Spatio-temporal evolution of water engineering facilities and social influences on the Grand Canal during the Ming and Qing dynasties

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Abstract

This research explores the spatial distribution patterns of water engineering facilities along the Grand Canal during the Ming and Qing dynasties. It employs the entropy method to assess the social development status of prefectures during these periods and uses the Tobit model to examine the primary indicators influencing the distribution of water engineering facilities. The results show that the spatial distribution pattern of water engineering facilities was characterized by aggregation during the Ming and Qing dynasties. In contrast, the Qing dynasty's distribution was more dispersed, with a shift in the construction focus of water engineering facilities towards the south. The spatial distribution pattern of water engineering facilities in the Ming Dynasty centered around the hotspot areas of Shuntian Prefecture, Yanzhou Prefecture, and Yangzhou Prefecture. During continuous improvements, these facilities exhibited a multi-point-regional aggregation phenomenon.The influence of commercial development indicator on the spatial distribution of water engineering facilities is positively correlated in both the Ming and Qing dynasties. However, the impacts of the indicator on different types of water engineering facilities vary between the two dynasties. During the Ming Dynasty, the indicators of transportation accessibility and cultural prosperity facilitated the construction of regional water engineering facilities, whereas in the Qing Dynasty, they significantly influenced several types of water engineering facilities. During the Ming and Qing Dynasties, neither the agricultural development indicator nor the population size indicator significantly affected the distribution of water engineering facilities. However, there was a negative correlation between the population size indicator and the distribution of water distribution facilities in the Ming Dynasty. This study enhances the importance of environmental protection in historical societies and provides a valuable reference for other international studies of linear cultural and material heritage.

Keywords The Grand Canal, Water engineering facilities, Spatial and temporal evolution, Influencing factors, Tobit modeling

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Cheng *et al. Heritage Science*   (2024) 12:262

Page 2 of 18

Introduction

The Grand Canal is the longest known man-made canal, and during the Ming Dynasty, the Tonghui River was overhauled and the Huitong River was reopened. It is 1794 kms long and connects the political and economic centers of China [1]. Due to the extensive area covered by the canal, the construction of water engineering facilities is crucial for addressing issues such as canal navigation, agricultural production, and flood control [2]. Additionally, the Grand Canal has significant impacts on the economic development and cultural exchange of the prefectures along its route. In the early 20th century, Chinese scholars began studying canals, focusing on canal changes, management organizations, and historical development. Significant works include *The Canals of China* [3] and *Selected Historical Materials of Chinese Canals* [4]. Concurrently, international scholars also produced valuable research on the construction and management of Chinese canals and the history of water conservancy development. Since the 1980 s, the Chinese canal water conservancy project has garnered attention, with Chinese scholars making significant contributions to the study of the development history of water conservancy projects [5, 6], from the overall construction of water engineering facilities to examining individual hydraulic structures. As part of national infrastructure, research on historical infrastructure construction, spatial distribution [7], and its relationship with the regime includes waterworks facilities [8]. Currently, research on water engineering facilities focuses primarily on documentation and local studies, with less emphasis on the relationship between water engineering facilities and social elements such as politics, economy, culture, and folklore. International scholars have conducted extensive research on canals, encompassing studies on the channel structures and facility construction of the Canal du Midi in France [9, 10], the structural system, maintenance, and restoration of the Pontcysyllte Aqueduct and Canal ports in the UK [11, 12], as well as the operation and management of the Rideau Canal water engineering heritage in Canada [13, 14]. In recent years, researchers from other countries have increasingly focused on water conservancy technology and the preservation of water heritage. These studies intersect with disciplines such as archaeology [15], agronomy, biochemistry [16], architectural technology, and tourism development [17], contributing to the research on water engineering facilities. Regarding research methods, spatial distribution and spatial-temporal evolution analysis employ spatial autocorrelation [18], kernel density estimation [19], gini coefficient, and other techniques, whereas the investigation into influencing factors utilizes pearson regression, ordinary least squares [20], tobit regression [21], and similar methods. furthermore, There are studies that has employed the Historical GIS (HGIS) method and Spatial Data Infrastructure (SDI) principles to analyze the spatial development of historical infrastructure [22, 23]. This paper delves into the spatial distribution and influencing factors of water engineering facilities along the Beijing-Hangzhou Grand Canal, building upon existing research. Both natural and social environments influence the siting of water engineering facilities along the Grand Canal. In the process of collecting data and organizing relevant ancient literature, we chose to study the impact of natural factors on the spatial distribution of water engineering facilities as a separate topic. The research team selected two categories of factors, hydrology and topography, and applied structural equation modeling to reveal the correlation between the spatial distribution of water engineering facilities along the Grand Canal and the natural environment [24]. Therefore, this paper will not delve into these factors in detail but will mainly focus on the influence of social factors on the spatial distribution of water engineering facilities, including political, economic, and cultural aspects.

Research materials

Research scope

The scope of this study covers the prefecture areas through which the Grand Canal and its tributaries flowed during the Ming and Qing dynasties. Based on meticulous organization of ancient maps, canal atlases, and other relevant literature from *Historical Maps of China* [25] the research team utilized ArcGIS Pro 3.0.0 software to redraw the network map of the Grand Canal. The scope of the study during the Ming and Qing dynasties is illustrated in Fig. 1.

Data on water engineering facilities

This study collected water engineering facility data through field surveys and compilation of historical documents. By compiling literature, we obtained detailed information on water engineering facilities of the Grand Canal, including their locations, administrative affiliations, purposes, construction times, and forms. Water engineering facilities were classified into seven categories based on their purposes: water storage facilities, water distribution facilities facilities, overflow facilities, water retaining facilities, water control facilities, riverworks facilities, and annexed facilities. The specific classification and functions are shown in Table 1.

Cheng *et al. Heritage Science*   (2024) 12:262

Page 3 of 18

The study reveals 779 water engineering facilities in use and constructed during the Ming Dynasty, and 1168 water engineering facilities in use and constructed during the Qing Dynasty. Simultaneously, the coordinates of the water engineering facilities were acquired using the map coordinate extraction function. The research team conducted surveys of 147 existing water engineering facility relics, meticulously documenting their coordinates, three-dimensional models, preservation status, and surrounding environment. Well-preserved water engineering facility nodes were selected, and their drone-captured point cloud models are compiled in Fig. 2.

Social development indicators system
Selection of social influence factors
Social development has multifaceted and profound impacts on water engineering facilities, including political factors, levels of commercial and agricultural development, population size and behavior, transportation convenience, local culture, and values. National policies significantly influenced the opening of the Great Canal and the construction of its water engineering projects.


Ming dynasty   Qing dynasty
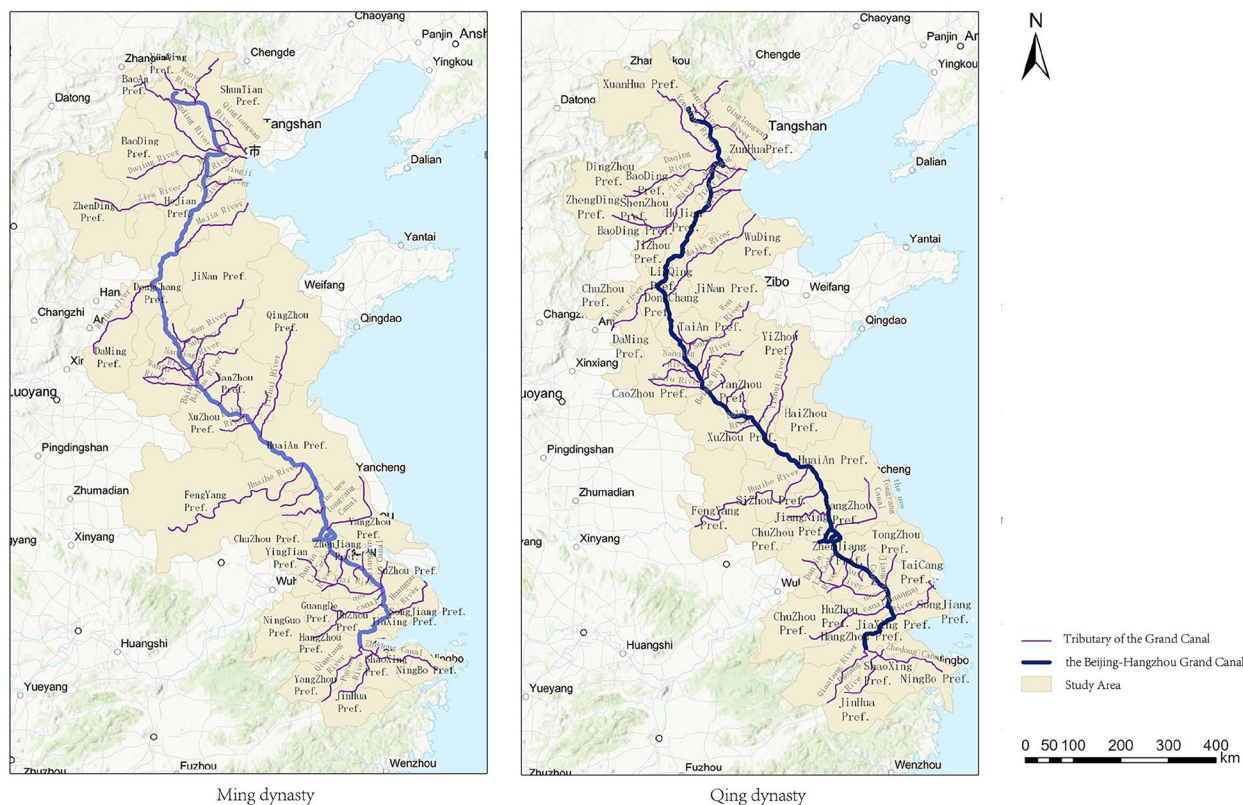
Fig. 1 Scope of research map of Ming and Qing dynasties

Table 1 Classification of water engineering facilities

Classification	Representation facilities	Functions
Water storage facilities	Ponds, reservoirs, etc.	As canal water storage to ensure sufficient water during dry periods
Water distribution facilities	Channels, culverts, etc.	Transfer of water from other rivers or lakes to the canal to replenish the water supply
Overflow facilities	Overflow weirs, rolling dams, etc.	Raise the water level to divert excess water to meet the needs of ship navigation
Water retaining facilities	Dikes, dams, etc.	Water retention and flood control to protect the riverbank from the impact of water flow
Water control facilities	Gate, etc.	Flood and tidal barriers to raise water levels
Riverworks facilities	Slough improvement facilities , etc.	Riparian protection and emergency response
Annexed facilities	Wharves, relay stations, bridges, etc.	It has a wide range of uses

Cheng *et al. Heritage Science*   (2024) 12:262

Page 4 of 18
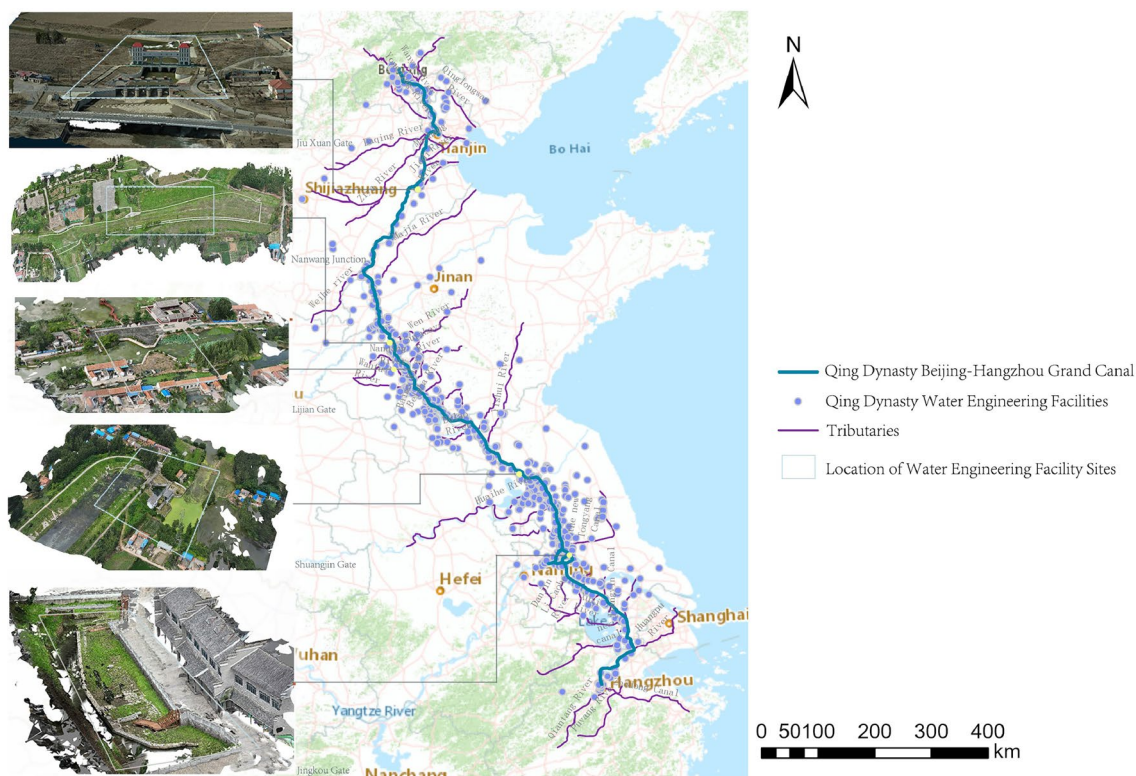
Fig. 2 Aerial drone point cloud model summary map

For instance, in 1405, the Tonghui River was constructed to address the need for construction materials and food transport during the reconstruction of Beijing [26]. In May 1407, the government repaired the dams and canals in the Beijing section to address water supply issues. Cessation of maritime transportation in 1415, reliance on inland waterways, increased reliance on inland waterways for food security in the north [27]. Additionally, the government was responsible for constructing water engineering facilities and established specialized management agencies. The Central Water Conservancy Bureau was responsible for managing national water engineering projects and the construction of canal waterways. By establishing rules and procedures, local officials were actively encouraged to participate in the construction of water engineering facilities. It's evident that political factors have a direct impact on the construction of water engineering facilities, without the need for complex quantitative research.Therefore, this paper will focus on further quantitative research on economic and cultural aspects in the social domain.

Economic and cultural development involves the entire urban social system, with significant changes occurring in Ming and Qing social development and government policies.This study aims to establish a more scientific measure for assessing the changes in the historical development of Ming and Qing societies. It constructs measurement indicators from five dimensions to evaluate social development during the Ming and Qing dynasties, as presented in Table 2.

Regarding indicator of commercial development, local commercial taxation in the Ming dynasty became a significant source of national revenue, with goods flowing north and south along the canal, subject to customs duties. Therefore, the number of chaoguan and local commercial taxes were selected as indicators to measure commercial development in various regions of the Ming dynasty. Taxation in the Qing dynasty mainly comprised land tax, salt tax, customs duties, and miscellaneous taxes [28]. Among these, the salt tax was a unified levy imposed on salt merchants. the chaoguan collected tariffs on goods in transit [29]. Therefore, this study selected the salt tax and chaoguan as factors reflecting the scale of local commercial development in the Qing dynasty. As for indicator of agricultural development, the quantity of fertile land and the collection of land tax in each prefecture during the Ming and Qing dynasties served as factors to measure the scale of agricultural development in the respective regions [30]. Concerning population size indicator, the xiangli system functioned as a grassroots

Cheng *et al. Heritage Science*　　(2024) 12:262

Page 5 of 18

Table 2 Ming dynasty Tobit model regression results

Dynasty	Indicators	Representation	Impact factor	Factorization and calculation	Standard deviation	Average
Ming	Commercial developmen	Business Scale	Tax on trade	Commercial tax collected by each prefecture	711107.73	397524.35
		Tax authority	Chaoguan	Number of chaoguan constructed in the capital	0.41	0.2
	Agricultural development	Agricultural scale	Fertile land	Fields used for farming	108494.41	70304.93
			Land tax	The sum of the land tax levied by each prefecture	486504.33	350973.33
	Population size indicator	Size of population	Li	Number of li in the village system	707.56	844.02
	Transportation convenience	Transportation	Jidi Pu	Number of jidi pu constructed in prefecture	77.23	95.23
			Relay station	Number of relay station constructed in prefecture	5.01	5.1
	Cultural prosperity	Mainstream culture	Ciren	Number of surviving ciren with 10 or more poems	15.02	8.77
		Folk culture	Inscription on stone tablet	The First List of Protected Monuments and Inscriptions in China	2.196	0.93
			Intangible cultural heritage	List of national and provincial non-heritages in China	5.814	3.3
Qing	Commercial developmen	Business Scale	Salt tax	Salt tax paid by each prefecture	41384.37	43372.20
		Tax authority	Chaoguan	Number of chaoguan constructed in the capital	0.70	0.37
	Agricultural development	Agricultural scale	Fertile land	Fields used for farming	31696.317	51810.42
				The sum of the land tax and salt tax levied by each prefecture	165517.13	240803.96
	Population size indicator	Size of population	Population	Population per prefecture	1400297.52	1289169.69
	Transportation convenience	Transportation	Jidi Pu	Number of jidi pu constructed in prefecture	31.86	64.95
				Number of relay station constructed in prefecture	5.99	7.83
	Cultural prosperity	Mainstream culture	Jinshi	Number of jinshi in each prefecture	240.75	229
		Folk culture	Inscription on stone tablet	The First List of Protected Monuments and Inscriptions in China	3.02	0.85
			Intangible cultural heritage	List of national and provincial non-heritages in China	89.47	50.98

Interpretation of impact factors see Appendix A for an explanation

management system in the Ming dynasty [31]. Thus, the number of xiangli could directly reflect the local population size. In the Qing dynasty, the local population count was chosen instead. Regarding indicator of transportation convenience, the postal relay system was a significant communication and transportation system in ancient China. In both the Ming and Qing dynasties, this system primarily consisted of relay stations and jidi pu. This study collected data on these factors to reflect the

level of transportation convenience in various regions. In terms of indicator of cultural prosperity, the level of cultural prosperity in various regions is reflected in various aspects. Different natural and social environments have shaped unique regional cultures, which have continuously developed into current material and non-material cultural heritage. These factor reflects the characteristics of regional folk culture. The number of poets in the Ming dynasty and the number of successful candidates in the

Cheng *et al. Heritage Science*   (2024) 12:262

Page 6 of 18

Qing dynasty's imperial examination in each prefecture are considered important indicators for measuring the level of cultural development in the Ming dynasty. They can reflect the development of mainstream culture in various regions.

Data sources

In the Ming Dynasty, the data on chaoguan, land tax, fertile land and population factors are mainly from the *Code of Great Ming Dynasty*, while the data on commercial taxes, Relay stations and jidi pu are from the relevant prefectural records. In the Qing Dynasty, the data on land tax, fertile land and population factors were taken from the *Qing Historical Manuscripts*, while the data on the chaoguan, relay stations and jidi pu were collected from the *Qin Ding Da Qing Huidian*. In addition, the data on salt tax comes from the relevant prefectural records of the Qing Dynasty. As for the cultural prosperity indicator, the data on intangible cultural heritage come from the China Intangible Cultural Heritage Website (https://www.ihchina.cn/) and the batches of cultural relics protection units announced by the State Administration of Cultural Heritage. The data of inscriptions come from the first batch of inscriptions and the list of cultural relics protection units. The number of words in the Ming Dynasty comes from the *All Ming Poetry* of the Ming Dynasty, and the number of Jinshi in the Qing Dynasty comes from the *Qing Dynasty Jinshi Inscription List*. (For more information, please see the Appendix B).

Methodology for the construction of the indicators

In this paper, the entropy method is used to measure the five comprehensive measurement indicators. The entropy method can eliminate the bias caused by subjective factors to determine the weights of the indicators and reduce the influence of data extremes, and can effectively deal with the superposition of information between the indicators [32]. Due to the obvious differences in the scale between the indicators, the standardization of the indicators is carried out using the method of standardization of extreme deviation [33]. The formula is as follows:

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)}. \tag{1}$$

The information entropy e_j is calculated as:

$$e_j = \frac{-1}{\ln n} \sum_{j=1}^{m} P_{ij} \ln P_{ij}, \tag{2}$$

P_{ij} is the ratio of the value of indicator j of the ith house to the sum of all houses; n is the number of houses and m is the number of indicators.

The indicator weight value w_j is calculated by the formula:

$$w_j = \frac{1 - e_j}{n - \sum_{j=1}^{m} e_j}. \tag{3}$$

Finally, a linear weighting method was used to calculate the indicators for each of the ith governments:

$$s_i = \sum_{j=1}^{m} w_j x_{ij} \, i = 1, \ldots, n. \tag{4}$$

Research methods

Global spatial autocorrelation, center of gravity analysis, hotspot analysis, kernel density analysis, tobit regression and other analytical methods are used to explore the distribution pattern of the water engineering facilities in the Beijing-Hangzhou Grand Canal and its influence mechanism.

Global spatial autocorrelation

In this study, the global spatial autocorrelation method is applied to describe the overall distribution of the number of water engineering facilities in different regions [34]. The global Moran's I indicates whether there is an aggregation property of water engineering facilities in space [35].

$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n} (x_i - \bar{x})^2}. \tag{5}$$

$$S_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}. \tag{6}$$

In Eq. n represents the number of water engineering facilities, S_0 is the aggregation of the spatial weights belonging to it. x represents each indicator used to quantify the spatial structure of the water engineering facilities, x_i and x_j represent the attribute values of objects i and j, and W_{ij} is the value of the spatial weights.

Center of gravity analysis

The center of gravity model is an effective method to reflect the spatial evolution of the object [36]. The change characteristics of the calculation results can reflect the spatial and temporal evolution characteristics of water engineering facilities, and its calculation formula is as follows.

$$X_t = \frac{\sum_{i=1}^{n} (M_i \times X_i)}{\sum_{i=1}^{n} M_i}, \tag{7}$$

$$Y_t = \frac{\sum_{i=1}^{n} (M_i \times Y_i)}{\sum_{i=1}^{n} M_i}, \tag{8}$$

Cheng *et al. Heritage Science*   (2024) 12:262

Page 7 of 18

where: (X_t, Y_t) is the coordinates of the center of gravity of the distribution of water engineering facilities in the study area during the Ming or Qing Dynasties; (X_i, Y_i) is the geometric center of the *i*th evaluation unit.

Hotspot analysis

In the study, the hotspot analysis method was used to determine the spatial distribution characteristics of the number of different House water engineering facilities in the study area [37]. The specific calculation formula is as follows:

$$G_i^* = \frac{\sum_{j=1}^{n} W_{ij} x_j}{\sum_{i=1}^{n} x_i}. \tag{9}$$

In Eq. G_i^* denotes the spatial autocorrelation statistic of water engineering facilities, x_j represents the attribute value of feature j, W_{ij} is the spatial weight between features i and j, and n is the total number of features.

Kernel density analysis

Kernel density analysis is primarily used to calculate surface density indicators, estimate data aggregation from sample data, and analyze changes in element density via the distance decay function. This method explores hotspot distribution and change characteristics in spatial regions. In this study, kernel density analysis will examine the spatial distribution density of hydraulic facilities. The analysis was performed using the Density tool in ArcGIS ToolBox. The estimation of $g(x)$ at a point x is calculated as:

$$g(x) = \frac{1}{nh} \sum_{i=1}^{n} k\left(\frac{x - X_i}{h}\right), \tag{10}$$

where: k is the kernel function; $h>0$ is the bandwidth; $(x-X_i)$ denotes the distance from the valuation point x to the event X_i.

Tobit regression

Since the social indicators are between 0 and 1, which are restricted dependent variables, the use of ordinary least squares for parameter estimation will lead to biased and inconsistent parameter estimates [38], and the choice of the Tobit model can effectively solve the regression problem of the restricted dependent variables [39]. The formula is:

$$y_{it}^* = \alpha + \beta x_{it} + u_i + \varepsilon_{it}, y_{it}^* > 0, \tag{11}$$

$$0, y_{it}^* \leq 0, \tag{12}$$

where y_{it}^* is the restricted dependent variable; x_{it} is the independent variable; α is the intercept term; β is the

value of the regression parameter; u_i is the individual effect; and ε_{it} is the random error term, which is independent and follows a normal distribution.

Results and discussion

Characteristics of spatial and temporal distribution

Evolution of the overall spatial distribution

The global spatial autocorrelation calculations of the number of water engineering facilities in each of the Ming and Qing dynasty prefectures were carried out by the formula (5) and (6), and the results are detailed in Table 3 below.

Spatial autocorrelation analysis of water engineering facilities in the Ming and Qing Dynasties revealed that Moran's I values were positive, and Z-scores passed the test at P<0.05. This indicates significant spatial clustering characteristics and autocorrelation of water engineering facilities in both dynasties. The Moran's I value was 0.23424 in the Ming Dynasty and 0.200471 in the Qing Dynasty, indicating a decreasing trend, suggesting a discrete trend in the continuous improvement of water engineering facilities.

To further explore the evolution of the overall construction focus of water engineering facility spatial distribution patterns, combined with the formula (7) and (8), the centroid transfer results of water engineering facilities are shown in Fig. 3. By comparing the results, it can be observed that the spatial distribution of the center of gravity of water engineering facilities in the Ming and Qing Dynasties exhibits an overall southward movement trend, with a transfer distance of 10287 ms. This indicates rapid growth in the construction of water engineering facilities in the southern region.

Evolution of spatial distribution patterns

Hotspot analysis of the spatial distribution of Grand Canal water engineering facilities is shown in Fig. 4. In the Ming Dynasty, the hotspot areas of water engineering facilities were mainly distributed in Shuntian Prefecture, Yanzhou Prefecture, and Yangzhou Prefecture. Among them, Yanzhou Prefecture and Yangzhou Prefecture were hotspots with a confidence level of 99%. Yangzhou Prefecture had 175 water engineering facilities, accounting for 22.5% of all water engineering facilities. The next was the aggregation area of Yanzhou Prefecture, with

Table 3 Summary of global spatial autocorrelation results for the Ming and Qing dynasties

Dynasty	Moran's I	Variance	z-score	z-score
Ming	0.234244	0.016945	3.400933	0.038983
Qing	0.200471	0.011505	2.102041	0.035550

Cheng *et al. Heritage Science*   (2024) 12:262

Page 8 of 18
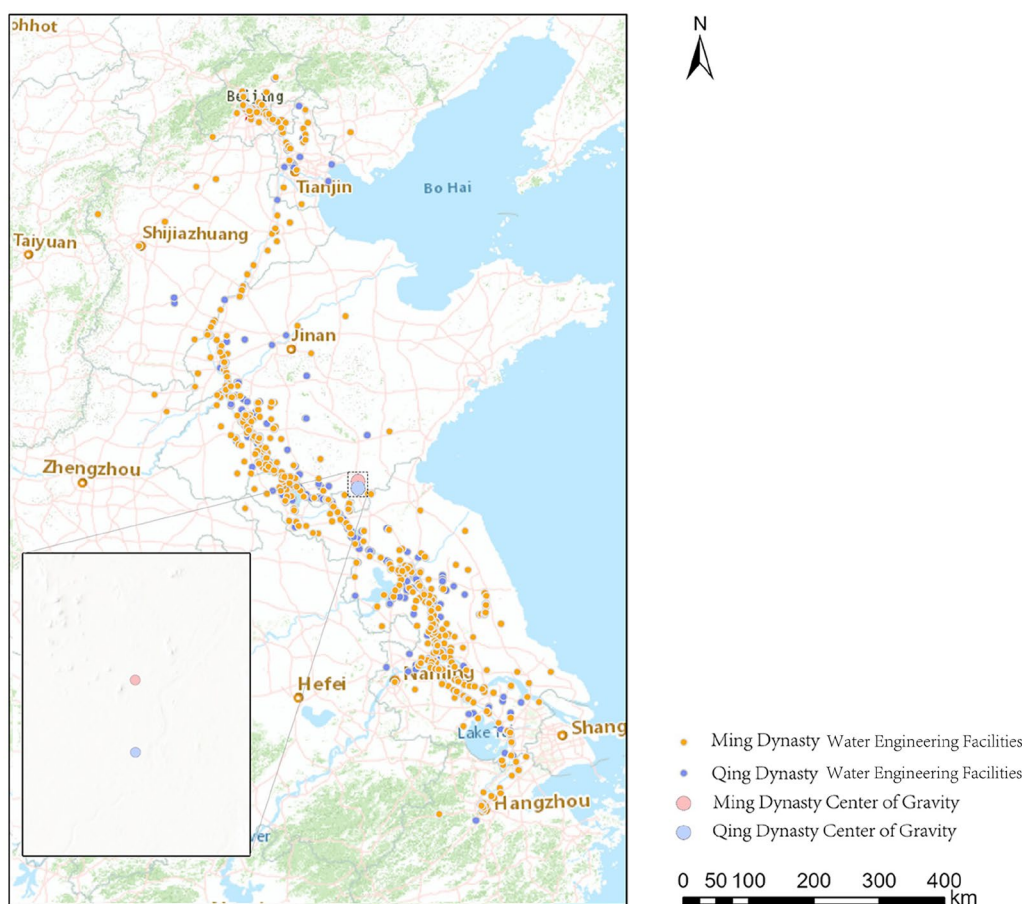
Fig. 3 Center of gravity map of water engineering facilities in Ming and Qing dynasties
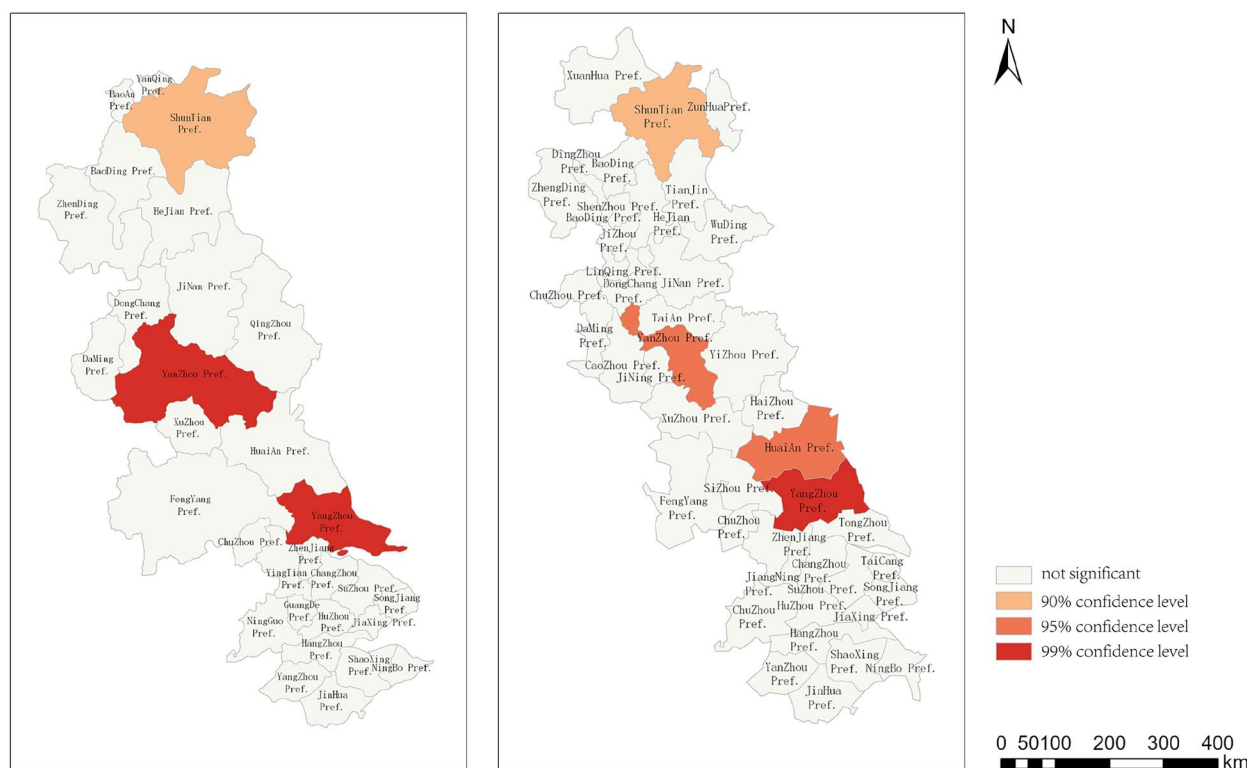
173 water engineering facilities, accounting for 22.2% of all water engineering facilities; in addition, there was a clustering phenomenon in the vicinity of Shuntian Prefecture, with water engineering facilities accounting for 14.2% of all water engineering facilities. In the Qing Dynasty, the hotspot areas of Grand Canal water engineering facilities were in Shuntian Prefecture, Yanzhou Prefecture, Huai'an Prefecture, and Yangzhou Prefecture. Among them, Yangzhou Prefecture was a hotspot area with a confidence level of 99%, with 234 water engineering facilities, accounting for 20.03% of all water engineering facilities. Huai'an Prefecture and Yanzhou Prefecture were hotspot areas with a confidence level of 95%, accounting for 13.27% and 12.67% of all water engineering facilities, respectively.

From the perspective of water engineering facility classification, the distribution of various types of water engineering facilities in each prefecture is shown in Fig. 5. In the Ming Dynasty, Huai'an Prefecture had the largest proportion of water retaining facilities, accounting for 23.91%. With continuous construction, the proportion increased in the Qing Dynasty, with water

retaining facilities in Huai'an Prefecture accounting for 24.25%. Yangzhou Prefecture had the largest proportion of water storage facilities, water control facilities, and overflow facilities, accounting for 36.36%, 28.09%, and 36.98%, respectively. In the Qing Dynasty, the proportion decreased in Yangzhou Prefecture, with water storage facilities at 34.78%, water control facilities at 22.15%, and overflow facilities at 34.30%. Yanzhou Prefecture had the largest proportion of water storage facilities and water distribution facilities, accounting for 36.36% and 26.92%, during the Ming dynasty; in the Qing Dynasty, Shuntian Prefecture has the largest proportion at 21.16% of annexed facilities, and Yanzhou Prefecture had the largest proportion of water distribution facilities. This study employed kernel density analysis to analyze the spatial distribution patterns of water engineering facilities along the Grand Canal in the Ming and Qing Dynasties, generating their kernel density distribution maps (Figs. 6, 7).

The results show that in both the Ming and Qing Dynasties, the Grand Canal water engineering facilities formed three overall aggregation areas. In the Ming Dynasty, the aggregation areas of water engineering

Fig. 4 Hotspot map of water engineering facilities in the Ming and Qing dynasties

facilities in Huai'an Prefecture and Yangzhou Prefecture were the most dense and had the largest aggregation area. In the Qing Dynasty, this trend continued to develop based on the Ming Dynasty. Among different types of water engineering facilities, in the Ming Dynasty, overflow facilities formed two aggregation areas, The density of the clustered areas in the central part of the country decreased in the Qing Dynasty. By comparing the kernel density distribution maps of water retaining facilities, water distribution facilities, and water control facilities in the Ming and Qing Dynasties, it can be concluded that water engineering facilities did not concentrate in a single area but exhibited a multi-point aggregation effect during the continuous improvement process. Annexed facilities and water storage facilities in the Qing Dynasty showed varying degrees of density enhancement based on the aggregation characteristics in the Ming Dynasty.

Analysis of influencing indicators
Time-series analysis of social development indicators
Regarding commercial development indicator, because of the greater weight of the influence of banknote customs in the Ming and Qing dynasties, their rapid growth led directly to a yearly increase in indicator. With regard to agricultural development indicator. Figures 8 and 9 demonstrate significant agricultural development, attributed to the government's policy of encouraging land reclamation during the Ming and Qing dynasties. This led to a threefold expansion of China's arable land area compared to the previous generation, along with a 77% increase in grain production [30]. Concerning population size indicator, the population grew significantly during the Ming and Qing dynasties, with particularly noticeable increases in the southern regions. For instance, the population of Suzhou increased from 2.01 million in 1578 to 5.2 million in 1810 [40]. As for transportation convenience indicator, there was a decline in the level of transportation convenience, especially evident in the southern regions. The main arterial relay roads, centered around Beijing and connecting various provinces, were established during the Ming dynasty [41]. However, subsequent developments were disorderly. In the Qing dynasty, limited financial resources for relay stations were concentrated on these main arterial roads, leading to their reorganization and a reduction in the number of relay stations and jidi pu [42]. Concerning indicator of cultural prosperity, the cultural prosperity index increased during the Qing dynasty, particularly evident in the prefectures along the Grand Canal. The Grand Canal not only facilitated commodity transportation but also carried rich spiritual and cultural elements. It facilitated the mutual integration of architectural technology, folk art, folk customs, and

Cheng *et al. Heritage Science*   (2024) 12:262

Page 10 of 18
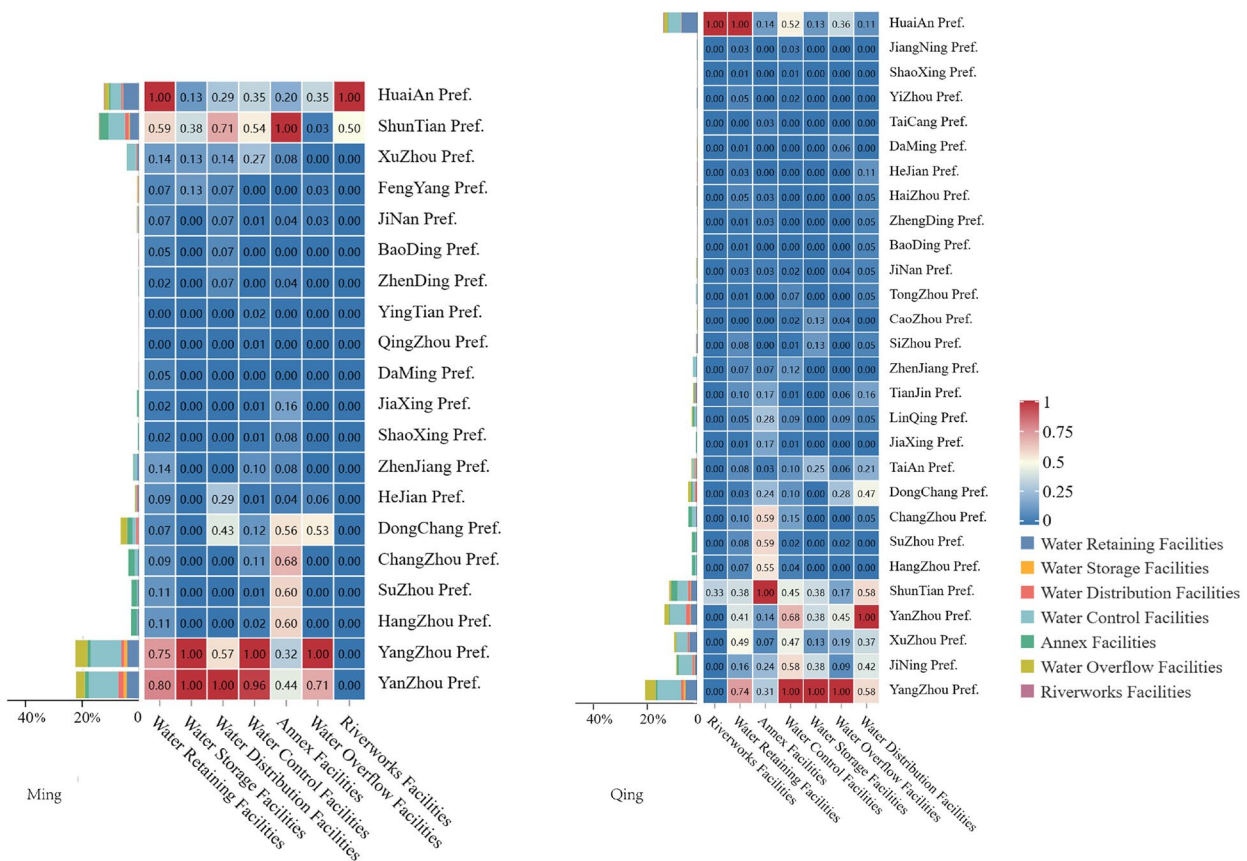
Fig. 5 Distribution and percent age of each type of water engineering facilities in the Prefectures

beliefs along its route [43], forming a unique cultural landscape and style [44].

### Impact effect analysis of social development indicators

The study applied Tobit model to regression analysis of factors affecting spatial distribution of water engineering facilities. Before model estimation, the variables were first tested for multiple covariance, and the results in Table 4 showed that the maximum variance inflation factor (VIF) values were all less than 5 [45], so there was no covariance problem. There aren't many historical records of riverworks facilities, and the limited data from these sites can make it difficult for the model to accurately compute the features and patterns of the data it receives, which lowers the model's accuracy. In addition, the model will calculate data incorrectly and overfit the training set. For this reason, the Tobit regression model does not address the riverworks facilities. The results of the Tobit regression models for the Ming and Qing Dynasties are shown in Tables 5 and 6 below.

The regression coefficient of commercial development indicator in the Ming Dynasty on the water engineering facility model is 0.44 with a p-value of 0.005,

while the regression coefficient of commercial development indicator in the Qing Dynasty is 0.417, also with a p-value less than 0.05. This indicates that the impact of commercial development in both the Ming and Qing Dynasties on the spatial distribution of water engineering facilities is positively correlated. From the perspective of water engineering facility classification, commercial development indicator in the Ming Dynasty have a positive correlation with the spatial distribution of water retaining facilities, water distribution facilities, ancillary facilities, and overflow facilities, while in the Qing Dynasty, there is a positive influence on the spatial distribution of damming facilities. Goods are transported and traded along the canal, resulting in numerous commercial towns. The main distribution centers in these towns require the construction of docks, towpaths, and wharves, among other shipping facilities, to ensure the smooth transportation of goods [46]. By the Qing Dynasty, local gentry gained greater influence, Their construction of numerous water engineering facilities has promoted the development of autonomous civil water management activities. Therefore, commercial development indicator played a
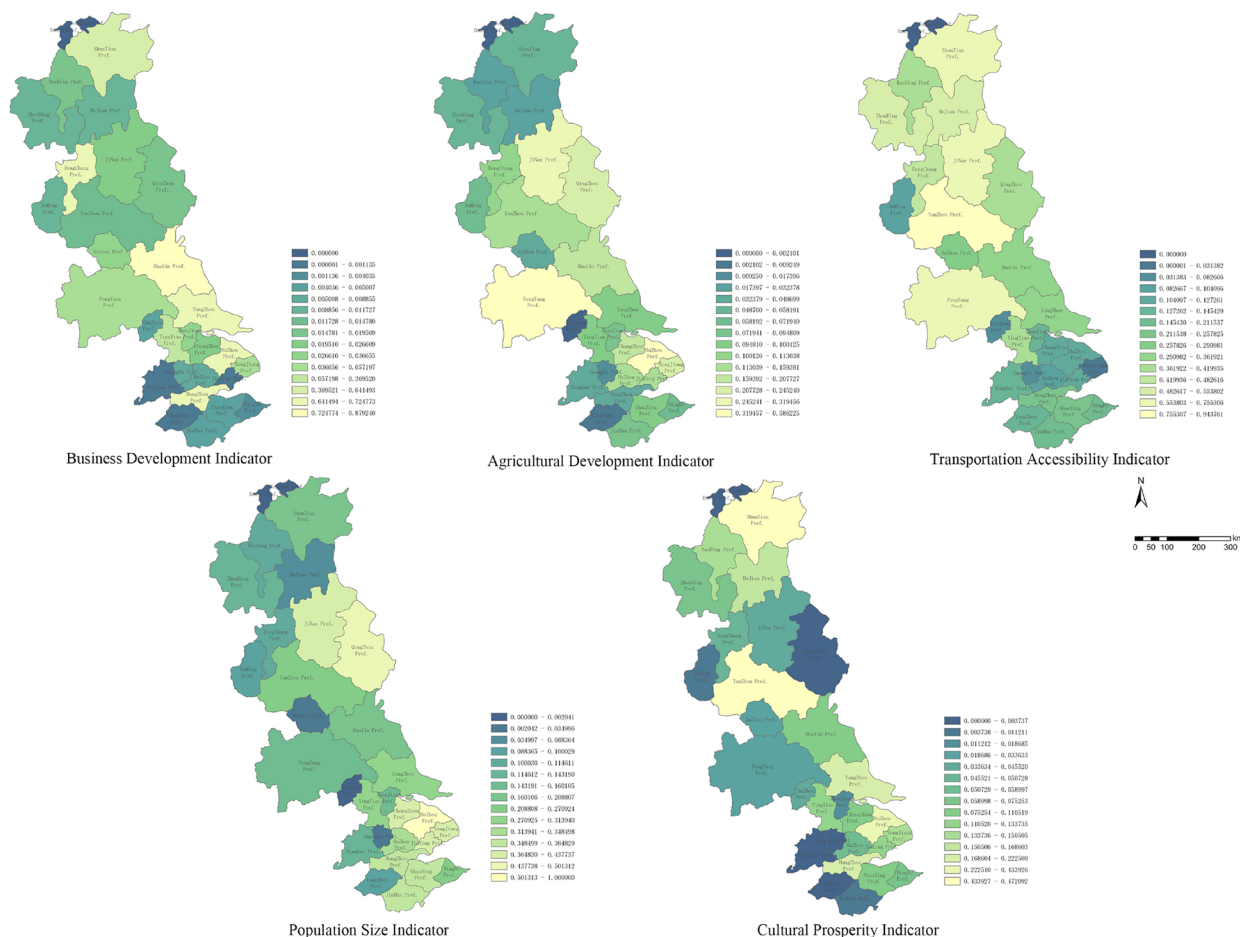
Cheng *et al. Heritage Science*   (2024) 12:262

Page 11 of 18
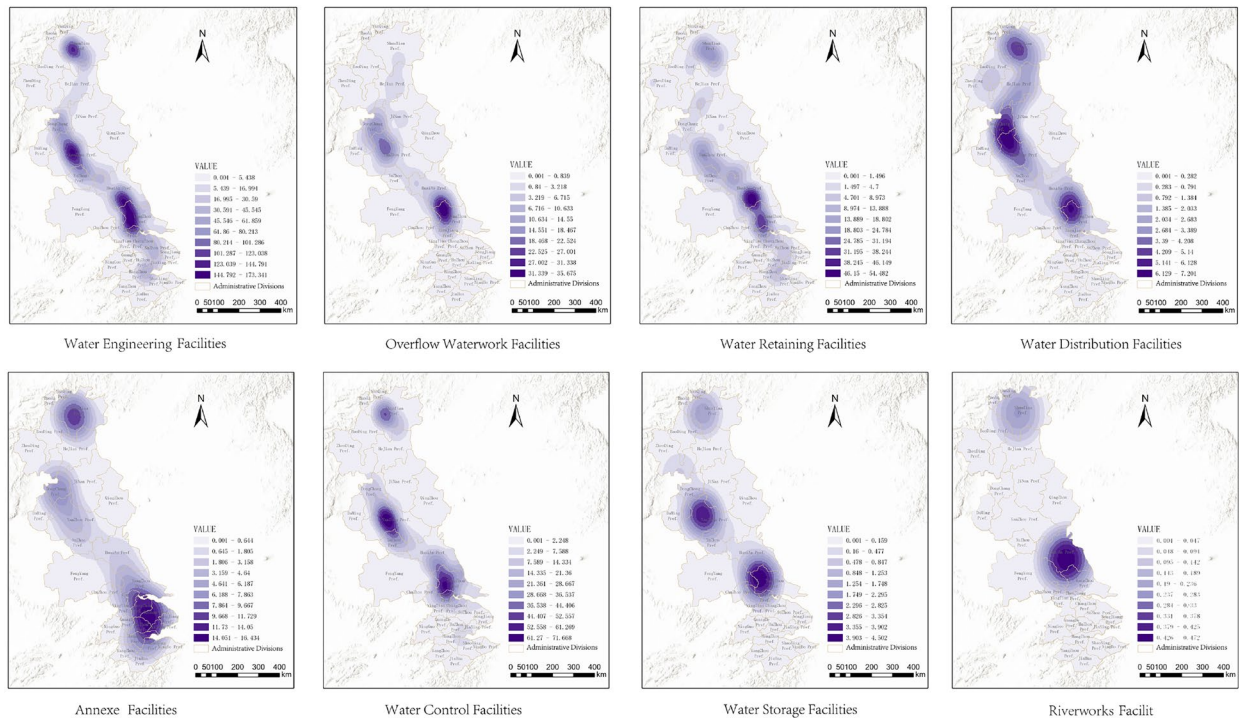
Fig. 6 Kernel density map of different types of wate engineering facilities in the Ming Dynasty

Fig. 7 Kernel density map of different types of water engineering facilities in the Qing Dynasty

Cheng *et al. Heritage Science*   (2024) 12:262

Page 12 of 18
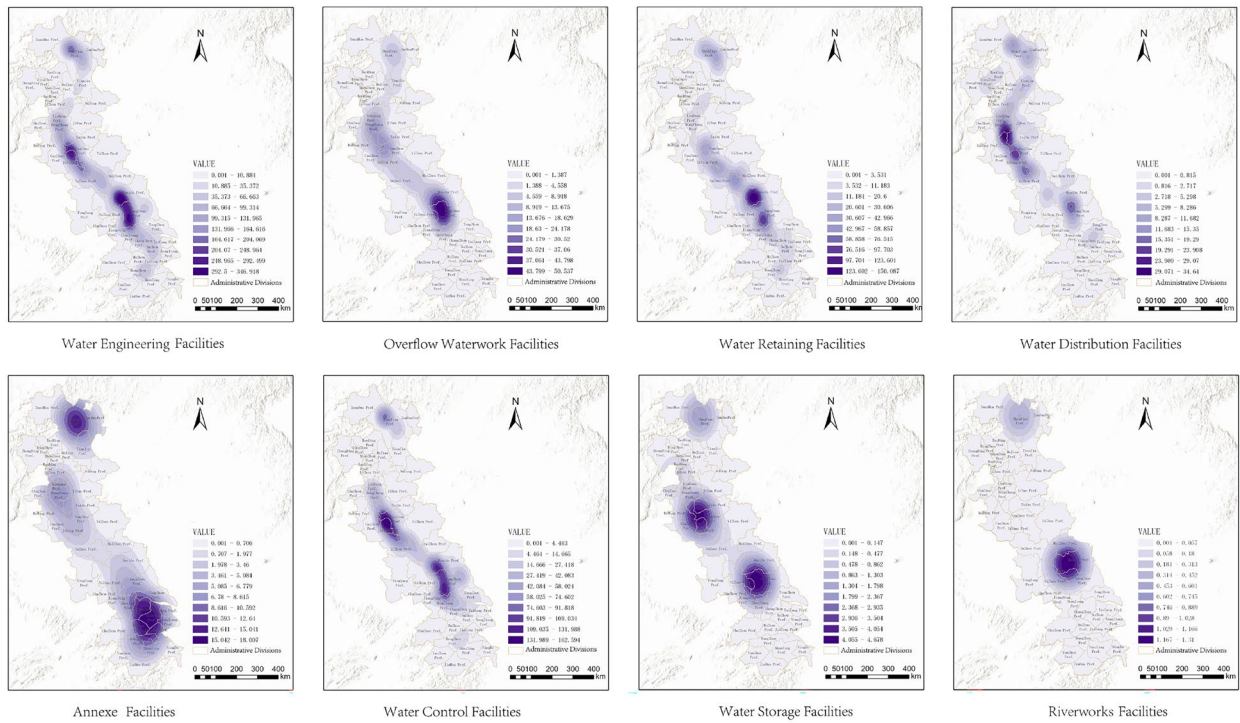
Fig. 8 Spatial and temporal patterns of development of various indicators of Ming society

significant role in promoting the construction of water engineering facilities.

From Tables 5 and 6, it can be observed that the agricultural development indicator of the Ming and Qing Dynasties did not show significant effects on the spatial distribution of water engineering facilities. Thus, it can be seen that the construction of the Grand Canal water conservancy system primarily served the transportation of grain northwards to meet the grain demands of the imperial court, bureaucrats, and the surrounding garrison. Moreover, due to the relative scarcity of water in localized sections of the Shandong Canal, during the Ming and Qing Dynasties, to ensure the water supply for the canal, it was strictly forbidden for people on both banks to divert river water for irrigating rice fields [47]. Therefore, water engineering facilities function to ensure the navigation of the canal, while the influence of arable land and land tax factors in agriculture on its spatial distribution is not significant.

In the area of population size indicator. Population size indicator from the Ming and Qing dynasties did not significantly influence the spatial distribution of water engineering facilities. Analyzing from the perspective of water engineering facility classification, the population size indicator from the Ming dynasty had a negative impact on the spatial distribution of water distribution facilities. Water distribution facilities were constructed to meet the demand for shipping water supply. The construction areas were relatively short of water resources, necessitating stricter protection measures. Historical records state that private citizens were prohibited from stealing or intercepting spring water for irrigation and domestic use. The environment was not conducive to population growth, resulting in smaller population sizes compared to water-rich areas. Overall during both the Ming and Qing dynasties, As water engineering facilities are predominantly planned by state agencies and constructed using mandatory labor from surrounding states and counties, large-scale population movements have

Fig. 9 Spatial and temporal patterns of development of various indicators of Qing society

Table 4 Summary of VIF values for each social indicator in the Ming and Qing Dynasties

Dynasty	Business development indicator	Agricultural development indicator	Population size indicator	Transportation accessibility indicator	Cultural prosperity indicator
Ming	1.335	1.768	2.655	3.205	2.218
Qing	1.634	1.35	1.504	1.699	1.547

not transpired, leading to an absence of significant correlation between population size indicator and the spatial distribution of water engineering facilities.

In the area of transportation accessibility indicator. According to the results of the water engineering facility model, the regression coefficient of the transportation convenience indicator during the Ming dynasty was 0.545, with a p-value of 0.022, indicating that the postal relay system promoted the construction of regional water engineering facilities. The transportation convenience indicator during the Qing dynasty did not

demonstrate a significant influence on the spatial distribution of water engineering facilities. Analyzing results from different types of water engineering facilities, water control facilities and water distribution facilities had positive effects during the Ming dynasty, while transportation promoted water supply facilities during the Qing dynasty. The postal relay system was an important freight transportation system during the Ming and Qing dynasties, for which the court provided substantial funding, aiming to maintain the normal operation of the postal relay system [48]. There were numerous water relay

Cheng *et al. Heritage Science*   (2024) 12:262

Page 14 of 18

Table 5 Ming dynasty Tobit model regression results

	Business development indicator	Agricultural development indicator	Population size indicator	Transportation accessibility indicator	Cultural prosperity indicator
Water engineering facilities	0.44 (0.005***)	−0.181 (0.696)	−0.176 (0.637)	0.545 (0.022**)	0.93 (0.037**)
Water retaining facilities	0.522 (0.002***)	0.297 (0.559)	−0.587 (0.167)	0.336 (0.195)	1.029 (0.043**)
Water control facilities	0.383 (0.057*)	−0.727 (0.307)	0.267 (0.622)	0.665 (0.039**)	0.839 (0.141)
Water distribution facilities	0.491 (0.004***)	0.521 (0.348)	−0.956 (0.037**)	1.265 (0.005***)	0.751 (0.170)
Annexed facilities	0.499 (0.006***)	−0.55 (0.427)	0.414 (0.423)	0.247 (0.392)	1.17 (0.028**)
Overflow facilities	1.251 (0.014**)	−0.458 (0.726)	−0.246 (0.826)	2.189 (0.075*)	−0.627 (0.635)
Water storage facilities	0.794 (0.134)	1.63 (0.362)	−2.607 (0.186)	0.515 (0.643)	2.794 (0.162)

***,** represent 1%, 5% significance levels, respectively

Table 6 Qing dynasty Tobit model regression results

	Business development indicator	Agricultural development indicator	Population size indicator	Transportation accessibility indicator	Cultural prosperity indicator
Water engineering facilities	0.417 (0.026**)	0.086 (0.481)	−0.066 (0.741)	0.031 (0.836)	0.282 (0.348)
Water retaining facilities	0.568 (0.016**)	−0.031 (0.911)	0.17 (0.290)	−0.006 (0.975)	0.225 (0.558)
Water control facilities	0.448 (0.152)	0.073 (0.835)	0.169 (0.423)	0.063 (0.815)	0.571 (0.260)
Water distribution facilities	0.176 (0.769)	−0.062 (0.738)	−0.079 (0.489)	0.292 (0.040**)	0.583 (0.039**)
Annexed facilities	0.256 (0.900)	−1.729 (0.420)	−1.4 (0.288)	−0.402 (0.807)	15.68 (0.000***)
Overflow facilities	0.421 (0.255)	0.388 (0.371)	0.021 (0.935)	0.096 (0.766)	0.687 (0.222)
Water storage facilities	0.139 (0.407)	−0.162 (0.361)	0.091 (0.401)	0.124 (0.361)	0.166 (0.538)

***, ** represent 1%, and 5% significance levels, respectively

stations along the Grand Canal, relying on the canal for rapid transportation and delivery, thus imposing higher requirements on the canal route, thereby promoting the construction of water engineering facilities.

In terms of cultural prosperity indicator. In the water engineering facility regression model, the cultural prosperity indicator from the Ming dynasty significantly influenced the spatial distribution of water engineering facilities. Simultaneously, it had a positive impact on the spatial distribution of water retaining facilities and annexed facilities. The cultural prosperity indicator from the Qing dynasty also had a positive influence on the spatial distribution of water distribution facilities and annexed facilities. The Ming government's efforts in regulating the Huitong River section and opening the Qingjiangpu Canal and other projects led to the emergence of many water-related folk customs, legendary stories, and commemorative buildings. Successive

Cheng *et al. Heritage Science* (2024) 12:262

Page 15 of 18

water workers accumulated a wealth of hydraulic knowledge, which was passed down in these regions [49]. The belief in water deities spread southward along the canal, becoming integrated into the lives of local residents and widely worshipped [50]. This belief brought about hydraulic knowledge and experience, thus exerting a profound influence on the spatial distribution of water engineering facilities.

Conclusions and outlook

This study focuses on the prefecture traversed by the Grand Canal during the Ming Dynasty, collecting historical data and extracting ten factors from both the Ming and Qing dynasties. The entropy method is employed to construct indicators for commercial development, agricultural development, population size, transportation convenience, and cultural prosperity. ArcGIS Pro 3.0.0 software is utilized to quantitatively analyze the spatial distribution characteristics of water engineering facilities along the Grand Canal, while the Tobit model is employed to study the influencing factors of water engineering facility spatial distribution. The main conclusions are as follows:

1. The spatial distribution of water engineering facilities in the Ming and Qing Dynasties exhibits an aggregated pattern. with a shift towards a more dispersed pattern during the Qing Dynasty compared to the Ming Dynasty. The center of gravity of construction of water engineering facilities moves south. The spatial distribution pattern of water engineering facilities during the Ming Dynasty was characterized by hotspots such as Shuntian Prefecture, Yanzhou Prefecture, and Yangzhou Prefecture. In the continuous development of the canal in the process of construction of waterworks facilities are not concentrated in a certain region, but showing multi-point sub-regional aggregation phenomenon.

2. During the Ming and Qing dynasties, commerce continued to develop and the number of chaoguan increased, and the greater weight of chaoguan contributed to the yearly increase in commercial development indicators. Agricultural development indicator from the Ming and Qing dynasties indicate significant agricultural progress. Regarding transportation convenience indicators, there was a decline in transportation convenience, with the most significant decrease observed in southern regions. Population size indicator show significant population growth during the Ming and Qing dynasties, particularly notable in southern regions. Regarding cultural prosperity indicator, there was an increase in the cultural prosperity index during the Qing Dynasty, particularly notable in prefectures along the Grand Canal.

3. The regression coefficients for commercial development indicator during the Ming and Qing dynasties were 0.44 and 0.417, respectively, with p-values below 0.05, The influence of commercial development indicator on the spatial distribution of water engineering facilities is positively correlated in both the Ming and Qing dynasties. The impacts of the indicator on different types of water engineering facilities vary between the two dynasties. During the Ming Dynasty, The regression coefficients for transportation convenience indicators and cultural prosperity indicator during the Ming Dynasty were 0.545 and 0.93, respectively, both with p-values below 0.05, the indicators facilitated the construction of regional water engineering facilities, whereas in the Qing Dynasty, they significantly influenced several types of water engineering facilities. During the Ming and Qing Dynasties, neither the agricultural development indicator nor the population size indicator significantly affected the distribution of water engineering facilities. However, there was a negative correlation between the population size indicator and the distribution of water distribution facilities in the Ming Dynasty.

This study delves into the spatial distribution of water engineering facilities along the Grand Canal and their close relationship with social development, aiming to provide theoretical foundations for the construction and preservation of the Grand Canal heritage corridor. This study employs the Tobit model in an empirical investigation within the historical heritage field to analyze the quantitative impact of China's urban historical development on canal constructionThis provides a new perspective for understanding the construction of the Grand Canal during the Ming Dynasty, the development of canal transportation, and cultural exchanges. This study enhances the importance of protecting historical social environments and provides guidance for effectively preserving, inheriting, and reasonably utilizing the cultural heritage of the canal. As one of the world's major linear cultural heritages, the study of the Grand Canal of China is not only significant domestically but also provides valuable references for the spatiotemporal evolution and historical development research of other international linear cultural material heritages.

Appendix A: Nomenclature/notation

(1) Water Engineering Facilities:Water engineering facilities refer to engineering facilities constructed for the purpose of safeguarding water security,

Cheng *et al. Heritage Science* (2024) 12:262

Page 16 of 18

improving the water environment and utilizing water resources, mainly including embankments, revetments, sluices, pumping stations, barrages and dams, and other facilities.

(2) prefecture: Can be extended to the official office, government and some of the gathering significance of the premises, etc., this article refers to China's administrative division of the Ming and Qing dynasties.

(3) Land tax refers to the tax grain transported from the southeast to the capital by river and sea in feudal China. This article refers to the tax grain transported to the capital via the Beijing-Hangzhou Grand Canal.

(4) Commercial tax refers to the tax levied on merchants for selling goods and other commercial activities in ancient China.

(5) palace graduate refers to those who passed the last level of the central government's court examination in the ancient Chinese imperial examination system, and is the name of those who passed the ancient imperial examinations.

(6) OLS: ordinary least squares

(7) P value: the probability under the null hypothesis of obtaining a real-valued test statistic at least as extreme as the one obtained

(8) Z score: a statistical measurement that describes a value's relationship to the mean of a group of values

Appendix B: Data sources

Code of Great Ming Dynasty

it was completed in 1502 A.D. with 180 volumes. In 1576 A.D., the book was rewritten, with 228 volumes, which provided more concentrated materials for the study of the central and local governments of the Ming Dynasty, such as institutions and offices, the appointment and removal of officials, the clerical system, the management of ethnic minority areas, the administration and supervision, the economic policies of agriculture, handicrafts, commerce, and the land system, taxation, household service, and finances, as well as the astronomical system, the calendar system, the customs, and the culture and education, etc., and it is an important material for the study of the Ming Dynasty's canonical systems. It is an important source of information for the study of the Ming dynasty's canonical system.

Qing Historical Manuscripts

Include important historical figures, events, and rules and regulations during the 296 years of the Qing Dynasty, reflecting the "great changes that have not been seen in thousands of years" that the Qing Dynasty experienced.

The prefectural records

They are collections of basic information on the history, humanities, geography, folklore, and fields of the prefectures. Local prefectural journal refers to the historical records that describe the local situation. There are two types of national general records and local state, county, prefecture and county records.

All Ming Poetry

There are more than 1390 authors of poems and about 20,000 poems in the collection. The authors of the poems of the Ming Dynasty are organized in the book.

Qing Dynasty Jinshi Inscription List

In the ancient Chinese imperial examination system, those who passed the final level of the central government's court examination were called jinshi.

The book has meticulously organized the place of origin and the name of the Jinshi of the Qing Dynasty through systematic checking and proofreading.

Data availability
No datasets were generated or analysed during the current study.

Materials availability
Not applicable.

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.

Cheng *et al. Heritage Science*   (2024) 12:262

Page 17 of 18

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