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Structural equation model of the spatial distribution of water engineering facilities along the Beijing-Hangzhou grand canal and its relationship with natural factors

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Abstract

Water engineering facilities are a crucial component of the Beijing-Hangzhou Grand Canal during the Ming and Qing dynasties, and their distribution is closely related to the hydrological and topographical characteristics of the area. In this study, we reconstructed the canal network distribution map and water engineering facilities database of the Ming and Qing periods using ArcGIS (Geographical information systems software) 10.8 software. We employed Amos (Analyze of Moment Structures) 26.0 software to investigate the influence of various natural environmental factors on the selection of water engineering facility sites. The results revealed a significant correlation between the spatial distribution of water engineering facilities and the main channel slope and slope direction, which had a direct impact. The estimated coefficient for the main channel slope was -0.166, showing a negative correlation with the spatial distribution of water engineering facilities, while the estimated coefficient for the main channel slope direction was − 0.112, also indicating a negative correlation. Moreover, the estimated coefficient for the watershed area where water engineering facilities were located was -0.096, demonstrating a negative correlation. In contrast, the effects of tributary slope and slope direction on the spatial distribution of water engineering facilities were indirect, mediated by the watershed area where these facilities were situated. The effect size for tributary slope was -0.017, showing a negative correlation, while the effect size for tributary slope direction was 0.010, indicating a positive correlation with the spatial distribution of water engineering facilities.The study achieves the integration of the heritage of water engineering facilities along the canal from point to line, provides data support for the construction of the cultural heritage corridor of the canal, and facilitates the promotion of heritage protection and rational layout, which is of great significance to the understanding of the canal culture.

Keywords The Beijing-Hangzhou Grand Canal, Water engineering facilities, ArcGIS, Hydrological terrain, Structural equation model

Introduction

There are more than 500 well-known canals in the world, many of which have been inscribed on the World Heritage List. Among them, the Old Town of Segovia and its Aqueduct in Spain was inscribed on the World Heritage List in 1985; the Canal du Midi in France, built between 1667 and 1694, was inscribed on the World Heritage List in 1996; The Four Lifts on the Canal du Centre and their Environs, LaLouviere and Le Roeulx in Belgium were also

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inscribed on the World Heritage List in 1998; in 2007 the Rideau Canal in Canada (Canal du Rideau) was inscribed on the World Heritage List in 2007 In 2007, the Rideau Canal in Canada was inscribed on the World Heritage List. The 202 km long canal, which runs from Ottawa to Kingston, is the best-preserved still-water canal in North America, constructed by the British using the "still-water" technique.

In June 2014, China's Beijing-Hangzhou Grand Canal was approved for inscription on the World Heritage List at the 38th World Heritage General Assembly. As the world's longest man-made river and one of the oldest canals, the Beijing-Hangzhou Grand Canal possesses the most complete water conservancy engineering facilities and has had an immeasurable impact on China's economic, political, and social development in various historical periods [1, 2].

The international cultural heritage conservation community has increasingly emphasized the preservation of canal routes and cultures, and academics have carried out a wealth of thematic studies on the canals inscribed on the World Heritage List. France's Canal du Midi, known as the "Impossible Project", has been the subject of research focusing on the structure of the river and the construction of facilities [3–5].Britain's Pontcysyllte Aqueduct and Canal are of great cultural value, and research has focused on the structural system of the crossing, maintenance and restoration, and heritage protection [6–8]. Canada's Rideau Canal, a marvel of 19th-century engineering, has been the subject of research focusing on biodiversity, heritage revitalization and restoration, and heritage conservation. The research focuses on biodiversity, heritage adaptive use renovation, and hydro-engineering heritage operation and management [9–11]; Amsterdam, with its super-long canals, the research includes urban spatial morphology, heritage monitoring, and adaptive use, etc. The most recent research focuses on the construction of flood control and drainage systems and the formation of a hydro-engineering management system in order to protect and realize the hydro-engineering functions of the canals [12–14]. Scholars from other countries, such as South Korea and North Korea, have studied the heritage of canal hydraulic installations more in relation to hydraulic technology and the preservation of hydraulic heritage. There are many international organizations focusing on "water and culture", such as the United Nations World Water Day and UNESCO. International research on the heritage of canal water engineering facilities involves many disciplines, ranging from archaeology, agronomy, hydraulic heritage, construction technology, heritage protection to tourism development, and the research results are very rich. The United States began to focus on the protection of linear cultural heritage such as canals as early as 1980 and constructed the concept of heritage corridors. By 2007, a total of 37 national heritage corridors and heritage areas had been published in the United States. In China, the School of Landscape Architecture of Peking University firstly proposed the concept of building a Grand Canal heritage corridor and the idea of its overall protection. Over the years, a basic framework for the overall protection of the Grand Canal has gradually been established. The systematic research and protection of the Beijing-Hangzhou Grand Canal urgently needs to be enriched and improved. Therefore, it is of great significance and value for China to learn from the experiences of European and American countries to comprehensively consider the scope of protection of the Beijing-Hangzhou Grand Canal and rational planning [15–20].

Compared with the rich experience in canal heritage protection and management in other countries, China's Beijing-Hangzhou Grand Canal applied for the world cultural heritage at a later time, and the current research of scholars on the Beijing-Hangzhou Grand Canal mostly focuses on the rich monolithic cultural heritage along the canal, which is not conducive to the research on the holistic, coherent and synergetic nature of the Grand Canal's protection, inheritance and utilization. At the same time, in the existing research on canal water engineering facilities, scholars have not systematically researched water engineering facilities as a separate type of heritage [21–23].

Research aim

The scope of the study covers the entire length of the Beijing-Hangzhou Grand Canal of more than 3,000 miles, which flowed sequentially from north to south through Beijing, Tianjin, Hebei, Shandong, Jiangsu, and Zhejiang provinces (Fig. 1). The timeframe focuses mainly on the Ming and Qing dynasties (1368–1912).

Site selection for the construction of water engineering facilities belongs to a systematic research topic, which is not only influenced by natural factors but also includes the political background and social conditions of the construction period. In terms of political factors, the Ming and Qing dynasties were the flourishing periods of China's feudal society [24], and the prosperous canal transportation system maintained the relative stability of the centralized rule, which to a certain extent contributed to the improvement and construction of the canal's water engineering facilities; in the middle of the nineteenth century, China was in the midst of internal and external troubles, and the transportation system of the Beijing-Hangzhou Grand Canal was deeply affected, with the construction of water engineering facilities declining until it was discontinued. In terms of

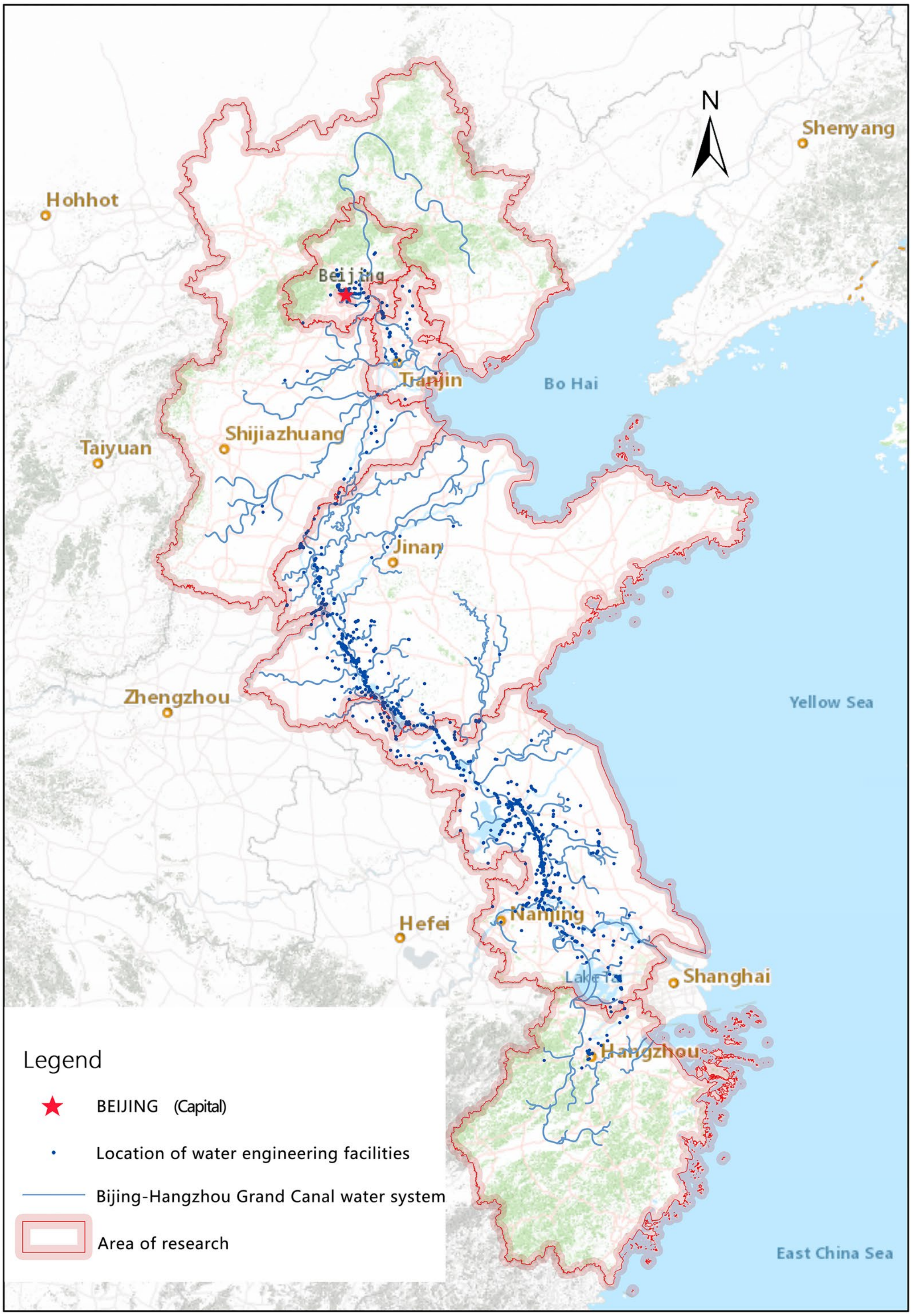

Fig. 1 Research scope (The map of China was provided by the National Network of Surveying, Mapping and Geographic Information)

social factors, the economic level, cultural prosperity, and population density of the areas through which the Beijing-Hangzhou Grand Canal flowed all influenced the location and construction of the water engineering facilities. However, natural factors, as non-man-made force majeure factors, had the most direct influence on

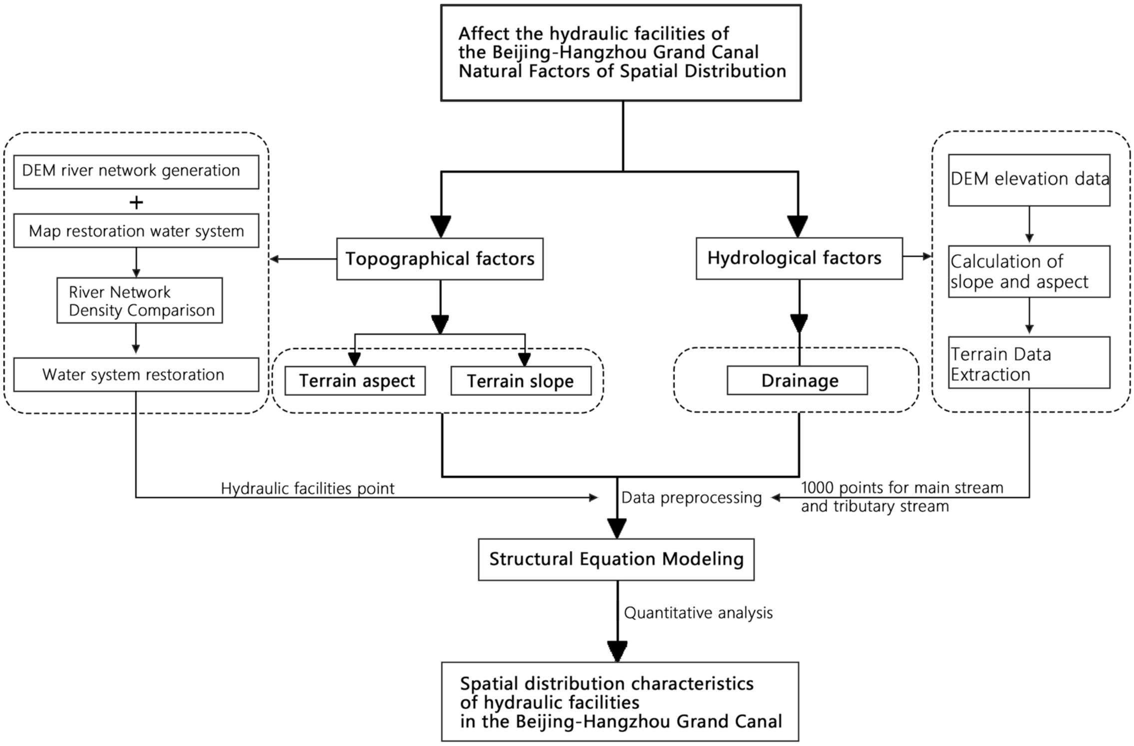

Fig. 2 Research idea and framework diagram

the siting of water engineering facilities and were used as the basis and conditions for the subsequent study of political and social factors. This paper discusses the study of the spatial distribution characteristics of natural factors on water engineering facilities as a separate research topic, and takes the whole line of water engineering facilities as the research object, constructs the structural equation model, and quantitatively explores the relationship between the spatial distribution of water engineering facilities and the natural environmental factors on the basis of qualitative analysis. Therefore, the following research hypotheses were constructed: there is a correlation between topographic factors and the spatial distribution of water engineering facilities, and there is a correlation between hydrological factors and the spatial distribution of water engineering facilities.

The overall idea and framework of the article are shown in Fig. 2. Firstly,the maximum difference in topographic elevation along the Beijing-Hangzhou Grand Canal is about 50 m [25], so the first problem that needed to be solved for the construction and functioning of water engineering facilities was the difference in water level generated by the complex topographic environment [26]. The topographic factor was taken as one of the factors to measure the influence on the spatial distribution of water engineering facilities. In addition, the slope and direction of the river channel are used to reflect the topographic characteristics, and we chose the variable of slope direction to represent the horizontal data of the topography of the locations of water engineering facilities, and the variable of slope as the topography to reflect the vertical data.

Secondly, The construction of water engineering facilities can reflect the hydrological environment of the region where they are located. Water engineering facilities not only solved the problems of water shortage and flooding along the route, but also gave full play to the benefits of canal navigation.The major tributaries of the Haihe River, Yellow River, Huaihe River, Yangtze River, Qiantang River, and other water systems have a certain degree of influence on the spatial structure and evolution of the mainstream of the Beijing-Hangzhou Grand Canal [27], and the water engineering facilities assume the role of improving the water environment of the natural river channels and the river transport intersection. Therefore, hydrological factors are considered as another important factor reflecting the spatial distribution of water engineering facilities.

The study needs to obtain topographic and hydrological data from the restored river network of the Beijing-Hangzhou Grand Canal.The DEM (Digital Elevation Model) map reflects the topography and geomorphology of the study area, and this paper restores the river network of the Beijing-Hangzhou Grand Canal of the Ming and Qing dynasties based on the DEM map. On the basis of the restored river network, a structural equation model is constructed to quantitatively analyse the hydrological and topographic factors, and to derive the spatial distribution characteristics of the water engineering facilities.

Research materials

Construction of a hydrological model of the Grand Canal during the Ming dynasty

In view of the unique hydrological and topographical conditions along the Beijing-Hangzhou Grand Canal, all kinds of water engineering facilities have different functions. Classified according to their functions, the water engineering facilities are mainly divided into the following six categories: water retaining facilities (embankments, dams, weirs, etc.); overflow facilities (overflow weirs, rolling dams, sluice gates, etc.); water conveyance facilities(canals, culverts, tunnels, tunnels, inverted siphons, etc.); water storage facilities (water closets, ponds, reservoirs, pools, etc.); water control facilities(gates, dipper gates, etc.); river facilities (dike, channel improvement facilities, shore protection facilities,etc.); and ancillary facilities(wharves, storage bridges, money passes, post stations, etc.); and ancillary facilities (wharves, warehouses, bridges, banknotes, and post stations). In order to study the influence of hydrological factors on the water engineering facilities, it is necessary to construct the hydrological network of the Beijing-Hangzhou Grand Canal in the Ming and Qing Dynasties (1368–1912) for further in-depth investigation.

Restoration of hydrology in the Grand Canal during the Ming Dynasty

This paper adopts the research method of opinion map literature, and carries out a fine restoration of the trunk of the Beijing-Hangzhou Grand Canal and the water system involved in the Ming Dynasty (1368–1644) on the basis of opinion maps. Based on *the Chinese Historical Atlas* [28], it traces the river network of the Beijing-Hangzhou Grand Canal in the Ming Dynasty, and compares it to see that the river channels of the Beijing-Hangzhou Grand Canal of the Ming and Qing Dynasties are almost the same. The river network was restored with the help of ArcGIS10.8, which is a digital means. In order to verify the accuracy of the restoration results, this paper compares the canal network image generated by tracing the map of the Ming Dynasty with the density image of the canal network generated by DEM, and finally produces the river network map of the Beijing-Hangzhou Grand Canal in the Ming and Qing Dynasties, which has a certain degree of error with the restoration map, but it can be used as the basis for the subsequent study of hydrological factors.

In ArcGIS 10.8 platform, this paper utilizes the hydrological analysis tool to extract the river network water system of the Beijing-Hangzhou Grand Canal [29]. Firstly, the DEM data of the canal flow area (data source National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://www.geodata.cn)) were imported into ArcGIS 10.8, so as to obtain a digital elevation model with a spatial resolution of 30 m. Export a remote sensing image of the study area. The spatial resolution was resampled to 1 km, and the absolute elevation error was averaged at 20 m globally. After that, this paper executed the Flow tool to calculate the cumulative amount of sink flow for each raster location in the selected study area. Surface runoff is generated when the catchment accumulation reaches a certain value. Therefore, by setting a threshold value and comparing the magnitude of the catchment accumulation to the threshold value, it is possible to determine whether surface runoff can be generated on a grid. The extraction of a river grid is significantly related to the threshold set. In general, a large threshold value results in a small density of extracted river network and a large number of river network classes in the watershed; a small threshold value results in a large density of extracted river network and a small number of river network classes in the watershed (Table 1). Selecting a reasonable extraction threshold is a key step in DEM-based watershed topographic characterization and yield-sink flow calculation.

In this paper, the raster calculator tool was used to calculate the hydrological data under different catchment area thresholds (Fig. 3). Finally, the raster river network vectorization tool was used to obtain the canal river network map. The results show that there is a certain relationship between the threshold size and the river network density in the cumulative calculation of catchment flow, and the inflection point of the curve between the threshold and the river network density is the selection point of the optimal catchment area threshold [30]. Therefore, in the calculation process, this paper tries to use different thresholds to generate the river network (the threshold increases, the river network density decreases), and found that as the threshold increases the river network density decreases sharply, the threshold between 50,000 and 150,000 will be the inflection point, and after that, the river network density change tends to be flat [31]. In this paper, the river network image generated by the threshold at the inflection point is selected to be compared with the restored river network map of the Ming Dynasty for graphical superposition and verification (Fig. 4) [32]. It is found that when the threshold value is selected as 100,000, the generated river network

Table 1 The generated river network density and total river length under different thresholds

Threshold	Total length of the river network (km)	Drainage area (km^2)	River network density (km/km^2)
8000	200,549.2346	527,576.423	0.38013
12,000	165,191.0055	527,576.423	0.31311
16,000	143,811.3446	527,576.423	0.27259
18,000	135,851.6716	527,576.423	0.2575
20,000	129,175.5694	527,576.423	0.24485
25,000	115,670.1398	527,576.423	0.21925
30,000	105,433.4189	527,576.423	0.19984
40,000	91,134.74787	527,576.423	0.17274
50,000	81,474.36909	527,576.423	0.15443
100,000	57,362.79592	527,576.423	0.10873
150,000	46,510.66016	527,576.423	0.08816
180,000	42,168.36508	527,576.423	0.07993
200,000	39,932.64226	527,576.423	0.07569
300,000	32,081.50036	527,576.423	0.06081
350,000	29,685.53095	527,576.423	0.05627
400,000	27,612.84118	527,576.423	0.05234
450,000	25,953.0304	527,576.423	0.04919
500,000	24,537.29836	527,576.423	0.04651
550,000	23,488.65261	527,576.423	0.04452

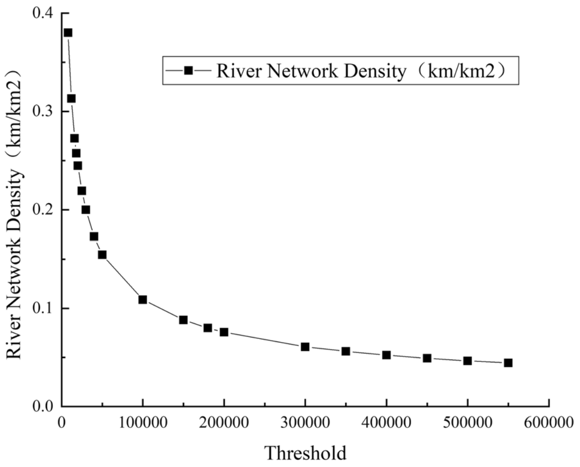

Fig. 3 Relation between threshold value and river network density

map is relatively close to the restored Ming Dynasty river network map, and at the same time, it is basically consistent with the restored Ming Dynasty river network mainstream map. According to the Historical Atlas of China, the water systems of the Ming Dynasty and Qing Dynasty are basically the same. Therefore, this paper chooses the river network map generated at a threshold of 100,000 as the basis for subsequent analysis of the surface water accumulation area of the Ming and Qing canals, and derives the hydrological data model of the main streams and tributaries of the Beijing-Hangzhou Grand Canal in the Ming and Qing dynasties (Fig. 5).

Obtaining locations of water engineering facilities

After completing the restoration of the river network of the Beijing-Hangzhou Grand Canal in the Ming Dynasty, this paper proceeds to the construction of a database for the specific research object of water engineering facilities along the route. In this database, this paper categorizes the water engineering facilities according to their main functions. They are mainly divided into the following six categories: water retaining facilities, such as embankments, dams, weirs, etc.; overflow facilities, such as overflow weirs, rolling dams, water reduction gates, etc.; water conveyance facilities, such as canals, culverts, tunnels, ferries, inverted siphons, etc.; water storage facilities, such as water closets, ponds, reservoirs, pools, etc.; water control facilities, such as gates, bucket gates, etc.; river engineering facilities, such as nooks, slough improvement facilities, and shore protection engineering facilities such as ding-dong dams, etc.; and ancillary facilities, such as wharves, warehousing, bridges, banknotes, and post stations. However, it should be emphasized that different categories of water engineering facilities need to cooperate and work together to ensure the smooth flow of the canal. Therefore, it is relatively limited in significance if a study is conducted on a certain category of water engineering facilities alone. Therefore, this paper does not categorize and calculate them.

Through detailed combing of ancient literature and public opinion literature, and data crawling using the WGS84 coordinate system, this paper has successfully acquired 1,350 valid coordinate points of the water engineering facilities of the Beijing-Hangzhou Grand Canal in the Ming and Qing dynasties [33] (Fig. 6). And 173 remains of water engineering facilities were used for location verification by field research method (attachment 1). In the process of field research, the team used UAV (Unmanned Aerial Vehicle) information collection technology to collect information on the existing sites along the canal, and produced a total of 144 3D point cloud modelling in the later stage, and 29 sites were photographic data. Due to space reasons, this paper selects six hydroelectric facilities remains of the 3D point cloud model display (Figs. 7, 8, 9, 10, 11, 12): According to their geographical location from north to south, they are Daiwan sluice gate, A-cheng lower sluice gate, Jingmen lower sluice gate, Nangwang junction site, Liulin sluice gate, and Huai'an board sluice gate site. By corroborating the research data with the documentary materials, the

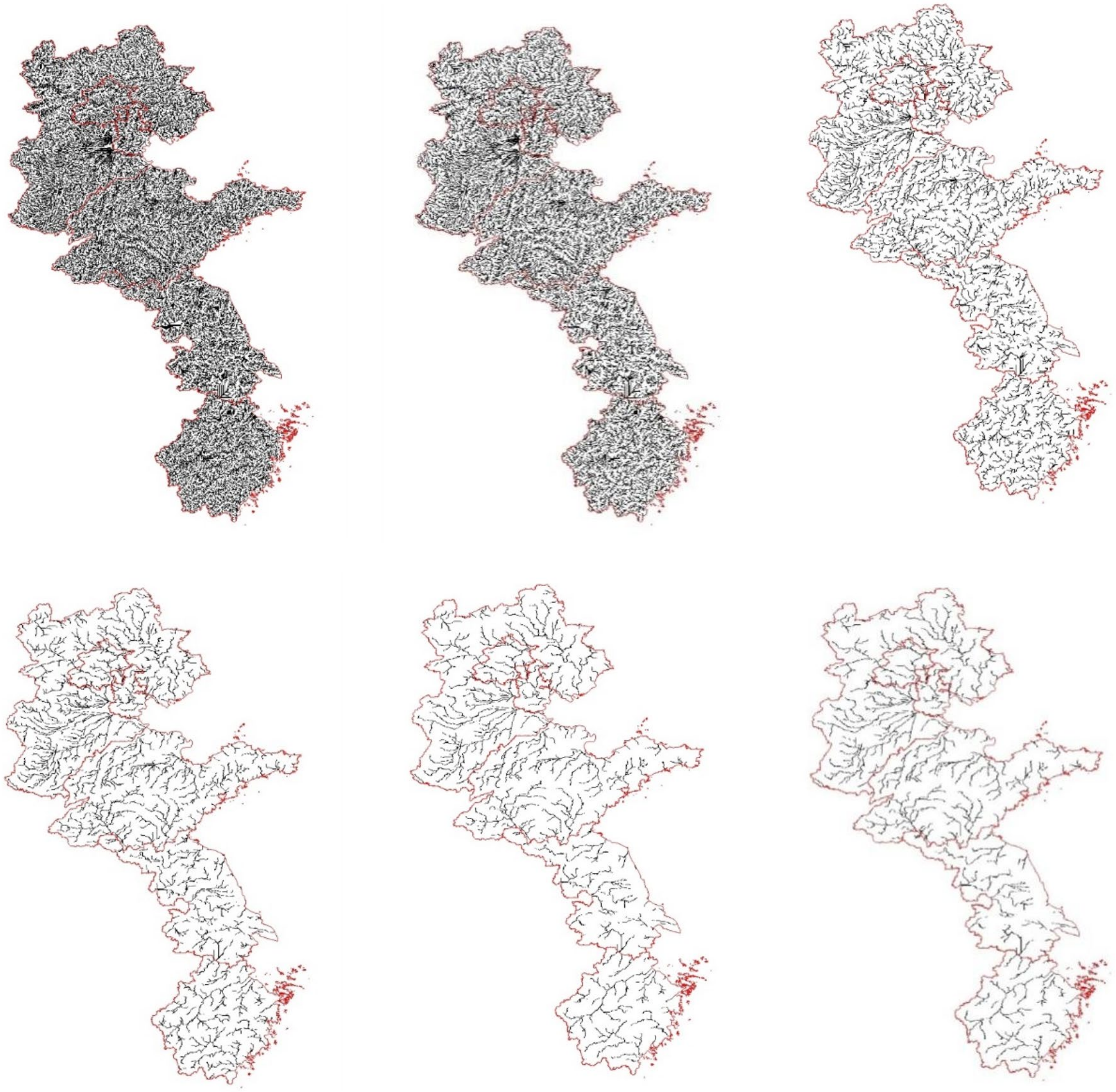

Fig. 4 Drainage patterns extracted under different thresholds

precise latitude and longitude of the water engineering facilities can be obtained.

On the basis of analyzing a large number of ancient books as well as modern literature, this paper divides the main stream of the Beijing-Hangzhou Grand Canal into 1,000 equal parts according to equal distances, so as to obtain 1,000 coordinate points along the canal. The data changes of these points can accurately reflect the change trend of hydrological terrain along the mainstream of the canal. Similarly, this paper also divided the tributaries of the canal into 1,000 equal parts, and further acquired 1,000 coordinate points. Combining the above three kinds of coordinate points, this paper can accurately extract the data of the corresponding points. These data provide an important pavement for the subsequent correlation study on the spatial distribution of the water engineering facilities of the Beijing-Hangzhou Grand Canal and their influencing factors.

Extraction of environmental impact factors

Extraction of hydrological factors

The watershed area determines the amount of water stored within the area of the study object, and is the upper limit of river runoff within this area. Therefore, the watershed area influences the distribution of the river system, as well as the river flow. By extracting the watershed area, this paper can indirectly reflect the size of the water volume at the location, so as to explore the spatial

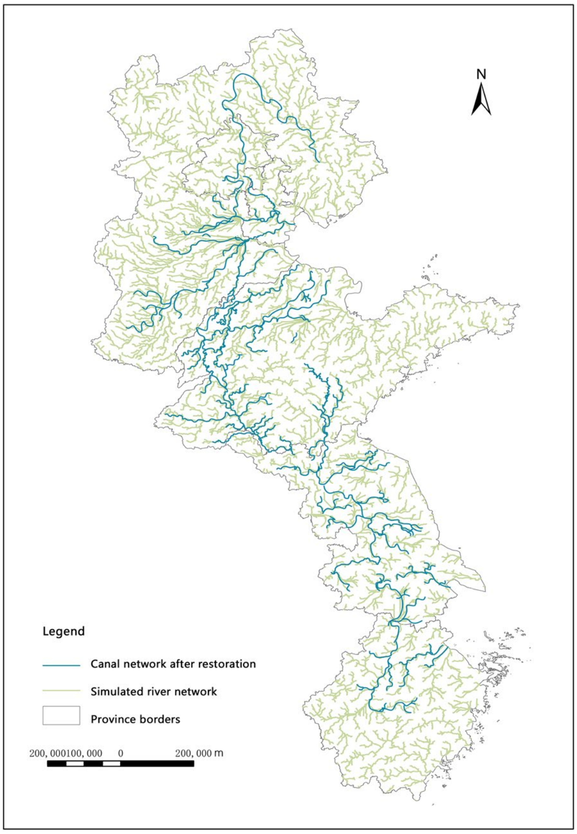

Fig. 5 Comparison of Ming Dynasty simulated river network and restored river network [Source of DEM map:National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://www.geodata.cn)]

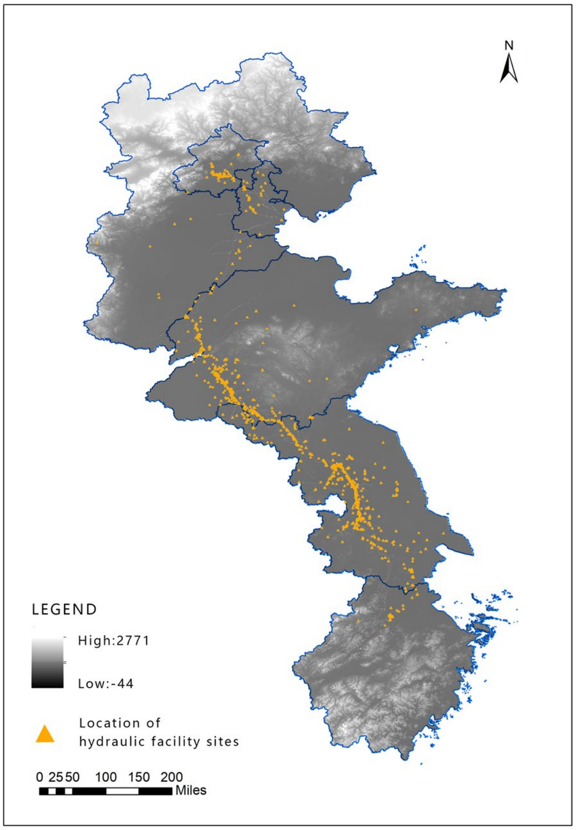

Fig. 6 Marks the selected points on the elevation chart [Source of DEM map:National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://www.geodata.cn)]

distribution relationship between hydrology and water engineering facilities. Considering that the traditional way of extracting hydrological factors is to calculate the flow rate and flow volume of the river on the basis of the river network data, but this method cannot accurately reflect the flow rate and flow volume of the Beijing-Hangzhou Grand Canal in the Ming and Qing Dynasties, this paper adopts a more suitable method to investigate the spatial distribution relationship between hydrology and hydro-engineering facilities.

Based on the restoration data of the above mentioned images of the river network of the Beijing-Hangzhou Grand Canal in the Ming Dynasty, this paper extracted the nodes of the river network generated when the threshold value was set to 100,000, established the river links, and determined the starting and termination points of each tributary, which were taken as the outlets of the catchment area. Subsequently, the paper divided the watershed area based on the catchment area and imported the coordinate points of the water engineering facilities into the system. Finally, the study resulted in watershed area data for the locations of these water engineering facilities (Fig. 13), which were analyzed and planned accordingly [34].

Fig. 7 Daiwan sluice gate

Topographic factor extraction

In space, the influence of topographic features on the siting of water engineering facilities in the Ming and Qing Dynasties Beijing-Hangzhou Grand Canal is

Fig. 8 A-cheng lower sluice gate

Fig. 9 Jingmen lower sluice gate

Fig. 10 Nangwang junction site

Fig. 11 Liulin sluice gate

Fig. 12 Huai'an board sluice gate site

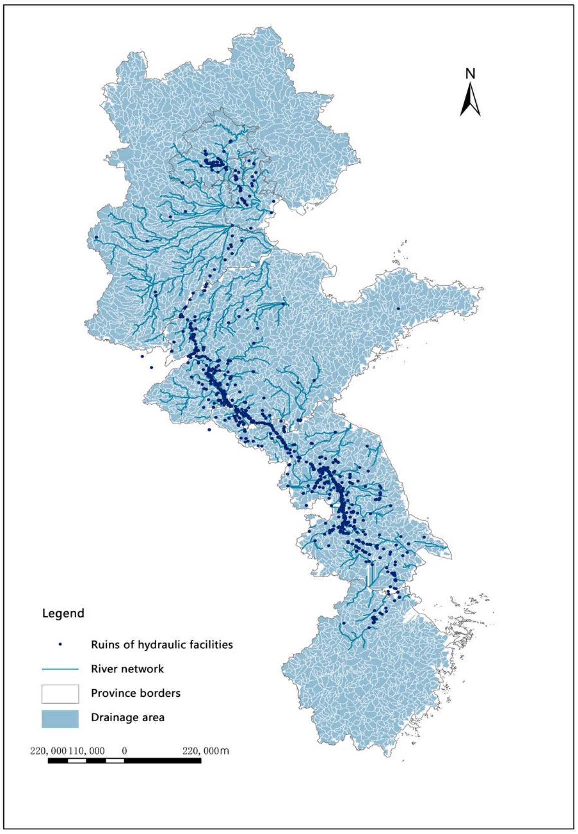

Fig. 13 Watershed area of Ming Dynasty water engineering facilities site

divided into two dimensions: horizontal and vertical, so we chose the variable of slope direction to represent the horizontal data of topography at the locations of the water engineering facilities, and the variable of slope as the topographic relief to respond to its vertical data [35]. Both data can be used to characterize the maximum variation of the topography in which the water engineering facilities site is located [36]. Since the topography of the Ming Dynasty did not change much compared with the modern topography, this paper uses DEM maps of the areas involved, calculates them, and extracts the data on the slope and slope direction of the corresponding water engineering facilities locations.

To summarize, this paper takes the watershed area of the water engineering facilities of the Beijing-Hangzhou Grand Canal in the Ming and Qing Dynasties as a hydrological influence factor, which is used to reflect the magnitude of the water flow at its location, so as to explore the connection between the river flow and the spatial distribution of the water engineering facilities; at the same time, the data of the slope and slope direction are extracted in order to embody the factors of topography, and the relationship between the spatial distribution of the water engineering facilities and the factors of topography is explored through the observation of the regularity of the data of the slope and the direction of the slope of the water engineering facilities at their location [37, 38]. Therefore, the hypothesis "the hydrological and topographical factors of the mainstream and tributaries of the Beijing-Hangzhou Grand Canal are relevant to the spatial distribution of water conservancy facilities" can be transformed into "the three factors of the mainstream and tributaries of the Beijing-Hangzhou Grand Canal, including the slope, direction of slope, and the watershed area where the water engineering facilities are located, have a correlation with the distribution of water engineering facilities distribution". Based on the above assumption, the following section will continue to analyze and discuss the data on slope, slope direction and watershed area of water engineering facilities to further reveal the specific ways and extent of the influence of these three factors on the distribution of water engineering facilities in the canal.

Research methodology

Structural equation modeling

Structural equation modelling is a multivariate statistical method based on the covariance matrix of variables by constructing latent variables and observed variables path analysis model between potential variables[1] and observed variables,[2] verify the model hypothesis and draw research conclusions of the correlation analysis method [39, 40]. Structural equation modelling has the advantages of high accuracy, inclusiveness and strict hierarchy. It is able to validate multiple sets of variable relationships at the same time and accepts errors in the data collection process. By adding relationships between variables, it verifies the extent to which multiple observed variables affect potential variables and analyses whether the relationship is a direct or indirect effect.

Research process

Model hypotheses

In this paper, the spatial distribution of water engineering facilities is taken as a potential variable, and the coordinate points of longitude, latitude and elevation of water engineering facilities are taken as measurement indicators to satisfy factor analysis. Meanwhile, through the extraction of natural influences in the above content, other factors are regarded as observed variables. In order to satisfy the requirements of path analysis, the following model assumptions were specified:

H1: There is a correlation between the slope of the mainstem and the spatial distribution of water engineering facilities.

H2: There is a correlation between the slope direction of the mainstem and the spatial distribution of hydroelectric facilities.

H3: There is a correlation between the size of the watershed in the region where the water engineering facilities are located and the spatial distribution of the water engineering facilities.

H4: There is a correlation between the slope of tributaries and the spatial distribution of water engineering facilities.

H5: There is a correlation between the slope direction of tributaries and the spatial distribution of water engineering facilities.

Data preprocessing

In the initial data calculation and extraction stage, some sample data have anomalies. In order to improve the efficiency of data use and meet the model fitting prerequisites, this paper will deal with the abnormal values [5, 41]. Error data such as "0" and "9999" are deleted. At the same time, under the premise of being able to reflect the overall topographic changes of the Beijing-Hangzhou Grand Canal, the data on natural influences were uniformly censored, and there were a total of 720 sets of sample data (attachment 2), and the descriptive statistical analyses of the descriptions of this set of data and the indicators are shown in Table 2.

Data standardization

Data of different magnitudes cannot be compared directly, therefore, this paper adopts the extreme value standardisation method to standardise the data of different variables. The specific formula is as follows [42–45]:

$$y_i = \frac{x_i - x_{min}}{x_{max} - x_{min}}$$

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[1] Objects that cannot be directly measured with actual data, but can only be described in general terms, are called potential variables, and together with the relevant measurement indicators, constitute factor analysis.

[2] Variables for which data can be measured directly to influence the outcome of the evaluation of latent variables are termed as observed variables.

Table 2 Description of variables and descriptive statistical analysis of indicators

Variable name	Minimum value	Maximum value	Average	Standard deviation	Number of observations
Latitude	114.92	121.33	118.24	1.48	720
Longitude	30.09	40.39	34.53	2.49	720
Elevation	− 16	322	21.99	23.07	720
Drainage area	4.16	509.70	190.11	97.09	720
Tributary slope	0.33	41.81	3.34	3.85	720
Tributary aspect	1.55	358.83	180.28	104.62	720
Main stream slope	0.33	35.69	3.84	4.54	720
Main stream aspect	0	358.73	175.76	105.58	720

where x_i is the original sample data, x_i is the standardized data, x_{min} denotes the minimum value in the original sample data, and x_{max} denotes the maximum value in the original sample data. Under the premise that there are no missing values in the sample data, structural equation modeling can be performed by standardizing the variables.

Model construction

The model fit index is a tool used to assess how well the model assumptions match the data, and if the fit index fails to meet the expected criteria, it indicates that the model may be problematic and needs to be corrected. When the chi-square value in the model fit index is reduced by model correction, this paper calculates structural equation model estimates using great likelihood estimation through AMOS 26.0 software. This paper analyzes the model correction structure by adding the covariance between the residuals to derive the model MI value statement. If the chi-square value is significantly reduced after adding the paths, and the changes in other fitting indicators are within the expected range, this indicates that the model correction is reasonable [46]. However, if the expected fitting index requirement still cannot be achieved after adding the paths, it is necessary to delete the unreasonable paths in the calculation process and further delete the unreasonable sample data in order to reduce the chi-square value and improve the model fitness. Considering the reasonableness of the existence of errors between variables, this paper adds three sets of covariance relationships, $e3 \sim e5$, $e2 \sim e5$, and $e1 \sim e5$, which reduce the chi-square values of 5.926, 21.723, and 11.162, respectively, and these results are in line with the computational standards and satisfy the established principles of the model assumptions.

In this paper, four types of metrics, namely, absolute fit metrics, relative fit metrics, adjusted fit metrics and information indexes, were used to assess the goodness of fit of the model. Among them, the absolute fit indexes include CMIN, GFI, CMIN/DF and RMSEA, the relative fit indexes include NFI, IFI, CFI and RFI, etc., the adjusted fit indexes involve only PNFI, while the information indexes mainly consider the AIC. The index ranges of the fit indexes are listed in Table 3. If the adjusted model fit indices meet the corresponding measurement criteria, the model can be considered valid. Table 4 lists the adjusted model fit indices, and by comparing with Table 3, it can be found that the values of absolute, relative and adjusted fit values are all within the standard range of the fit indexes, thus indicating that the adjusted model is indeed valid [5, 47, 48]. Based on this, a structural equation model was constructed as shown in Fig. 14.

Model results and discussion

Results

After determining the final structural equation model, this paper calculates the path coefficients, and accordingly analyses the correlation and the degree of influence of each influencing factor on the spatial distribution of water engineering facilities in the Grand Canal. The hypothesis test estimation results of the structural equation model are given in Table 5, where the estimated values are the standardised factor loadings, which can be used as the basis for analysing the correlation between variables.

Table 3 Comparison table of model fit indices criteria

Model	Acceptable standard	Model	Acceptable standard
CMIN	The smaller the better	IFI	>0.9
GFI	>0.9	CFI	>0.9
CMIN/DF	$1<\text{CMIN/DF}<3$	RFI	>0.9
RMSEA	<0.05	PNFI	>0.5
NFI	>0.9	ACI	< Saturated model < Independence model

Table 4 Model Fit Summary

Fit index	**Absolute fit index**				**Adjusted fit index**
Model	**CMIN**	**GFI**	**CMIN/DF**	**RMSEA**	**PNFI**
Default model	16.874	0.994	1.875	0.035	0.317
Saturated model	0.000	1.000			0.000
Independence model	1239.441	0.753	44.266	0.245	0.000
Fit index	**Relative fit index**				**Information index**
Model	NFI	IFI	CFI	RFI	ACI
Default model	0.986	0.994	0.994	0.958	70.874
Saturated model	1.000	1.000	1.000		72.000
Independence model	0.000	0.000	0.000	0.000	1255.441

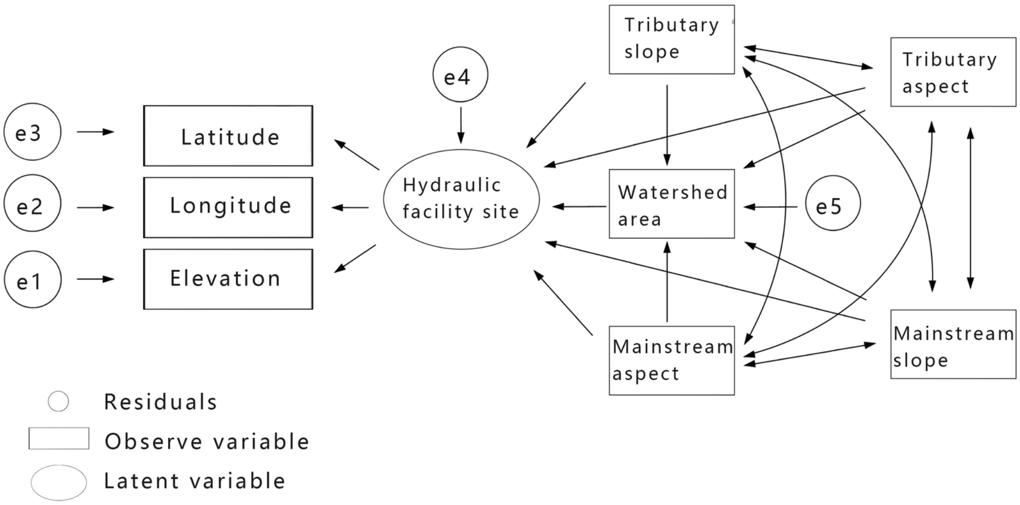

Fig. 14 Structural equation model affecting the spatial distribution of water engineering facilities

Table 5 Standardized regression weights

Conduction path		**Estimate**	**S.E**	**C.R**	**P Lable**
Main stream aspect	Drainage area	− 0.022	0.023	− 0.607	0.544
Main stream slope	Drainage area	− 0.011	0.054	− 0.306	0.759
Tributary aspect	Drainage area	− 0.101	0.023	− 2.825	0.005
tributary slope	Drainage area	0.178	0.074	4.977	***
Drainage area→	Water engineering facilities	− 0.096	0.006	− 2.764	0.006
Tributary slope→	Water engineering facilities	− 0.037	0.013	− 1.123	0.262
Tributary aspect→	Water engineering facilities	0.015	0.004	0.474	0.635
Main stream slope→	Water engineering facilities	− 0.166	0.01	− 4.706	***
Main stream aspect→	Water engineering facilities	− 0.112	0.004	− 3.329	***
Water engineering facilities→	Elevation	0.519			
Water engineering facilities→	Longitude	0.766	0.331	15.802	***
Water engineering facilities→	Latitude	− 1.087	0.529	− 13.352	***

"***" Represent P value less than 0.001

Table 6 Effectiveness analysis table

Conduction path	Effects	Effect index	Bias-corrected 95% CI	
			Lower	Upper
(Path 1) Main stream aspect → Drainage area → Water engineering facilities	Indirect effects	0.002	− 0.005	0.012
	Direct effects	− 0.112	− 0.175	− 0.049
(Path 2) Main stream slope → Drainage area → Water engineering facilities	Indirect effects	0.001	− 0.005	0.008
	Direct effects	− 0.166	− 0.240	− 0.090
(Path 3) Tributary aspect → Drainage area → Water engineering facilities	Indirect effects	0.010	0.002	0.022
	Direct effects	0.015	− 0.049	0.079
(Path 4) Tributary slope → Drainage area → Water engineering facilities	Indirect effects	− 0.017	− 0.038	− 0.005
	Direct effects	− 0.037	− 0.097	0.029
(Path 5) Drainage area water engineering facilities	Direct effects	− 0.096	− 0.162	− 0.035

Based on the data in Table 5, it can be observed that the absolute values of the factor loadings expressed by the estimates of the latent variables are all greater than 0.5 and significant at the 0.001 level. This result strongly suggests that the interpretation between the latent variables and their corresponding measures is statistically significant, thus supporting the validity of the spatial distribution of water engineering facilities as a latent variable and justifying the factor analysis.

At the level of path analysis, there is no significant correlation between the slope and direction of the main tributaries of the Beijing-Hangzhou Grand Canal and the spatial distribution of water engineering facilities; similarly, there is no significant correlation between the slope and direction of the mainstem and the area of the watersheds where the water engineering facilities are located. Similarly, there is no significant correlation between the slope and direction of the mainstream and the area of the watershed where the water engineering facilities are located. On the other hand, the area of the watershed where the water engineering facilities are located has a significant positive correlation with the slope of the tributaries and a significant negative correlation with the direction of the tributaries.

In order to explore more deeply the actual degree of influence of hydrological terrain-related factors on the spatial distribution of water engineering facilities, combined with the theoretical model constructed in this paper, this study adopted the Bootstrap method for 5000 repetitive samples to test the effect relationship of each influencing factor on the spatial distribution of water engineering facilities. As shown in Table 6, the calculation process set a 95% confidence interval (corresponding to significance at the 0.05 level) and the significance level of the path relationship was analysed. When the 95% confidence interval does not include zero, this proves that the pathway is significantly correlated.

According to the confidence interval analysis of the direct effect, the intervals for path 1 and path 2 do not include 0, indicating that the direct effect for these two paths is significant. The intervals for Path 3 and Path 4 include 0, indicating that the direct effects for these two paths are not significant. The interval for Path 5 does not include 0, indicating that the direct effect is significant. Regarding the confidence intervals for the indirect effects, the intervals for Path 1 and Path 2 include 0, indicating that the indirect effects for these two paths are not significant. The interval for path 3 does not include 0, indicating that its indirect effect is significant. The interval for path 4 does not include 0, also indicating that its indirect effect is significant. Path 5 does not have an indirect effect. The watershed area where the water engineering facility is located plays a fully mediating role in Path 3 and Path 4. Major tributary slope and slope direction acted indirectly on the spatial distribution of water engineering facilities through the size of the watershed area where the water engineering facility is located, where slope direction was positively related to the spatial distribution of water engineering facilities, while slope was negatively related to it.

Discussion

This paper takes the restored natural environment of the Ming and Qing Dynasty Beijing-Hangzhou Grand Canal as the basis and combines with the database of the water engineering facilities of the Beijing-Hangzhou Grand Canal to extract the data related to the hydrological topography. Then after using structural equation modelling to carry out quantitative research on the correlation between the spatial distribution of water engineering facilities and various factors, it is concluded that the influence of the natural environment on the spatial distribution of water engineering facilities is manifested in the following aspects.

Terrain factors

The slope of the main channel is directly negatively correlated with the spatial distribution of water engineering facilities According to the given information, an increase in the slope of the main stream leads to a decrease in the spatial distribution of water engineering facilities by 0.166 standard units, showing a direct inhibitory effect. As a result, the number of hydro-engineering facilities is relatively small and the distribution density is lower in the area with higher dry stream slope. This finding reflects the siting characteristics of the water engineering facilities in the Beijing-Hangzhou Grand Canal, where the spatial distribution of water engineering facilities is relatively small because most of the terrain has a steeper slope and mainly relies on the potential energy of the water to maintain the smooth flow of the river. The construction of water engineering facilities is to adjust the kinetic energy of the river to meet the needs of the canal function in the region.

The aspect of the slope of the main channel is directly negatively correlated with the spatial distribution of water engineering facilities The influence of the slope direction of the main stream on the spatial distribution of water engineering facilities is manifested in the fact that the spatial distribution of water engineering facilities decreases in density by 0.112 standard units whenever the slope direction increases by one standard unit. This phenomenon arises mainly from the process of change between the topographic adret (sunny) and ubac (shady) slopes (according to the geographic location of China, the values of slope direction from 0 to 180°show Adret, and the values of slope direction from 180 to 360°show Ubac). In the region of the main stream, if the value of slope direction is large, the distribution density of water engineering facilities will be relatively small. Therefore, in the mainstem region of the Beijing-Hangzhou Grand Canal, builders usually choose the adret (sunny) slope as the construction sites of hydroelectric facilities.

In contrast, the degree of influence of the slope of the mainstream on the spatial distribution of water engineering facilities is greater. After research and analysis, this paper concludes that ancient Chinese people would take the slope of the mainstream of the Beijing-Hangzhou Grand Canal as an important consideration for site selection when constructing water engineering facilities.

Hydrological factors

The basin area is directly negatively correlated with the spatial distribution of water engineering facilities The distribution density of water engineering facilities is negatively correlated with the watershed area in which they are located, i.e., for every unit increase in watershed area, the spatial distribution density of water engineering facilities decreases by 0.096 units. This indicates that the wider the watershed area, the lower the distribution density of water engineering facilities in the region, and the number of required construction is also reduced accordingly. In the Beijing-Hangzhou Grand Canal section, if the watershed area is large, then it can be inferred that the terrain in the area is relatively flat, and it is easy to form a large catchment area, so there is no need to build a large number of water engineering facilities to improve the condition of the river.

The slope of the tributaries is indirectly negatively correlated with the spatial distribution of water engineering facilities After a detailed study in this paper, it is found that there is no significant correlation between the slopes of the tributaries of the Beijing-Hangzhou Grand Canal and the spatial distribution of the water engineering facilities. However, the slope and direction of tributaries indirectly affect the spatial distribution of water engineering facilities through the watershed area where the facilities are located. Specifically, tributary slope affects the watershed area by influencing the volume and level of water in the river. Meanwhile, this paper found that the indirect effect of tributary slope on the spatial distribution of water engineering facilities is 0.017 standard units, and this effect is not significant. In addition, the results of this study show that there is a significant positive correlation between the tributary slope and the watershed area where the water engineering facilities are located. This is because areas with high tributary slopes tend to have faster river flow rates and are able to provide a greater volume of water to the mainstem river in the same amount of time, which in turn increases the water level. This phenomenon increases the watershed area to some extent. In summary, the results of this study show that areas with high tributary slope can meet the canal navigation needs under natural hydrological conditions.

The aspect of the tributaries is indirectly positively correlated with the spatial distribution of water engineering facilities According to the results of the study, the slope direction of the main tributaries of the Beijing-Hangzhou Grand Canal has a certain indirect effect on the spatial distribution of water engineering facilities, and the indirect effect of the promotion effect is 0.010 standard units. The mechanism of this effect lies in the fact that the direction of the tributary slopes affects the size of the basin in which they are located, which in turn affects the distribution of water engineering facilities. Specifically, there is a significant negative correlation between tributary slope orientation and the size of the watershed in which the water engineering facilities are located, i.e., the larger the value of tributary slope orientation, the smaller the size of the watershed in which the water engineering facilities are located. Therefore, if the topography of the tributary is negatively sloping and the watershed area is small, more water engineering facilities will need to be constructed at the site of the hydraulic facility in order to improve the channel and meet the needs of navigation. Comparing the effect values of tributary slope and direction (0.017 > 0.010), it can be seen that tributary slope affects the spatial distribution of water engineering facilities to a greater extent through the factor of watershed area at the location of water engineering facilities.

Conclusion

The choice of the location of water engineering facilities along the Beijing-Hangzhou Grand Canal is the result of the joint action of the natural and social environment. The shortcoming of this paper is that it does not involve the study of social influencing factors, other members of the team are collecting research data related to social factors, and will analyse the evolution of the spatial distribution characteristics of the water engineering facilities in the context of different eras from a variety of dimensions, such as political, economic, cultural and so on. In this paper, the influence of natural factors on the spatial distribution of water engineering facilities is studied as an independent topic, and these data and conclusions can be used to support subsequent research.

With the help of quantitative analysis, this study expresses the influence of various natural factors on the spatial distribution of water engineering facilities in the Beijing-Hangzhou Grand Canal through specific data. Through the construction of structural equation model, an effective comparative analysis is achieved, which reveals the inherent laws and characteristics of the spatial distribution of water engineering facilities in a more scientific and reasonable way. On this basis, one can establish a quantitative assessment model that fully reflects the value of the hydro-engineering heritage of the Beijing-Hangzhou Grand Canal and put forward a digital protection method specifically for the heritage of hydro-engineering facilities. Meanwhile, targeted development and utilisation strategies and promotion methods can also be formulated.

This research work also succeeded in achieving a comprehensive integration of the heritage of water engineering facilities along the Beijing-Hangzhou Grand Canal, providing important data support for the construction of cultural heritage corridors. The spatial distribution characteristics of the water engineering facilities derived from the study can be applied to the determination of heritage locations in most areas. That is, the greater the slope of the main canal channel, the more difficult it is to find water engineering facilities sites. It is easier to find water engineering facilities sites on the adret (sunny) slope of the main channel (slope direction values from 0° to 180° in the northern hemisphere). It is not easy to find water engineering facilities sites in areas with large watersheds and tributary slopes with large slopes. water engineering facilities sites are more likely to be found in areas where the topography of the canal tributaries is ubac (shady) slope (slope direction values from 180 to 360°in the Northern Hemisphere) or where the tributary slopes are ubac (shady) slope and the catchment area is small. By combining UAV(Unmanned Aerial Vehicle) information collection technology with detailed data analysis, this study obtained detailed descriptions of important information about the current status and geographical location of the remains. This information is extremely important and realistic for verifying the accuracy of historical data.

In summary, this research work injects new theoretical content into the systematic research framework of the Beijing-Hangzhou Grand Canal. It not only promotes the integration and development of canal protection from point to line but also provides constructive advice on the rational layout of the canal's cultural heritage space through detailed data and in-depth analyses. These efforts not only help to enhance the overall value of the canal's cultural heritage resources but also provide strong support for the diversified needs of social development. At the same time, they are also of positive significance in promoting a better understanding and appreciation of canal culture among the public.

Abbreviations

DEM	Digital elevation model
CMIN	Chi-square
GFI	Goodness-of-fit index
CMIN/DF	Minimum chi-square/degree of freedom
RMSEA	Root mean square error of approximation
NFI	Normed fit index
CFI	Comparative fit index
PNFI	Parsimonious normed fit index
AIC	Akaike information criterion
e	Error residual
MI	Modification indices
S.E.	Standard error
P value	Probability value

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WC was mainly responsible for the collection and arrangement of the database and translated the final manuscript. ZYW, LL, and YYH wrote the main manuscript text and were responsible for drawing pictures and table. Other members participated in the review of article content.

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Declarations

Competing interests

The authors declare no competing interests.

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