 360 km	The lake region section is distributed in parts of Jiangsu and Zhejiang, crossing multiple lakes and lowlands. The water area is wide, and the terrain is relatively flat	With abundant water and stable flow, it is suitable for large vessels to pass, but flood control is needed during the flood season	Jining, Xuzhou, Huai'an, Yangzhou	The lake region section connects multiple lakes, achieving natural water regulation. It provides important support for agricultural irrigation, navigation, and urban water supply along the shore
River transport confluence section	Approximately 120 km	This section is where the canal intersects with other major rivers. The terrain is complex, making it a crucial hub for water and land transportation	The hydrological conditions of the river transport confluence section are highly uncertain due to the confluence of multiple rivers. Scientific regulation of water volume is required to ensure navigation and flood control	Liaocheng, Xuzhou, Suqian, Huai'an, Yangzhou, Zhenjiang	The river transport confluence section connects the canal with important rivers like the Yangtze and Qiantang, making it a vital corridor for north–south material exchange
Nature river section	Approximately 970 km	This section utilizes modified nature river channels, retaining natural bends and flow directions with diverse terrain	The nature river section has complex hydrological conditions with significant seasonal variations in water flow. During dry seasons, water levels may drop, affecting navigation. Flood control and drainage measures are required during the flood season	Tongzhou, Tianjin, Cangzhou, Dezhou, Linqing, Liaocheng, Xuzhou, Suqian, Huai'an, Zhenjiang, Changzhou, Wuxi, Suzhou, Jiaxing, Hangzhou	The nature river section utilizes the original nature river channels, reducing engineering difficulty and cost. It plays a significant role in regional economic and cultural exchanges

Based on the basic information database and the current status of the water engineering heritage, the research team used the coordinate picking function of Ovitalmap to successfully obtain the geographic coordinates of the water engineering facilities, categorizing them by function (Fig. 3). To ensure data accuracy, the research team conducted field visits along the entire Beijing-Hangzhou Grand Canal to verify the locations of some existing water engineering facilities and created corresponding 3D point cloud models. Some research results (Figs. 4, 5, 6, 7, 8, 9) are presented below, culminating in the establishment of a comprehensive and complete database of water engineering facilities along the Beijing-Hangzhou Grand Canal.

The river network data in the study were referenced from the "Historical Atlas of China". Since the river network system of the Beijing-Hangzhou Grand Canal during the Ming and Qing Dynasties has not changed significantly compared to the present day, this study used modern DEM data and the hydrological analysis tools in ArcGIS 10.8 to extract a hydrological map nearly identical to the historical river network. The base map used in the study is from the official map in ArcGIS 10.8 (http://goto.arcgisonline.com/maps/World_Terrain). The topographical map of the Beijing-Hangzhou Grand Canal referenced in the study was redrawn from Han Yuan Yao's "History of the Beijing-Hangzhou Canal". The edge list data for the relationships between water engineering facilities in Gephi were generated based on the geographic coordinates of the facilities, combined with the topography and river network system. Specific steps are detailed in the model construction section.

This study includes various water engineering facilities constructed during the Ming and Qing Dynasties along the Beijing-Hangzhou Grand Canal for purposes such as grain transport, irrigation, flood control, and water resource management. These facilities were uniformly treated as network nodes in the analysis.

Research methodology

The Analytic Network Process (ANP) is a multi-criteria decision-making method proposed by Professor T.L.Saaty of the University of Pittsburgh in the 1970s, which combines qualitative and quantitative aspects [29]. Social Network Analysis (SNA) is a subtype of network analysis methods primarily utilized for investigating dependency relationships among social entities. By simplifying complex systems, it aids in providing in-depth descriptions of how social entities influence the entire network [30]. This method comprehensively considers the complex interrelationships between factors and provides a more precise and comprehensive means of tradeoffs for decision-making. The method is currently used in the fields of social networks [31, 32], ecological networks [33–35], information dissemination [36–38], urban planning and governance [39], and business studies [40, 41]. Given the successful application of social network analysis (SNA) in revealing relationships between social entities, this paper applies this method for the first time to study the relationships between historical heritage sites.

After comparing numerous network analysis tools, this paper chose Gephi for network analysis. Gephi is an open-source network analysis and visualization software that relies on Graph Theory and Social Network Analysis (SNA) methods. Graph Theory provides the mathematical foundation for studying the basic structure of nodes and edges in networks, while SNA uses quantitative analysis to visualize network characteristics and individual relationships within social structures. Compared to other network analysis tools, Gephi excels in the comprehensive visualization of centrality studies and has stronger data processing capabilities [42, 43]. Applying Gephi in this study can effectively reveal the status and contribution of each water engineering facility within the network. Therefore, this software is suitable for the visualization study of centrality in this paper. Although Gephi has performance issues when handling large-scale networks, its current features are sufficient to meet the research needs of this study.

The basis of SNA is the network graph, consisting of nodes and edges. In this paper, each water engineering facility in the Beijing-Hangzhou Grand Canal's water transport network is considered a node, and the water flow connections between facilities are regarded as edges. By constructing a relational network of water engineering facilities in the Beijing-Hangzhou Grand Canal and overlaying the latitude and longitude of each heritage site for visualization, the research team deeply explored the relationships between facilities and their impact on the overall network.

As research on complex networks continues to advance, many scholars use various characteristic parameters to represent the features of different complex networks. This paper, focusing on the functions of canal water engineering facilities within the network, extracts three related indicators for network analysis: degree, betweenness centrality, and closeness centrality. These indicators play a crucial role in revealing the connection network among water engineering facilities.

Degree

Degree refers to the number of edges directly connected to a node in a network[44]. A node that is directly connected to many other nodes has a high degree. High-degree nodes are typically influential in information dissemination and connection establishment. In directed

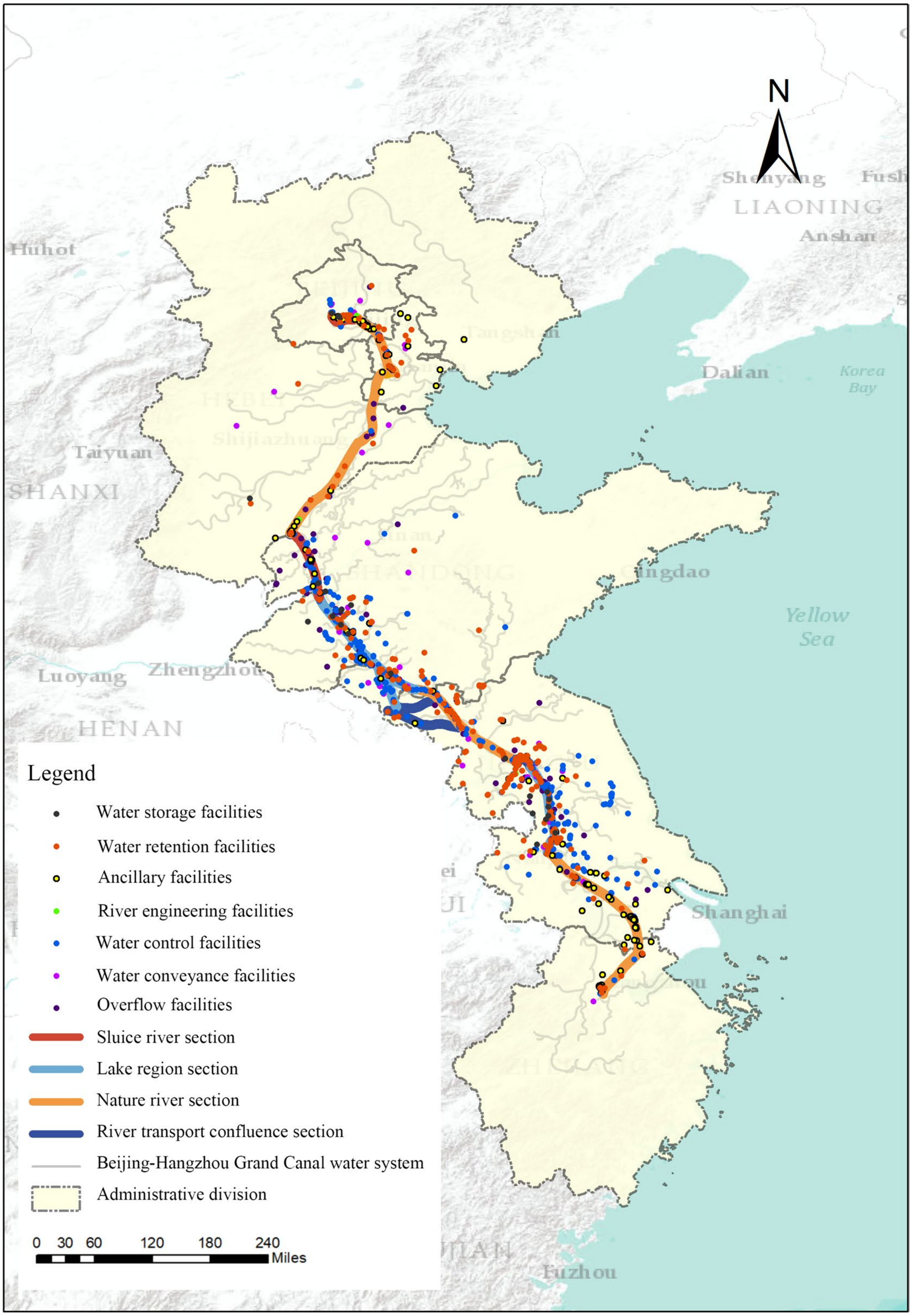

Fig. 3 Distribution of Water engineering facilities in the Beijing-Hangzhou Grand Canal (Figure created by the research team)

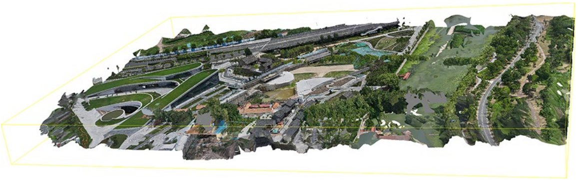

Fig. 4 3D point cloud model of plate lock (Figure created by the research team)

Fig. 5 3D point cloud model of Daiwan Lock (Figure created by the research team)

Fig. 6 3D point cloud model of Jingkou lock (Figure created by the research team)

Fig. 7 3D point cloud model of Linqing lock (Figure created by the research team)

graphs, degree is divided into out-degree and in-degree. Nodes with a high out-degree have a significant broadcasting effect, while those with a high in-degree have a strong aggregation effect [45].

In the network of water engineering facilities along the Beijing-Hangzhou Grand Canal, the degree of a facility is the number of other facilities it is directly connected to, indicating its range of direct connections. A higher degree means the facility has closer direct connections with other nodes in the network. The specific formula is as follows:

Fig. 8 3D point cloud model of Liulin lock (Figure created by the research team)

Fig. 9 3D point cloud model of Liangxiang Lock (Figure created by the research team)

$$C_D(i) = \sum_{j}^{N} X_{ij(i \neq j)} \tag{1}$$

where i is the focal node, j represents all other nodes, N is the total number of nodes, $C_D(i)$ is the degree of node i, which calculates the number of direct connections between node i and other nodes j ($i \neq j$, excluding self-links), and X is the edge list.

Betweenness centrality

Betweenness centrality measures how often a node lies on the shortest path between two other nodes in a network, indicating its capacity to influence connections indirectly [44]. High betweenness centrality suggests a node plays a crucial role in linking others within the network [46], acting as a pivotal intermediary for information dissemination, communication, or linkage.

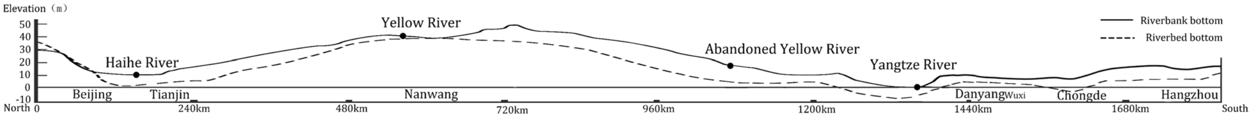

Fig. 10 Topographic profile of the entire length of the Beijing-Hangzhou Grand Canal (Figure created by the research team)

In the network of Beijing-Hangzhou Grand Canal Water engineering facilities, a higher betweenness centrality value for a facility implies better accessibility to other facilities, indicating a stronger transportation hub role. To facilitate a more accurate comparison of nodes across the entire network, the study normalizes the arithmetic results. The specific formula is as follows:

$$C_B(i) = \sum_{j<k} \frac{b_{jk}(i)}{b_{jk}} \tag{2}$$

In the formula, $C_B(i)$ represents the betweenness centrality of node i, b_{jk} represents the number of shortest paths from node j to node k. $b_{jk}(i)$ represents the number of shortest paths from node j to node k that pass through node i. j and k represent any two different nodes in the network, and $j \neq k \neq i$).

Closeness centrality

Closeness centrality is an indicator reflecting the proximity of a node to other nodes in a network. It is expressed as the inverse of the average shortest path distance from the node to all other nodes [44]. A higher value of closeness centrality indicates that the node has quicker and more direct access to other nodes in the network [47], implying higher centralization and information transfer capability.

In the relationship network of Water engineering facilities in the Beijing-Hangzhou Grand Canal, a higher closeness centrality value of a water engineering facility indicates that it has better accessibility to other Water engineering facilities, implying a stronger transshipment function. To facilitate a more accurate comparison of nodes across the entire network, the study normalizes the arithmetic results. The specific formula is as follows:

$$C_c(i) = \sum_{j}^{N} \frac{1}{d(i,j)} \tag{3}$$

In the formula, $C_C(i)$ represents the closeness centrality of node i. N is the total number of nodes in the graph. $d(i, j)$ denotes the shortest distance between node i and node j, where j represents any other node in the network and $(i \neq j)$.

Model construction

The research team compiled a database of Water engineering facilities along the Beijing-Hangzhou Grand Canal through extensive research of ancient literature and fieldwork. This database includes precise geographical coordinates, construction timelines, and other relevant information for each site. Based on the terrain of the Beijing-Hangzhou Grand Canal and the flow direction of water (Fig. 10), the study designates nodes where water exits as source nodes and nodes where water enters as target nodes. The List of Edges of Water engineering facilities is then populated according to the flow direction of water. Since degree, betweenness centrality, and closeness centrality in this study are all based on the number of node connections rather than edge weight, the weight of edges is uniformly set to 1. Importing the List of Edges of Water Engineering Facilities Relationships into Gephi software, the study establishes the Beijing-Hangzhou Grand Canal Water Engineering Facilities Relationships Network, consisting of 1146 nodes and 1196 edges. This indicates that

Fig. 11 Relationship network model of Water engineering facilities in Beijing-Hangzhou Grand Canal

there are 1196 connections among the 1146 Water engineering facilities (Fig. 11).

Building upon the aforementioned findings, the research team initially extracted points along with their respective latitude and longitude coordinates from the established database. These data were then overlaid onto the operational workspace. Subsequently, the Geo Layout layout algorithm was employed to enhance visualization and conduct a more thorough network analysis. Lastly, the network visualization underwent optimization through parameter adjustments within the preview interface, and the resulting visualization was overlaid onto the map to produce visual representations of the Beijing-Hangzhou Grand Canal, highlighting the presence of each Water engineering facility (Figs. 16, 17, 18).

Results and discussion

Overall network characteristics

The network of water engineering facilities in the Beijing-Hangzhou Grand Canal consists of 1146 nodes and 1196 edges, creating a complex network. Utilizing Gephi software for analysis, one can derive the diameter, average path length, degree, and other parameters of this network, with specific calculation results displayed in charts (Table 2, Figs. 12, 13, 14, 15).

Table 2 Overall network structure indicators (Table created by the research team)

Network indicator	Numerical value
Network density	0.001
Network diameter	143
Average path length	47.217
Betweenness centrality	0–0.0399

Concerning the overall network structure, the average path length of the Water engineering facilities relational network in the Beijing-Hangzhou Grand Canal is 47.217, with a network density of 0.001. These metrics suggest decentralized connections and slow information transfer. Additionally, the network diameter reaches 143, indicating the presence of distant nodes (Table 2).

Analysis of Fig. 12 reveals that the degree in the network spans from 1 to 9. Within this range, there are 43 nodes with a degree of 4 and above, comprising merely 3.7% of the total Water engineering facilities in the Grand Canal. This finding indicates that the majority of nodes in the network have weak connections to neighboring nodes, typically linking to only one to three nodes.

Illustrated in Figs. 13 and 14, the majority of in-degree and out-degree values for degree are 1, suggesting predominantly single-wire connections between Water engineering facilities. Upon closer examination of the out-degree values, we find that over 130 Water engineering facilities have an out-degree of 0, indicating that these nodes primarily serve as information receivers rather than active initiators, and do not proactively establish connections with other Water engineering facilities, thus acting as terminal nodes in the network.

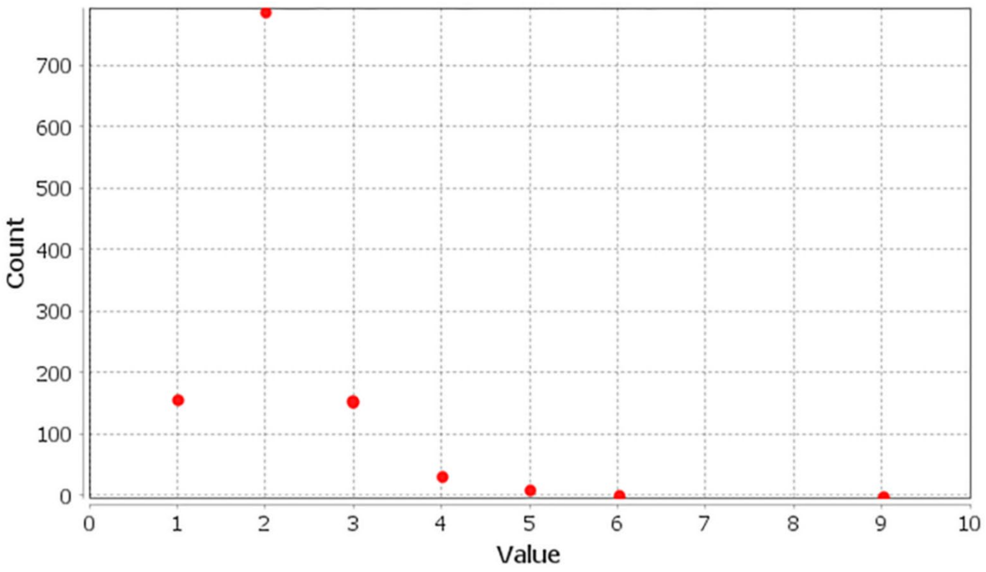

Fig. 12 Degree Distribution

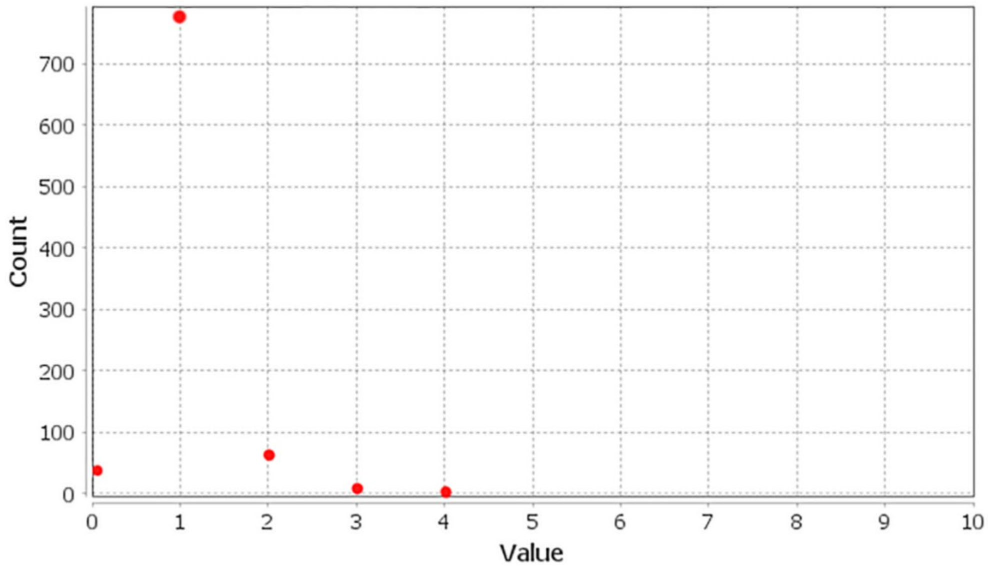

Fig. 13 In-Degree Distribution

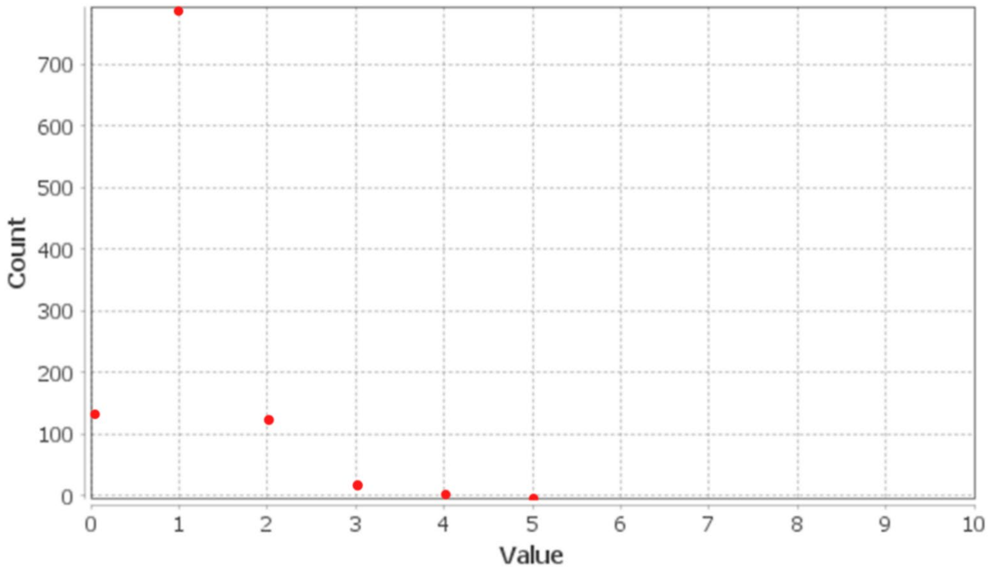

Fig. 14 Out-Degree Distribution

Within the network, the betweenness centrality of nodes ranges from 0 to 0.0399. Notably, 176 Water engineering facilities possess a betweenness centrality of 0, indicating their limited role as intermediaries within the entire network. Moreover, these facilities are situated in the network's peripheral regions and do not serve as intermediaries.

Most nodes in the network have closeness centrality values concentrated between 0 and 0.5, representing 81.2% of the total nodes. Additionally, 18.8% of nodes have closeness centrality values ranging from 0.5 to 1 (Fig. 15). Notably, 86 nodes have a closeness centrality value of 1, while 138 nodes have a closeness centrality value of 0. The study findings indicate that the overall network exhibits relatively weak connectivity, resulting in slow communication between nodes. Moreover, the central region of the network comprises a small number of nodes, implying a scarcity of agglomeration centers. Furthermore, some nodes are positioned at the network's edge, with minimal connections to other nodes.

In conclusion, the relationship network of Water engineering facilities in the Beijing-Hangzhou Grand Canal

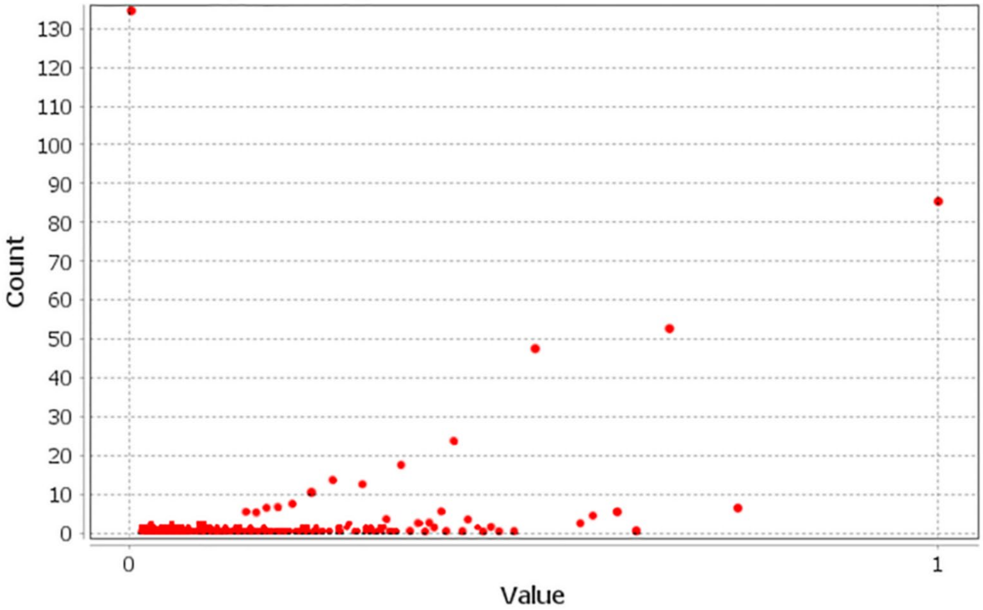

Fig. 15 Closeness Centrality Distribution

is extensive with numerous nodes, yet exhibits relatively low network density and weak inter-node connections. Additionally, the overall network's closeness centrality value is notably higher than its betweenness centrality value, suggesting that Water engineering facilities primarily serve as transshipment hubs in the water transportation network, essential for the efficient operation of canal transportation in the Grand Canal.

Characteristics of spatial distribution of overall network connections

Spatial distribution characteristics of degree

To depict the spatial distribution of degree results more intuitively, this study integrates the latitude and longitude data of each water engineering facility and visualizes them using graphical methods (Fig. 16).

Figure 16 analysis reveals that the variance in degree across the network is relatively minor, suggesting a balanced connection degree between each node and its neighbors. Nonetheless, the generally low value suggests limited node influence on the surrounding nodes, highlighting the insufficiency of water engineering facilities, resulting in a predominantly low cluster density along the Beijing-Hangzhou Grand Canal. It's notable that water engineering facilities with high degree predominantly cluster around Hongze Lake in the lake region, exhibiting a dense, cluster-like distribution.

Hongze Lake lies within the region densely populated with nodes exhibiting high degree values, positioned at a crucial juncture between the Huaihe River and the Beijing-Hangzhou Grand Canal. During the Ming and Qing dynasties (1368–1912), Yellow River backflow into the Huaihe River led to sediment accumulation at the bottom of Lake Hongze, gradually raising the lake bed and even causing north–south backflow in the Grand Canal. To ensure smooth transportation, the Ming and Qing governments constructed numerous interconnected water engineering facilities in the Hongze Lake area, such as Gaojiayan, Wujiadun, Gaoliangjian, and Zhoujiaqiao [48], which collectively played a pivotal role in water storage and transportation preservation.

Specifically, there are 43 nodes with a degree of 4 and above in the overall network, representing only 3.7% of the total number of water engineering facilities in the Beijing-Hangzhou Grand Canal (Fig. 16). Among these nodes, 21 are located in the lake region, 14 in nature river section, 14 in sluice river sections, and 1 in the river transport confluence section. Water engineering facilities with high degree include the Hongze Lake North Rolling Dam, Zhaijia Dam, Hulutou Water Reduction Dam, Nanyang Lock, and Zhaoyang Lake Lock. The degree ranking of water engineering facilities in the network is presented in Table 3. In the relationship network of the Beijing-Hangzhou Grand Canal, these water engineering facilities exhibit broader connections compared to others and serve as key connectors in the entire network.

Overall, the degree differences among nodes in the network are small, and the connections are balanced, indicating good connectivity. However, the influence of

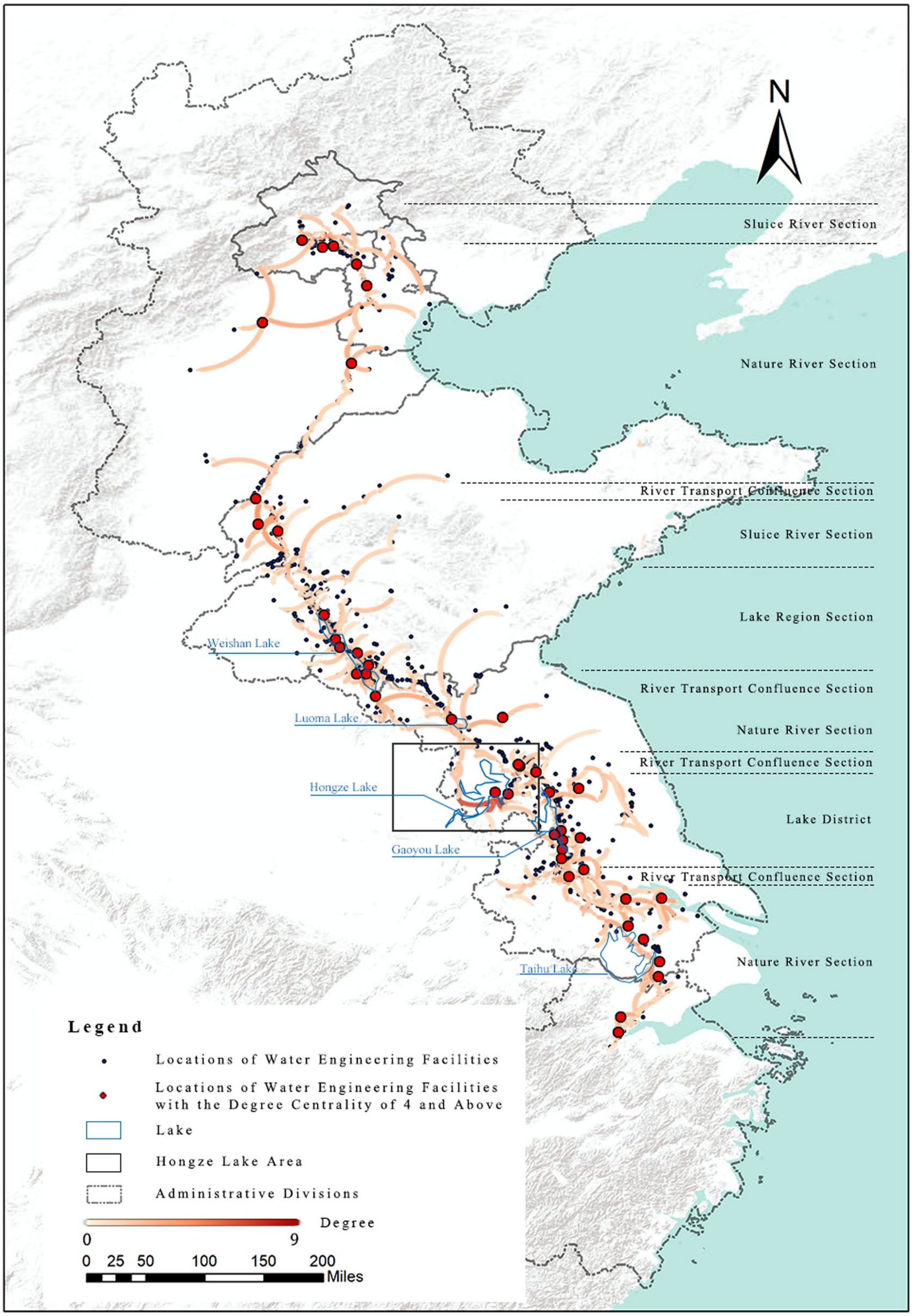

Fig. 16 Visualization plots of degree distributions

Table 3 Degree statistics for Water engineering facilities in the network (Table created by the research team)

Water engineering facilities	In-degree	Out-degree	Degree	Degree Ranking
Hongze Lake North Overflow Dam	4	5	9	1
Zhaijia Dam	1	5	6	2
Huangtiangang Lock	2	3	5	3
Yangjiamiao Drainage Stone Lock	2	3	5	3
Gutou South Lock	1	4	5	3
Zhaoyang Lake Lock	1	4	5	3
Nanyang lock	1	4	5	3
Zhongzhong lock	2	3	5	3
Xingji lock	2	3	5	3
Hulutou diversiondam	3	2	5	3
Xiuyi Bridge Stacked Beam Lock	3	2	5	3
Guangji Bridge	0	4	4	4
Desheng Dam	1	3	4	4
Wujiang Ander Bridge	3	1	4	4
Wujiang Canal Ancient Towpath	3	1	4	4
Yongli	1	3	4	4
Wuxi Wangting Weir	3	1	4	4
Wuqiao	3	1	4	4
Xinba (2)	2	2	4	4
Majiadu Lock	2	2	4	4
Lujin Barrage Lock	2	2	4	4
Yanhe lock	1	3	4	4
Gaojianxun South Half Lock	1	3	4	4
Gaoyouzhou ZhuLake	2	2	4	4
Baoying Yuelongguan Ruins	1	3	4	4

each node on its surrounding nodes is limited. This suggests that each node primarily serves local or regional functions. When planning new facilities, it is advisable to enhance the degree of certain nodes and add redundant paths to increase network resilience.

The Hongze Lake region, as an area with a dense distribution of high-degree nodes, significantly contributes to the stability of the canal network and water resource management. Therefore, this region should be a focus for heritage protection. The following recommendations can be considered for protection and restoration efforts: Firstly, upgrade and expand the infrastructure in the Hongze Lake area to enhance the functionality of high-degree nodes. For example, construct modern water engineering facilities and transportation hubs to improve the canal's transportation capacity and disaster resilience. Secondly, strengthen water resource monitoring and management in the Hongze Lake area to ensure stable water quality and quantity, supporting the normal operation of the canal. Lastly, the historical issue of sediment accumulation from the Yellow River must still be addressed. Relevant authorities should develop comprehensive emergency plans and disaster prevention facilities, regularly dredge the river, and establish sediment interception and treatment facilities to prevent sediment buildup from affecting the canal's navigability and ensure its long-term smooth operation.

Although high-degree nodes account for only 3.7% of the network, they can effectively support the network's continued operation during natural disasters or human disruptions by buffering and dispersing pressure. Therefore, maintaining and protecting these high-degree nodes is also critical for the network's normal operation.

Characteristics of spatial distribution of betweenness centrality

Gephi calculated the values of betweenness centrality for water engineering facilities in each channel structure. A visualization is presented to facilitate the analysis of the spatial distribution of the study results (Fig. 17).

Figure 17 illustrates the spatial distribution of betweenness centrality in the overall network of water engineering facilities in the Beijing-Hangzhou Grand Canal, revealing a distinct "center-periphery" pattern. High

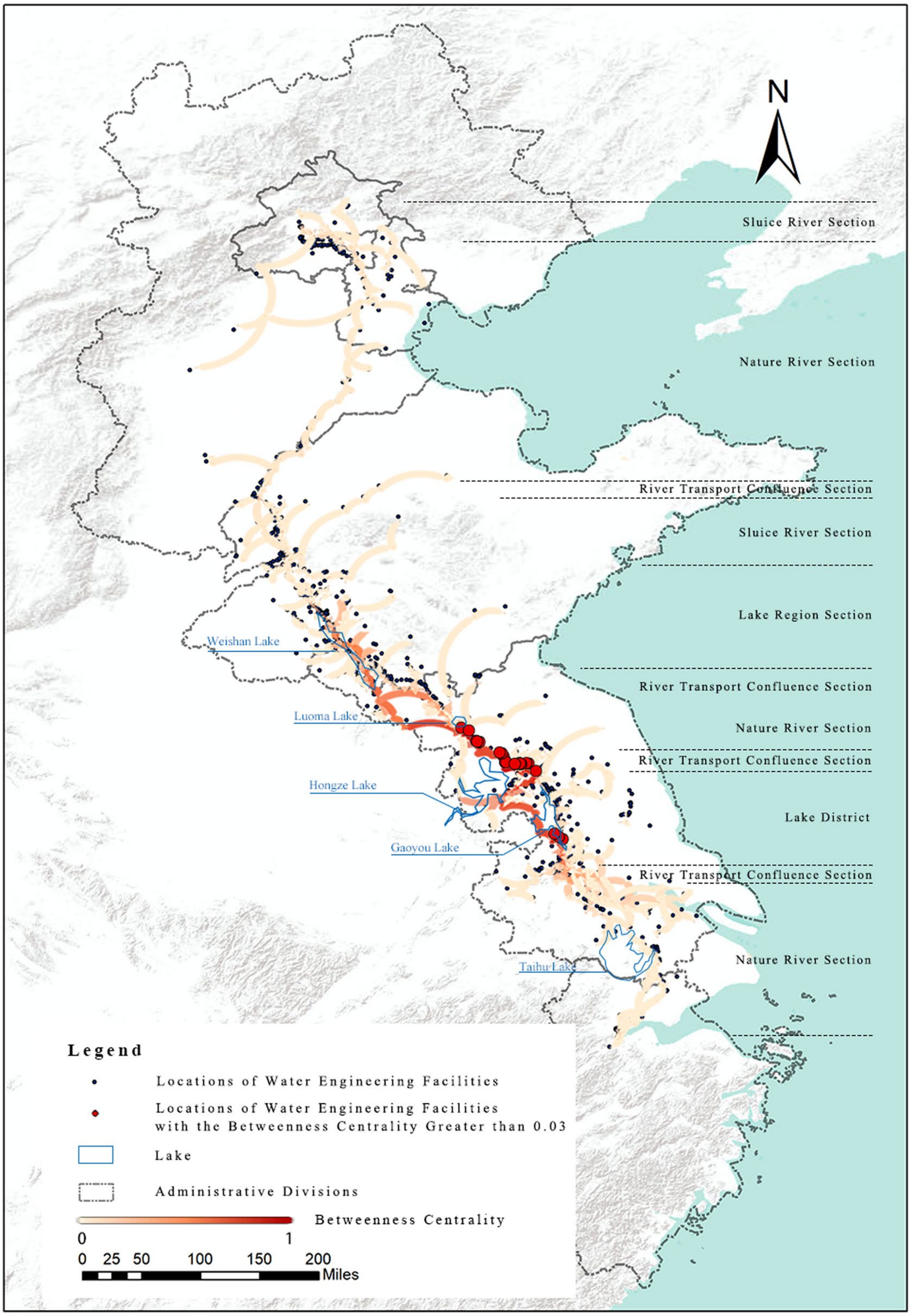

Fig. 17 Visualization plots of betweenness centrality distribution

betweenness centrality water engineering facilities are predominantly concentrated in the Lake region section from Liucheng to Zhenjiang, the River transport confluence section, and the Nature river section. Among these, the Lake region section comprises the majority.

This outcome is closely linked to the geographical setting of the Lake region section where water engineering facilities are situated. This section encompasses several lakes, including Hongze Lake and Luoma Lake, with extensive water areas [49], leading to a more diverse connection and closer relationships among water engineering facilities surrounding the lakes. These unique geographical advantages equip the Lake region section with the essential conditions for water engineering facilities to serve as intermediaries collectively, establishing it as a crucial water transportation hub on the Beijing-Hangzhou Grand Canal, distinct from the isolated connections of most adjacent water engineering facilities in other water routes.

Specifically, only 29 nodes in the entire network have betweenness centrality greater than 0.03, representing 2.53% of the total number of water engineering facilities (Fig. 17). These nodes include Zhaijia Dam, Shuangjin Lock, Cuizhen Water Reduction Stone Dam, Xinyuan Yangdatan Embankment, Liu Laogian Water Reduction Lock, Tien-Fei Dam Masonry Embankment, and Tongjizheng Lock. Water engineering facilities in the network are ranked based on betweenness centrality (Table 4). These facilities serve as crucial transportation hubs in the Beijing-Hangzhou Grand Canal network, warranting immediate attention and protection.

Overall, the water engineering facilities in the central part of the Beijing-Hangzhou Grand Canal have a high betweenness centrality, indicating that these areas play vital bridging and hub roles within the network. This characteristic makes the central region a key focus for cultural heritage protection. Protection measures for these important nodes should be more comprehensive and stringent. This includes enhancing the monitoring and maintenance of historical relics to prevent damage from natural disasters or human activities. Additionally, digital technologies can be utilized for the information management of these crucial nodes, ensuring the sustainable protection of cultural heritage. Furthermore, these core nodes hold significant transportation and logistics positions within the entire water engineering network. Therefore, investing in the construction of more ports, storage facilities, and transportation hubs in these high betweenness centrality areas can be considered to enhance their logistical capacity and efficiency.

Table 4 Statistics on betweenness centrality of Water engineering facilities in the network (Table created by the research team)

Water engineering facilities	Betweenness Centrality	Betweenness centrality ranking	Water engineering facilities	Betweenness Centrality	Betweenness centrality ranking
Zhaijia dam	0.039876935	1	Liuyuantou Lock	0.037865301	16
Shuangjin lock	0.039770819	2	Sicao Dam	0.036986594	17
Shuangjinmen stone lock	0.039663175	3	Wangjiagou lock	0.036850704	18
Cuizhen diversiondam	0.039554005	4	Yangjiamiao spillway stone lock	0.034960454	19
Cuizhen	0.039443308	5	Tien-Fei Dam masonry embankment	0.033845848	20
Shanyangxian Guanjia Lake	0.039331084	6	Lujin Barrage Lock	0.033776376	21
Xinyuan Yangdatan Embankment	0.039217333	7	Gaoyouzhou Zhu Lake	0.032801478	22
LiKouwuJi Monthly Embankment	0.039102055	8	Tianfei Dam Embankment	0.032581611	23
Zhuluo Dam	0.038985251	9	Second Dam (Yuhuang Second Dam)	0.03252588	24
Gizui Dam	0.038866919	10	Qingfeng culvert	0.032491526	25
Nananzi Embankment	0.038747061	11	Yu Dam	0.032468623	26
Beianzi Embankment	0.038625676	12	Barrier yellow dam	0.0318533	27
Liu Laogian Water Reduction Lock	0.038252359	13	Shunhuang Dam	0.031822762	28
Liulaojian Stone overflow Dam	0.038124866	14	Tongji main lock	0.031790698	29
Yingliu lock	0.037995847	15			

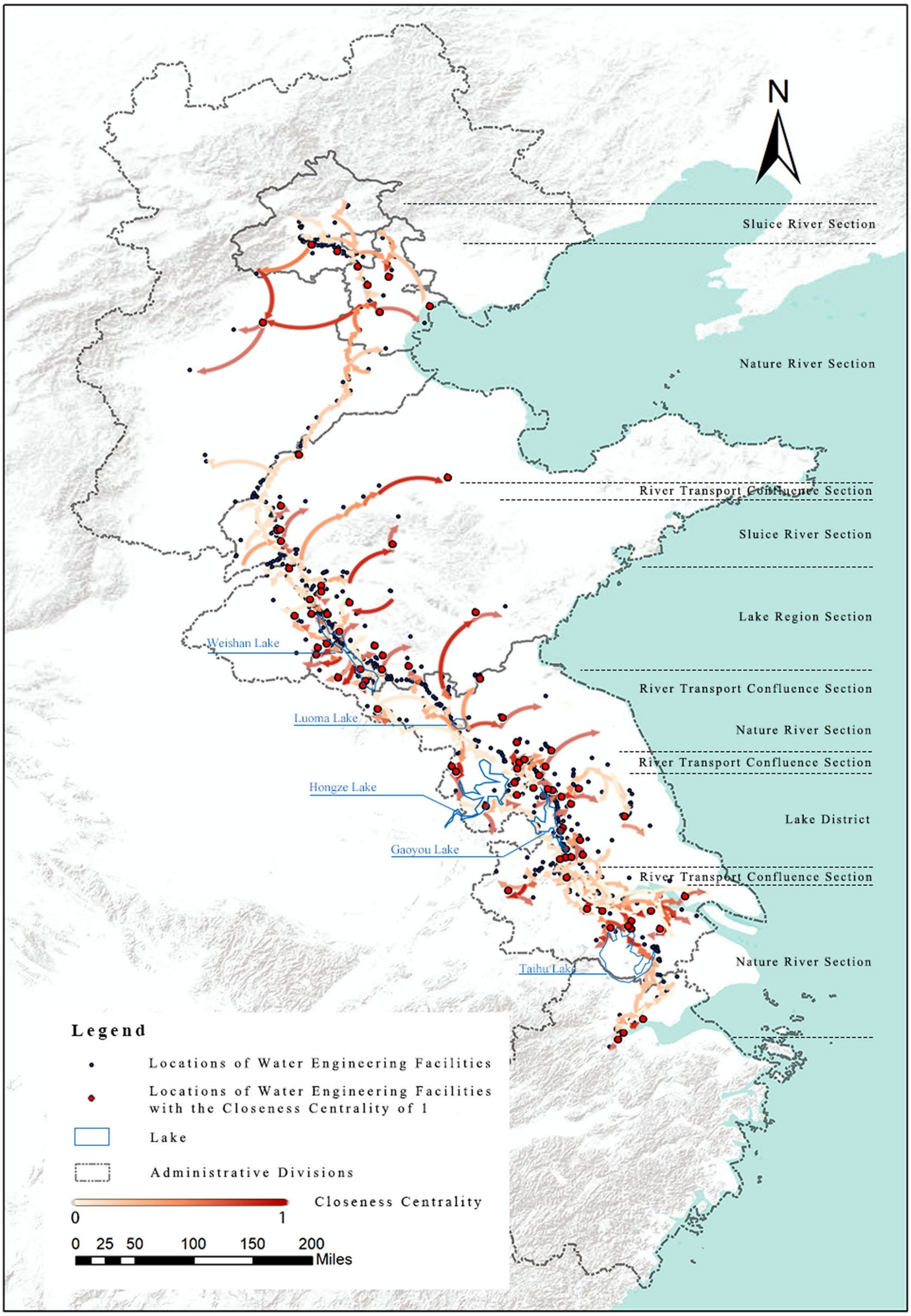

Fig. 18 Visualization plots of closeness centrality distribution

Characteristics of spatial distribution of closeness centrality

Computational analysis by Gephi yields the closeness centrality values of water engineering facilities in each channel structure, which are then combined with the latitude and longitude data of these facilities and visually presented (Fig. 18).

Figure 18 reveals that the spatial distribution of closeness centrality among nodes in the entire network exhibits dispersed characteristics, with nodes having higher values primarily located in the tributary areas of the canal, particularly prominent in the North Canal section of the Nature river section.

Nature river sections, owing to their high density of river networks and numerous tributaries [50], exhibit a complex and extensive network structure. This network structure facilitates Water engineering facilities in the river section to establish connections with other facilities, and the presence of tributaries further enhances network connectivity and proximity to the center. Moreover, Nature river sections experience fast and turbulent flows, necessitating additional Water engineering facilities to regulate river flows and maintain water stability. These facilities are pivotal for water resource management and regulation, serving as key links in the network and providing essential support for the operation of the river section. Influenced by geographic conditions and water flow characteristics, nodes in this river section are more likely to influence other nodes, thereby affecting closeness centrality.

Specifically, in the overall network, nodes with a closeness centrality of 1 indicate that they are in the core position of the network (Fig. 18). In the network of Water engineering facilities along the Grand Canal, there are only 86 such nodes, accounting for 7.5%, indicating that these 86 nodes serve as the network's transport hubs. Among them, 42 are in the Lake region sections, 22 in Nature river sections, 17 in sluice river sections, and 5 in River transport confluence sections. These include the Nanwang Diversion Bound Sand Dam, Shanxu Hall Embankment, Zhangfukou Crossing Embankment, and Wenhe Pickle Dam. Water engineering facilities with a closeness centrality of 1 provide critical transit benefits in

Table 5 The Water engineering facilities with closeness centrality values approaching 1 in the network (Table created by the research team)

Water engineering facilities	Closeness Centrality	Water engineering facilities	Closeness Centrality
Wuqiao	1	Jieshou lock	1
Yinjiazhuang Embankment	1	Shanxu Hall Embankment	1
Tuoqing Dam	1	Qinghe County Hekou locks	1
Heilongkou	1	Xiazhen lock	1
Bodu Harbor	1	Huangpu ditch	1
Qingming Bridge	1	Baoying Lake Embankment	1
Yangzhuangtou	1	Qinglong lock	1
Datong	1	Sanli ditch	1
Xuegongfengchong Drainage Canal	1	Saibaqian Embankment breach	1
Nanwang Diversion Bound Sand Dam	1	Erbao Liuzhai Stone Cave	1
Sunjiazhuang culvert	1	Three-hole lock	1
Old Hangzhou Longshan Lock	1	Wukongqiao Stone Lock	1
Beixin lock	1	Gecko Bridge	1
Chongde Chang'an Weir	1	Dingmao Dai Ruins	1
Zhujiadang	1	Zhangfukou Embankment	1
Xiaohaiyue lock	1	Shuqing Dam	1
Zhang'a lock	1	Dike worker in Kamloops	1
Xiaohekou Harbor Old Chiku Chai Dam	1	Wangyeng Reduction Dam	1
Qingguoxiang pier group and ancient towpath	1	South Bank Embankment	1
Golden lock	1	Linhuang Weir	1
Shaba lock	1	Ye Yun lock	1
Erjing embankment	1	Zhuxin Embankment	1
Water reduction locks 2 and 3	1	Wenhe picket dam	1
Wuli lock	1	Yuwangtai Shuhekou Big Earth Dam	1
Touer lock	1	Tianfei Dam	1

the Beijing-Hangzhou Grand Canal network and warrant attention and protection (Table 5).

Overall, the spatial distribution of nodes' closeness centrality in the network is scattered, with higher values primarily located in the canal tributary areas. To address this phenomenon, relevant departments can establish more ancillary infrastructure in the canal tributary areas, forming a complete support network to ensure the overall system's reliability and efficiency. High closeness centrality means these nodes have faster information transmission and resource acquisition capabilities within the network, giving them an advantage in responding to environmental emergencies and resource allocation. Therefore, environmental management along the canal should strengthen real-time monitoring of water quality, air quality, and the ecological environment to ensure a rapid response to environmental issues when they arise.

Network linkage characteristics of each channel structure

Each of the four types of channel structures possesses unique characteristics in terms of geographic location and water resource distribution. Therefore, this study classified and tallied the Water engineering facilities for each type of channel structure and computed three indicators: degree, closeness centrality, and betweenness centrality. Additionally, the data for these indicators were equally distributed across all Water engineering facilities to determine their average values.

Analysis of the data in Table 6 reveals that among the channel structures of the Beijing-Hangzhou Grand Canal, the Lake region section ranks highest in degree, betweenness centrality, and mediacy centrality, representing a significant advantage over other channel structures. This suggests that the Lake region section boasts the greatest comprehensive connection strength. Furthermore, it underscores the close relationship between the overall linkage role of each channel structure and the number of Water engineering facilities included. As the section with the highest number of Water engineering facilities among the four channel structures, the Lake region section comprises 644 nodes, constituting 56% of the total number of Water engineering facilities, thereby providing a robust foundation for the Lake region section to establish an indispensable position in all aspects.

Upon analyzing the average values of the three primary indicators for each channel structure, it is found that the Nature river section exhibits the highest average values of degree and mediator centrality. Additionally, the River transport confluence section among the four primary channel structures demonstrates the highest mean value of betweenness centrality, surpassing the others by 2–4 times. This finding underscores the predominant role of each Water engineering facility in the Nature river section in directly or indirectly connecting other nodes in the network, with these facilities predominantly situated at the network's center. Conversely, Water engineering facilities in the River transport confluence section prominently facilitate network transit, outperforming other river channels.

Furthermore, upon further investigation, the research team discovered that in the Nature river section, water control facilities significantly influenced the degree and betweenness centrality of the section, whereas in the River transport confluence section, river engineering facilities played a critical role in augmenting the betweenness centrality of the section (Table 7).

Water control facilities encompass various water conservancy projects designed to regulate river water levels or flow, including hydraulic structures like locks and Doumen locks. For instance, the Sinusi Water Conservancy Center in the Nature river section is situated in the middle and lower reaches of the Zhangwei South Canal in the Haihe River Basin, where it plays a pivotal role in flood control. The Sinusi Water Conservancy Center is connected upstream to the Wei Canal and downstream to the Zhangwei Xinhe and South Canal. It serves as a large-scale sluice gate, facilitating flood control, discharge, irrigation, and other functions.

The historical significance of the Sinusi Water Conservancy Center dates back to the Yellow River's diversion into the Zhangqiu Canal in the second year of Hongzhi (1489). The Sinusi Water Conservancy Center, formerly the Sinusi lock. To mitigate flooding, in the fourteenth year of Jiajing (1535), the Ming

Table 6 Indicator statistics for each channel structure in the network (Table created by the research team)

The channel structure	Number of nodes/pc	Total degree	Mean value of degree	Total closeness centrality	Mean value of closeness centrality	Betweenness Centrality	Mean value of betweenness centrality
Nature river section	214	454	2.121	62.880	0.294	0.333	0.002
River transport confluence section	57	117	2.053	11.598	0.203	0.478	0.008
Sluice river section	233	479	2.056	45.060	0.193	0.544	0.002
Lake region section	644	1344	2.087	133.611	0.207	2.839	0.004

Table 7 Indicator Statistics for Water Engineering Facilities in the nature River and River Transport Confluence Sections (Table created by the research team)

The Channel structure	Type of Water engineering facilities	Number of nodes/pc	Mean value of degree	Mean value of closeness centrality	Mean value of betweenness centrality
Nature river section	Water conveyance facilities	8	1.750	0.252	0.000
	Water retention facilities	62	2.161	0.315	0.002
	Ancillary facilities	82	2.049	0.266	0.000
	River engineering facilities	2	2.000	0.109	0.001
	Water control facilities	39	2.256	0.363	0.002
	Overflow facilities	21	2.190	0.244	0.003
	Water storage facilities	0	0	0	0
River transport confluence section	Water conveyance facilities	3	2.000	0.089	0.013
	Water retention facilities	29	2.138	0.266	0.010
	Ancillary facilities	2	1.000	0.000	0.000
	River engineering facilities	3	2.333	0.360	0.021
	Water control facilities	16	2.063	0.142	0.004
	Overflow facilities	4	1.750	0.067	0.002
	Water storage facilities	0	0	0	0

government repaired the Sinusi lock in Dezhou and four locks in Jingzhou Botou town to redirect water flow eastward. However, in the early Qing Dynasty, neglect of the Sinusi lock resulted in frequent canal flooding in the Shandong and Zhili areas. The Qing government undertook numerous repair efforts, culminating in effective river control by the Sinusi Water Conservancy Center in the 27th year of Qianlong (1762), after extensive widening, repairing, and strengthening. This center became a crucial water management project, ensuring canal water level stability and flow.

River engineering facilities encompass structures such as river training facilities, bank protection facilities, and other water engineering facilities, which play a crucial role in canal channel maintenance, flood control, riverbed dredging, etc. For instance, the Tien-Fei Dam masonry embankment, constructed in the seventh year of the Wanli reign during the Ming dynasty, is situated at the confluence of the Yellow River, Huaihe River, and Canal. Serving as a protective embankment for the Li Canal at the Yellow-Huaikai confluence section, it withstands the impact of torrential currents. During the Qing Dynasty, frequent flooding occurred in the Yellow and Huaihe River regions until the Kangxi period, prompting the reconstruction of the Tien-Fei Dam masonry embankment to address the increasing merging trend of the Yellow and Huaihe Rivers. In 2012, archaeological excavations revealed the site of the Tien-Fei Dam masonry embankment, featuring a main dam body approximately two meters high and over 40 m long, serving as a significant physical testament to water control efforts during the Ming and Qing Dynasties.

Conclusion and prospect

This study employed network analysis to construct the relationship network of Water engineering facilities along the Beijing-Hangzhou Grand Canal, exploring their intrinsic correlations. The study concludes: firstly, the network exhibits a large number of nodes and extensive scale, but low overall density and relatively weak interconnections. Additionally, some nodes are more distantly linked, while the transportation capacity of Water engineering facilities generally exceeds their transit capacity. Secondly, Water engineering facilities with higher degree are primarily located in the Lake region section, forming dense clusters. The spatial pattern of betweenness centrality reveals a "center-periphery" structure divided into three segments, while closeness centrality demonstrates a decentralized pattern, particularly concentrated in canal tributaries, especially the Nature river section. Finally, each channel structure within the Beijing-Hangzhou Grand Canal network plays a distinct role, collectively ensuring smooth canal operation. Water engineering facilities in the Lake region section are pivotal, Nature river section nodes exhibit strong direct connections and transit functions, with notable performance by water control facilities. River transport confluence section nodes serve as significant bridges, while river engineering facilities play a dominant linkage role.

The interconnections among the water engineering facilities of the Beijing-Hangzhou Grand Canal are intricate, collectively forming an extensive water transport network. This study employs network analysis methods to construct the relationship network of the canal's water engineering facilities, aiming to gain a deeper understanding of each facility's role within the water transport system and to identify key nodes within the network. Future research can further delve into these nodes. Deep analysis of key nodes can help relevant agencies propose more targeted protection and optimization strategies, ensuring the sustainable development of the water transport network. For example, the study results indicate that the central part of the Beijing-Hangzhou Grand Canal, which concentrates high-centrality nodes, serves as the core hub of the canal network. Some nodes in the canal tributaries function as auxiliary transfer points, supporting and enhancing the operational efficiency and resilience of the entire canal network. For the maintenance and protection of core hub nodes, relevant departments can utilize digital technology for 3D modeling and information management to ensure the sustainable development of the heritage. Additionally, these nodes are crucial for transportation and logistics, so relevant departments should prioritize the construction and maintenance of infrastructure around these key nodes. For important auxiliary nodes in the canal tributaries, more ancillary infrastructure should be established in these areas to enhance system stability and efficiency. Moreover, an efficient monitoring and emergency response system should be set up to ensure a swift response to environmental issues.

In conclusion, this study has conducted a preliminary exploration of the application of social network analysis in the fields of water engineering and cultural heritage. It provides an innovative interpretation of the network relationships among the water engineering facilities of the Beijing-Hangzhou Grand Canal, offering new perspectives and insights for related research fields. In the future, this method can be applied to the study of other linear heritage sites or water engineering projects worldwide, contributing valuable outcomes to the advancement of water engineering, cultural heritage, and social network analysis.

Abbreviation

ANP	Analytic network process

Acknowledgements
Not applicable.

Author contributions
Cheng Wang was mainly responsible for the collection and arrangement of the data-base and translated the final manuscript. Lifeng Tan was responsible for formulating paper ideas and overall research objectives, leading the execution of research plans, and providing guidance to the research team. Xin Qiu was responsible for model construction and writing the text, drawing pictures and tables. Cheng Wang and Xin Qiu contributed equally to this work and should be considered co-first authors. Yiwen Zhang and Guanhua Wang participated in writing part of the text of the manuscript, Zhichao Sun produced some charts and wrote parts of the documents. All authors reviewed the manuscripts.

Funding
Supported by the Ministry of Education's Humanities and Social Sciences. Research Project "Research on the Protection Strategy of the Hydraulic Heritage of the Tianjin Section of the Beijing-Hangzhou Grand Canal in the Ming and Qing Dynasties". (No. 23YJC760115). The National Natural Science Foundation project "Research on the Composition and Influence Mechanism of Ming Dynasty Coastal Defense Engineering Works System" (52078324).

Availability of data and materials
The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Manuscripts reporting studies not involve human participants, human data or human tissue.

Competing interests
The authors declare no competing interests.

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Received: 5 March 2024 Accepted: 8 August 2024

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