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Spatio-temporal evolution and distribution of cultural heritage sites along the Suzhou canal of China

Yan Huang[1] and Shengdan Yang[1*]

Abstract

The Grand Canal is one of the most important hydraulic engineering projects in Chinese history. The city of Suzhou has abundant and concentrated cultural heritage sites in the southern section of the Grand Canal. However, due to natural hazards, anthropogenic damage, and lack of human management, the cultural heritage sites have suffered irreversible damage. Digital preservation of these sites will make it possible to maintain their aesthetic and cultural value. This paper takes cultural heritage sites along the Suzhou Canal as its research subject and establishes a cultural heritage dataset using geographical information system (GIS). The paper uses geocoding and spatial analysis methods based on GIS, including nearest neighbor analysis, kernel density analysis, center of gravity analysis, and standard deviation ellipse. The paper explores the distribution of 104 cultural heritage sites along the Suzhou Canal across six historical periods and discusses the influencing factors for evolution of the distribution. The results show that: (1) major constructions on the Grand Canal water system were started in the Pre-Sui period and completed in the Sui and Tang Dynasties; (2) the degree of clustering of the distribution has increased since the Sui and Tang Dynasties until Modern Times; (3) the high-density area has been centered around the ancient city since the Pre-Sui period, and has shown a migration trend towards the Shantang Canal since the Ming Dynasty; (4) the center of gravity first moved from northwest to southeast along the Canal and then moved northeast towards the ancient city; (5) the aggregation of the sites peaked in the Qing dynasty (1636 CE-1911 CE), and the elliptical direction of distribution has become stable since then; and (6) the types of the cultural heritage in the evolution process are affected by the joint effects of natural and human factors, namely, elevation, canals, population, water transportation, and intangible cultural heritage, among which the canal characteristics play the decisive role. This study reveals the internal evolution mechanisms of the cultural heritage in the Suzhou Canal area and presents a scientific basis for the protection and utilization of the cultural heritage in other parts of the world.

Keywords Cultural heritage, Evolution, GIS, Influencing factors, Spatial analysis, Suzhou canal

Introduction

Historical background of the Suzhou Canal

Waterways have been crucial in all civilizations, playing important roles in transportation, irrigation, commerce, travel, etc. The Beijing-Hangzhou Grand Canal in China (GCC) is the longest and oldest artificial waterway in the world, stretching from Beijing in the north to Hangzhou in the south, with a total length of 1794 km [1, 2]. In today's context, when cultural self-confidence is advocated by the Chinese government, a construction program for the Grand Canal National Cultural Park has been issued [3]. The overall construction of the GCC started in the fifth century BCE and ended in 1327 CE [2]. It was expanded and renovated

*Correspondence:
Shengdan Yang
ysd20@mails.tsinghua.edu.cn
[1] Department of Environmental Art Design, Academy of Arts and design, Tsinghua University, Beijing 100084, China

many times throughout history. During the twelfth century, the GCC became the most important multifunctional artery in China, ranging from the north to the south [4]. The Jiangnan Canal, the southern section of the Grand Canal, was first dredged in the Spring and Autumn Period (770–476 BCE) [1]. The Jiangnan Canal flows through Suzhou from the northwest to the south, and the length of the Suzhou Canal is 96 km [5].

Suzhou, whose history spans more than 2500 years, has had a profound cultural presence since King Helu of Wu State ordered the construction of the ancient city in 514 BCE [1]. The city moat surrounding the ancient city was connected to the canals inside the city via water gates, and it was the earliest waterway of the Grand Canal, Suzhou section [5]. In 506 BCE, considering the territorial expansion of dependent states, Wu Zixu put forward the suggestion to King Helu that a canal should be constructed to transport grain between the State of Chu and the State of Wu [1]. The Xu Canal was built then and was regarded as the earliest start of the Suzhou section of the Grand Canal [6]. After that, the Suzhou Canal was built and improved continuously from ancient dynasties to Modern Times [1]. In 495 CE, King Fuchai of Wu ordered the excavation of the Canal, starting from Suzhou and passing through Wuxi to reach the Yangtze River, with a total length of 170 km. This formed the earliest section of the Jiangnan Canal [6]. In 610 CE, based on the existing canal channel, Emperor Yang of Sui ordered the excavation of the Jiangnan Canal, which flowed from Zhenjiang to Suzhou and connected with Hangzhou. Since then, the canal system in Ancient Suzhou City has been incorporated into the Jiangnan Canal [5]. The transmission of decree documents, the mobilization of the ancient armies, and the transportation of provisions all depended on the Grand Canal [7]. The Canal acted as the lifeline to connect Suzhou and Beijing, and thus strengthened the political unity of the national government [1]. In the early ninth century, Wang Zhongshu, the mayor of Suzhou, supervised the construction of the age-old Track Road of Wujiang along the Eastern shore of Lake Tai, to separate the Grand Canal from Lake Tai [8]. In 825 CE, when Bai Juyi was appointed as the governor of Suzhou, he built the Bai Causeway to strengthen the connection between Suzhou and the Grand Canal [5]. In the 1950s, the main water course entering the city moat from the Shangtang River and Shantang River evolved into the new channel which flowed southward towards Hengtang and connected with the city moat from the Xu River. In the 1980s, a new channel was built from Tantai Lake to Baodai Bridge, and then connected with the Jiangnan Canal [9].

State of the art methods in canal heritage research

In the 1980s, the Chinese geographer Shupeng Chen systematically put forward the concept of the geo-informatic map and suggested the use of GIS-based series mapping for solving regional problems [10]. Influenced by his work, many experts and scholars have used the GIS technologies in the conservation of cultural heritage in the GCC. Professor Yu Kongjian's research team thoroughly sorted through the cultural heritage sites along the Canal through literature review and field investigations and summarized the projects in an in-depth heritage list [11], which provided a solid data source for this research. Yu et al. [11] set three selection criteria for the scope of the cultural heritage sites which are related to the canal: (1) functional correlation, (2) geographical correlation, and (3) historical correlation. Mao et al. [2] established an integrated framework for cultural heritage protection along the GCC and developed four digital systems for visualization of cultural resources, including GIS, 3D simulation, a planning supporting system, and a data collection system [10]. Tsung et al. [12] introduced a framework of infrastructure sustainability indicators for the Grand Canal, which comprises economic, environmental, and social measures [12]. Porfyriou [4] identified and examined the urban form of Chinese historic water towns along the Canal through field visits and a literature search, and he emphasized the impact of the historic preservationist Ruan Yisan's planning interventions on the heritage conservation [4]. Rong and Wang (2021) interpreted the Hangzhou section of the Canal by building connections between heritage sites and historical events and built a five-indicator model to reveal the degree of interrelationships [13]. Zhao et al. [14] built a GIS-sDNA model to show the in-site phenotype of 18 rural settlements along the Tianjin section of the Grand Canal, and divided the settlement space into four types, thus proposing new cognitive perspectives to conserve the in-site characteristics [14]. But few studies have quantitatively analyzed the mechanisms of evolution of the heritage sites along the Suzhou Canal.

Aim and scope

At present, the existing GIS studies of the cultural heritage protection along the Grand Canal are undertaken from an interdisciplinary perspective, integrating geographical, cultural, archaeological, and landscape factors into comprehensive discussions. The research subjects include heritage buildings [15], heritage corridor [13, 16], landscape planning [17], sustainability infrastructure [12], settlement space [14], and intangible cultural heritage (ICH) [18]. However, there has rarely been research on the correlation between cultural mapping and influence factors of historical development along the Suzhou Canal, and there remains a lack of statistical analysis of the evolutionary process. To construct an integrated approach to interpret the evolutionary mechanisms of cultural heritage in Suzhou, it is urgent to strengthen the exploration of relevant geographical methods. Given the government's goal of constructing a national cultural park, this paper takes the cultural heritage sites along the Suzhou Canal as the research focus and introduces GIS spatial analysis methods to highlight the distribution of various cultural heritage sites.

The Suzhou Canal has existed from the Spring and Autumn Period to Modern Times, and this research divides the historical development into six successive periods according to significant events in the Canal's construction: Pre-Sui (600 BCE-581 CE), Sui and Tang (581 CE-907 CE), Five Dynasties to Song (907 CE-1279 CE), Yuan and Ming (1271 CE-1644 CE), Qing (1644 CE-1911 CE), and Modern Times (1912 CE to present). Except for the longer first Pre-Sui period, and the shorter last one, each period covers about 300 years (Table 1).

A cultural series mapping incorporating temporal and spatial dimensions was created to show the development of cultural heritage distribution from the Pre-Sui period to Modern Times. The purpose of this paper is to further explore the spatio-temporal distribution characteristics of cultural heritage by addressing the following four questions:

(1) What is the quantitative relationship between heritage types and historical periods?
(2) What are the changes in the lengths of Grand Canal waterways throughout the evolution?
(3) What are the spatial distribution characteristics of heritage sites along the Canal in each of the six historical periods?
(4) What factors promote the evolution of distribution? How should the correlation of the evolution of distribution and the related influencing factors be characterized?

Materials and methods

Study area and data sources

In this study, the spatial scope is the current boundary of Gusu, Huqiu, Wuzhong, and Wujiang Districts in Suzhou City (Fig. 1), and the cultural heritage sites in this research refer to the tangible cultural heritage works which were built for the historical development of the Suzhou Canal and showed distinctive cultural attributes. A systematic search was conducted for the cultural heritage sites along the Suzhou Canal, and volumes, records, publications, and historical maps on Suzhou Canal were reviewed to find the relevant data. The sites in this study were chosen from UNESCO's 2014 World Cultural Heritage List [19] and three publications with the attached cultural heritage lists: *Research Report on the Heritage of Suzhou Ancient City Section of the Grand Canal* [8], *The Grand Canal Landscape Corridor* [11], and *Spatio-temporal Development of the Beijing-Hangzhou Canal* [21]. In this research, the cultural heritage types are selected for their attachment to the Canal in the aspect of construction, transportation, commerce, management, and citizens' life. Only the sites which are culturally, historically, and functionally connected to the Canal are included in the final analysis, and those sites which are only geographically related to the Canal are excluded. For example, some sites may have been built specifically to serve the needs of the Grand Canal, such as water conservancy projects and canal administrative facilities. Others may have developed around the Canal due to its importance as a transportation and trade route, and the cultural exchange and interaction could be facilitated by the movement of goods and people along the Canal [8].

Using these criteria, a total of 96 tangible cultural heritage sites along the Suzhou Canal were selected, and information about the type, age, spatial location, protection level, and preservation status was collected. In addition, spatial data on roads, city boundaries, water bodies, Digital Elevation Model (DEM) data with a 90 m precision,

Table 1 Historical periods and major advances

Historical period	Major advances	Duration
Pre-Sui (600 BCE-581 CE)	Origin of the GCC, Suzhou section	1181 years
Sui and Tang (581 CE-907 CE)	Formation and development of the GCC as an independent hydrological system	326 years
Five Dynasties to Song (907 CE-1279 CE)	Growth and progress in the canal system	372 years
Yuan and Ming (1271 CE-1644 CE)	Peak in constructing the canal system in Suzhou Ancient City	373 years
Qing (1644 CE-1912 CE)	Stable and complete layout of the canal system	268 years
Modern Times (1912 CE-present)	Reconstruction of the GCC, Suzhou section	111 years

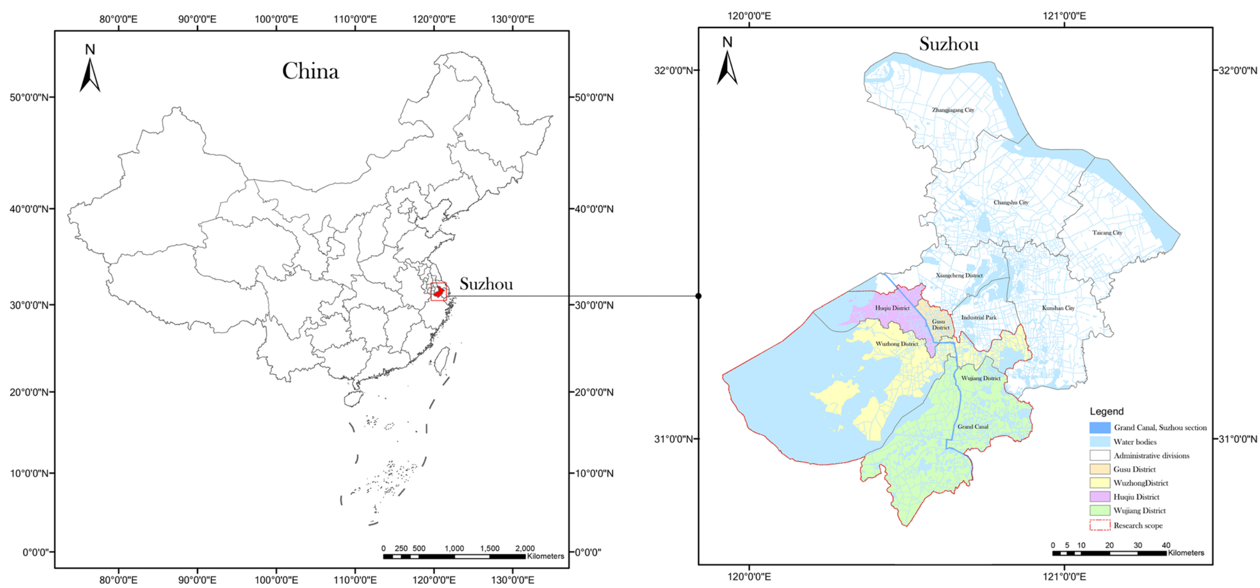


Fig. 1 Location of the Suzhou Canal area in China

and other attribute data were collected through the geographic analysis platform to form a dataset. Historical Chinese archives were also reviewed to summarize the geographical, hydrological, ecological, economic, and social conditions of Suzhou in various historical periods [6, 23]. The data regarding population, canal system in Ancient Suzhou City, and weight of goods transported via water in the Jiangnan Canal were collected from the *Chronicle* of the local history published by the Suzhou Government (http://dfzb.suzhou.gov.cn, accessed in November 2022).

Historical geocoding

The textual historical data contains unreliable information, such as obsolete addresses, temporal gaps, and fuzzy maps, which requires further proof and conversion [22, 24]. The historical addresses of cultural heritage sites are not locations in spatial references and are thus indirect sources of information for modern map users. Considering the inaccuracy in the historical data, geocoding is used to resolve the gap between historical and current addresses. In this research, geocoding transformed the historical spatial information into latitudes and longitudes in the WGS84 coordinate system on ArcGIS 10.8. The spatial analysis used point element shapefiles of the cultural heritage sites on GIS [24]. During the geocoding of these unverified addresses, a scroll review of online maps, existing documents, and historical maps reached results closer to the accurate locations. To offset the deviations in geocoding, we compared the past addresses on the historical maps and attached them to those of the modern locations on Google Map, recognizing and recording the modern addresses in the dataset.

Classification and quantitative analysis

This study divides the cultural heritage sites into seven basic types, namely, canals, water conservancy projects, canal administrative facilities, human settlements, ancient architecture, steles, and recent buildings [11, 14, 20, 25]. Table 2 presents the definition of these seven cultural heritage types and calculates the number of each of these types. Of the 96 sites, 44 are water conservancy projects, accounting for 45.8% of the total. To further characterize the temporal development of the architecture types, quantitative analysis depicted the change in the number of the sites over these ancient dynasties.

Spatial analysis based on GIS

With ArcGIS 10.8 software, this study used kernel density analysis, nearest neighbor analysis, gravity analysis, and standard deviation ellipse methods to explore the spatial distribution characteristics of cultural heritage sites. These methods were used to quantitatively study the spatial variation patterns, and each of these methods contributes to a particular subject to ensure comprehensive analysis. These analyses provided an evolution map of each period and a time series development of distribution.

Table 2 Definition and statistical results of the seven basic types of cultural heritage

Cultural Heritage	Definition	Count
Canals	Grand Canal, canal system, and waterways related to the Grand Canal	8
Water conservancy projects	Water heritage integral to the Canal's function, including causeways, hydrological facilities, bridges, and wharves, etc. [20, 25]	44
Canal administrative facilities	Administrative facilities to regulate the official affairs related to the Canal, including bureaus, custom houses, granaries, post offices, etc. [8]	6
Human settlements	Ancient cities, townships, villages, and historical blocks which formed and developed along with the Canal [26, 27]	9
Ancient architecture	Architectural heritage internally related to the Canal, including city gates, guild halls, pagodas, temples, gardens, and cultural sites [8, 11, 19, 25]	26
Steles	Imperial steles, hydrologic steles, stone stupas, etc., related to the history of the canal [20]	5
Recent buildings	The sites of former factories, consulates, etc. [8]	6

Nearest neighbor analysis

In this study, the nearest neighbor analysis method is used to calculate the nearest neighbor index (NNI) and judge the spatial distribution patterns of points in different time periods. This method is useful for identifying patterns of clustering or dispersion among the cultural heritage sites along the Canal and can help determine whether the sites are distributed randomly or are clustered together in certain historical periods. The NNI shows the degree of proximity of sites, and the calculation formula is shown below:

$$R = \frac{\overline{d}}{d_E} = 2\sqrt{D}\overline{d} \tag{1}$$

In this formula, $\overline{d}$ represents the average of distances between the nearest cultural heritage sites, d_E is the theoretical nearest neighbor distance, and D refers to the point density; d_E is calculated as follows:

$$d_E = \frac{1}{2}\sqrt{\frac{A}{n}} = \frac{1}{2\sqrt{D}} \tag{2}$$

A refers to the total area of the administrative district with cultural heritage sites and n is the number of cultural heritage sites. If NNI is less than 1, the spatial distribution pattern of point elements is clustered; if NNI is equal to 1, the spatial distribution type is random; if NNI is greater than 1, it tends to be dispersed [28].

Kernel density analysis

Using the kernel density analysis tool, the kernel density distribution maps of the cultural heritage sites are generated with different time periods. This information can help identify areas of particular significance or concentration along the Canal and can also help identify areas where further research or preservation efforts may be needed. If the kernel density is larger, the distribution of sites is denser. The formula is shown below:

$$f_n(x) = \frac{1}{nh}\sum\nolimits_{n=1}^{k} k\left(\frac{x - X_i}{h}\right) \tag{3}$$

where h means a search radius greater than 0, and $x - X_i$ is the distance between the estimated point x and the event X_i [28].

Center of gravity analysis

This research uses an averaging tool to calculate the center of gravity of the cultural heritage sites and display the movement track of the geographic center in different time periods. This method is useful for visualizing the change in the centroid of the sites and indicating where further efforts may be needed to better understand the change in that area.

$$Mx_i = \sum\nolimits_{i=1}^{n} x_i/n,\ My_i = \sum\nolimits_{i=1}^{n} y_i/n, \tag{4}$$

In this formula, Mx_i and My_i refer to the coordinates of the centers of gravity of cultural heritage distribution, respectively; and x_i and y_i represent the coordinates of cultural heritage sites, respectively:

$$D_{ij} = \sqrt{\left(M_{yi} - M_{yj}\right)^2 + \left(M_{xi} - M_{xj}\right)^2} \tag{5}$$

where D_{ij} represents the displacement of the centers of gravity of different time periods [29].

Standard deviation ellipse

This research uses the directional distribution tool to draw standard deviation ellipses in different historical periods. This method is used to measure the dispersion of site distributions along the Canal and detect the directional trends in a time series.

$$\mathrm{SDE}_X = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \overline{x})^2}{n}} \tag{6}$$

$$\mathrm{SDE}_Y = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \overline{y})^2}{n}} \tag{7}$$

where x_i and y_i represent the coordinates of sites, n refers to the total number of cultural heritage sites, and $\{\overline{x}, \overline{y}\}$ means the average center of all sites:

$$\tan\theta = \frac{A + B}{C} \tag{8}$$

$$B = \sqrt{\left(\sum_{i=1}^{n}\widetilde{x}_i^2 - \sum_{i=1}^{n}\widetilde{y}_i^2\right) + 4\left(\sum_{i=1}^{n}\widetilde{x}\widetilde{y}\right)^2} \tag{9}$$

$$\mathrm{C} = 2\sum_{i=1}^{n}\widetilde{x}_l\widetilde{y}_i \tag{10}$$

where $\tan\theta$ is the tangent of the ellipse rotation angle, and $\widetilde{x}_i, \widetilde{y}_i$ means the deviation of xy coordinates from the average center, respectively:

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n}\left(\widetilde{x}_i\cos\theta - \widetilde{y}_i\sin\theta\right)^2}{n}} \tag{11}$$

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^{n}\left(\widetilde{x}_i\sin\theta - \widetilde{y}_i\cos\theta\right)^2}{n}} \tag{12}$$

In this formula, σ_x represents the length of the long axis of the ellipse, and σ_y is the length of the short axis of the ellipse [30].

Results

Evolution of cultural heritage types over time

The age of the cultural heritage site is mainly based on the construction date of the heritage project, and the 96 cultural heritage sites are categorized into six historical periods according to their age. Figure 2 shows both the count and increase in cultural heritage sites in each historical period. From the Pre-Sui period to Modern Times, the number of cultural heritage sites has increased from 13 to 96. The growth rate of the sites from the Sui and Tang Dynasties to the Yuan and Ming Dynasties has gradually increased, with 4 new sites built in the Sui and Tang Dynasties, 10 new sites added from Five Dynasties to Song Dynasty, and 12 new sites in the Yuan and Ming Dynasties. There was a sharp increase in the number of sites in the Qing Dynasty, with 53 newly added sites. In Modern Times, 4 sites have been added.

A matrix is created for the number of newly built heritage sites in each period, with seven rows of heritage types and six columns of historical periods. A 3D bar plot is made on OriginPro to depict the temporal evolution of the seven basic heritage types from the Pre-Sui period to Modern Times (Fig. 3). According to Fig. 3, the number of water conservancy projects in the Qing Dynasty is the largest (30), followed by that of ancient architecture in the Qing Dynasty (14). To adapt to the development in canal management, construction on the water conservancy projects continued in four successive periods from the Sui and Tang Dynasties to the Five Dynasties

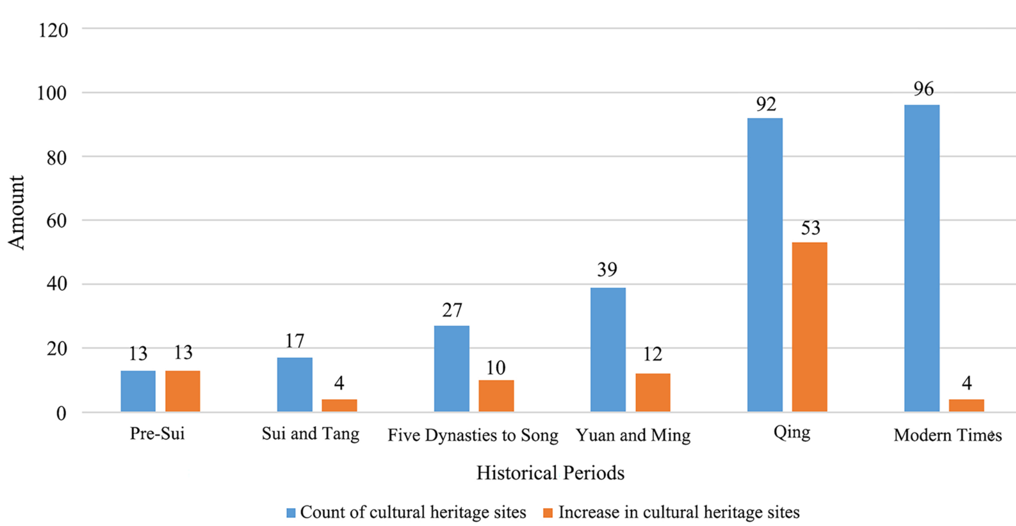


Fig. 2 The change in the count and increase in cultural heritage sites over time

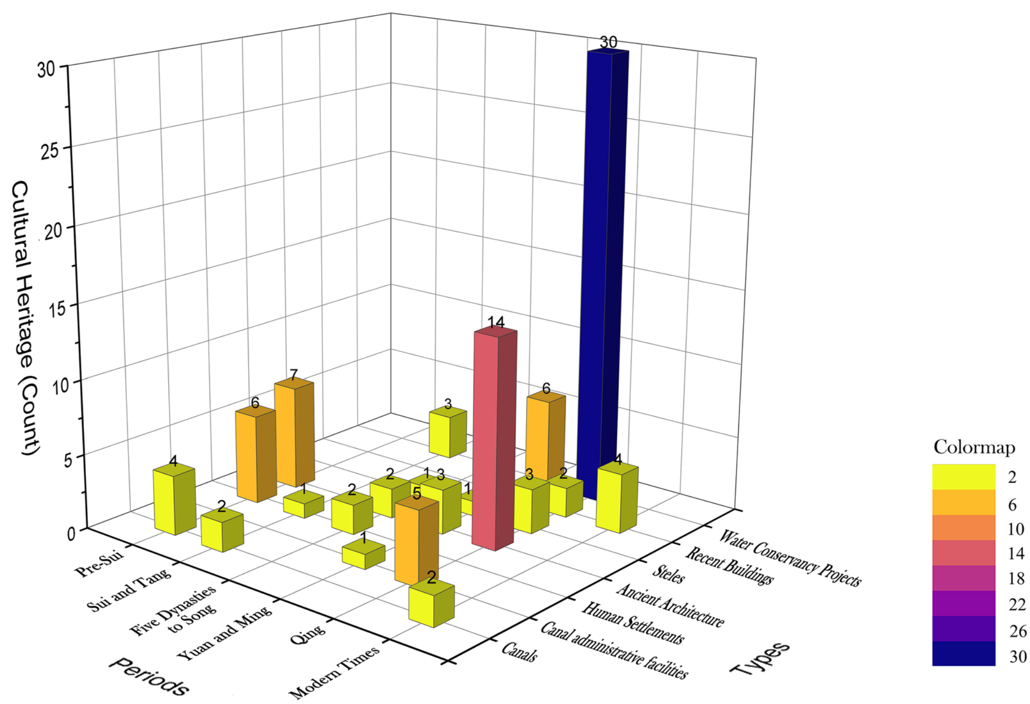


Fig. 3 Data visualization of historical periods and cultural heritage types

to Song Dynasty, to the Yuan and Ming Dynasties, to the Qing Dynasty, with 3, 5, 6, and 30 projects built, respectively. There was one canal administrative facility built in the Yuan and Ming Dynasties, and five more were built in the Qing Dynasty. Among the Pre-Sui sites were seven early human settlements, namely, Ancient Suzhou City, ancient towns of Mudu, Hushu pass, and Luzhi, ancient villages of Mingyuewan and Luxiang, and the Pingjiang Historical District. Attached to Ancient Suzhou City were five remaining city gates, namely, the Xu, Pan, Chang, Qi, and Jin Gates, mandated by King Helu of Wu in the Spring and Autumn Period and the Warring States Period [4].

Evolution of the waterways over time

In this research, waterways are divided into two parts: the Grand Canal water system and the canal system inside Ancient Suzhou City. The Grand Canal water system includes the Canal, still in use (starting from the Wuqi Bridge to the Precious Belt Bridge), and canals of antiquity (the Shantang Canal, the Shangtang Canal, the Xu Canal, the city moat and the Suzhou-Jiaxing Canal). The changes in the length of the Grand Canal water system and canal system in the ancient city are interconnected with the significant events in its historical development. Through interpretations of historical maps, the waterways in Ancient Suzhou City were extracted and mapped in a series of diagrams to show their temporal and spatial changes. On ArcGIS 10.8, georeferencing was used to map the ancient waterways under WGS 1984 coordinates, and the lengths of the Grand Canal water system and canal system and the overall lengths of the waterways were calculated and shown in Table 3.

Figure 4 shows the change in the lengths of the Grand Canal water system and canal system from Pre-Sui to Modern Times. Major changes in the length of the Grand Canal water system happened during the Pre-Sui period and Sui and Tang Dynasties. The construction of Suzhou Canal started from the creation of Xu Canal in 506 BCE, which was 36.3 km in length, and has undergone several major changes since then [6]. In 495 BCE, the digging of the Canal started from the Chang Gate of the ancient city and flowed 26.6 km northwest to connect with the Yangtze River [6]. In 610 CE, the canal was dredged and widened to form the Jiangnan Canal, which extended 61.6 km south to connect Suzhou with Hangzhou [26]. In 815 CE, the Shantang River was dredged to connect Ancient Suzhou City and Huqiu, which was 6.6 km long [6]. Two other obvious increases in the length of the Grand Canal water system occurred in Modern Times. In 1950, a new channel was made in the west of the ancient city, which was 4.9 km long, and in 1982, another new channel with a length of 8.1 km was added in the south of the ancient city to flow through Tantai Lake [6].

Table 3 Modification of the waterways in the six historical periods

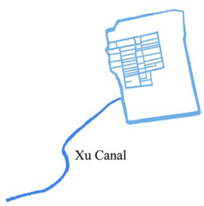
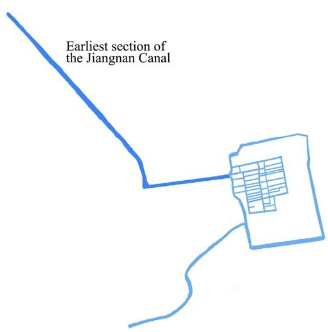
Period	Year	Water system layout[1]	Significant events	Length of the Grand Canal water system (km)[2]	Length of the canal system inside Ancient Suzhou City (km)[3]	Overall length of the waterways (km)[4]
Pre-Sui	514 BCE	N/A	The walled city of Helu was constructed with 8 land gates and 8 water gates [8]	**N/A**	N/A	N/A
	506 BCE		Construction on the Xu Canal, which connected the city moat with Tai Lake [6]	**36.3**	N/A	N/A
	495 BCE		Construction on the earliest section of the Grand Canal in Suzhou, connecting Suzhou and Yangtze River [8]	**62.9**	N/A	N/A

Table 3 (continued)

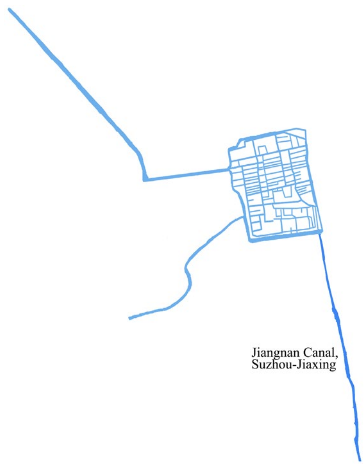
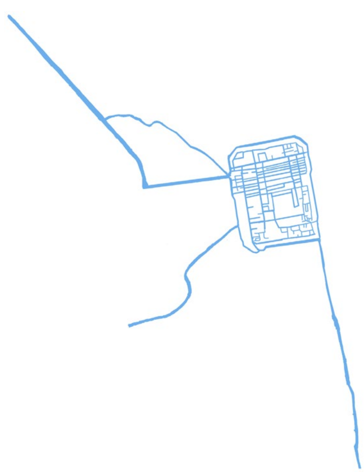
Period	Year	Water system layout[1]	Significant events	Length of the Grand Canal water system (km)[2]	Length of the canal system inside Ancient Suzhou City (km)[3]	Overall length of the waterways (km)[4]
Sui and Tang	610 CE		Construction on the Jiangnan Canal, which connected Suzhou to Jiaxing and Hangzhou [8]	**124.5**	63.9	188.4
	815 CE		Construction on the Shantang Canal [4]	**131.0**	63.9	194.9
Five Dynasties to Song	1229 CE		N/A	**130.7**	82.4	213.1

Table 3 (continued)

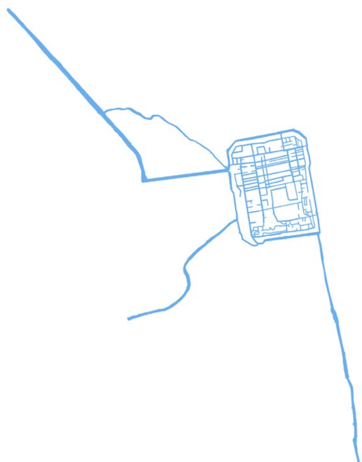
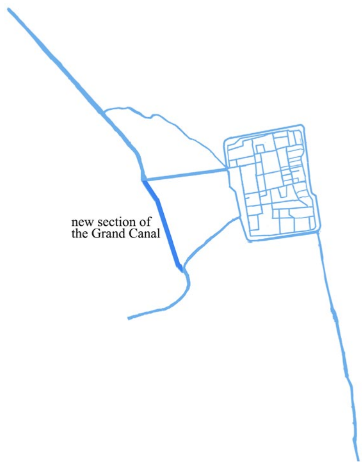
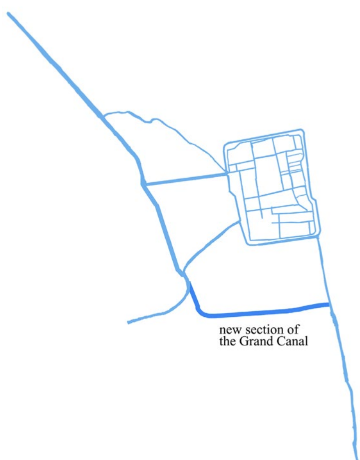
Period	Year	Water system layout[1]	Significant events	Length of the Grand Canal water system (km)[2]	Length of the canal system inside Ancient Suzhou City (km)[3]	Overall length of the waterways (km)[4]
Yuan and Ming	1639 CE		N/A	**131.1**	86.3	217.4
Qing	1896 CE		N/A	**131.1**	62.4	193.4

Table 3 (continued)

Period	Year	Water system layout[1]	Significant events	Length of the Grand Canal water system (km)[2]	Length of the canal system inside Ancient Suzhou City (km)[3]	Overall length of the waterways (km)[4]
Modern Times	1950 CE		Construction of a new channel in the west of the ancient city [6]	**135.8**	60.4	196.2
	1986 CE		Construction of a new channel in the south of the ancient city [6]	**144.1**	37.0	181.1

N/A means "not applicable" in the table

[1] Newly added waterways in each historical period are shown in dark blue with their names

[2] The lengths of the Grand Canal water system are marked in bold characters

[3] In this measurement, the canal system in Ancient Suzhou City refers to the canals inside the ancient city, with the city moat excluded

[4] The overall length of waterways is the sum of the length of the Grand Canal water system and the canal system inside the ancient city

According to the records of Suzhou's water conservancy department [23, 31], the canal system in Ancient Suzhou City underwent several major constructions in the Tang, Song, and Yuan Dynasties, after Suzhou's initial establishment in 514 BCE [32]. In the Tang, to prevent the sinking of lands, several water conservancy projects were built, such as the Wujiang Levee and Lou River [5]. In the mid-Song Dynasty, water-control techniques were applied in the surroundings of Suzhou, and since then, a canal system has been developed in the gently sloping terrain [33]. In 1229 CE, the length of the canal system grew to be 82.4 km long. The length of the canal system reached a peak in the late Ming Dynasty, which was 86.3 km long, and declined to 62.4 km long in the Qing Dynasty because of the partial filling of the channel [31].

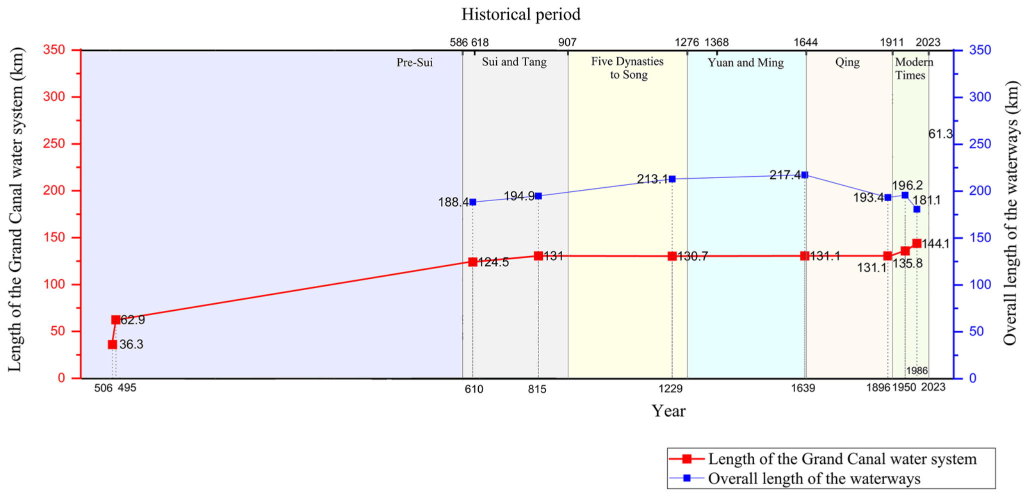


Fig. 4 Changes in the length of the Grand Canal water system and overall length of the waterways

Table 4 NNI analysis of cultural heritage sites in the six historical periods

Period	Expected mean distance/meters	Observed mean distance/meters	Nearest neighbor index	Z-score	P-value	Pattern
Pre-Sui	4980.95	5982.01	1.2010	1.3863	0.1657	Random
Sui and Tang	5127.65	6592.83	1.2857	2.2538	0.0242	Dispersed
Five Dynasties to Song	4068.75	3811.62	0.9368	− 0.6282	0.5299	Random
Yuan and Ming	3394.08	2122.83	0.6255	− 4.4748	0.0000	Clustered
Qing	2432.07	1308.05	0.5378	− 8.4805	0.0000	Clustered
Modern Times	2380.86	1264.08	0.5309	− 8.7923	0.0000	Clustered

Spatio-temporal evolution of distribution

Analysis results of NNI

According to the results in Table 4, the major distribution type of cultural heritage sites is clustered. The distribution type of sites in the Sui and Tang Dynasties is quite different from the other five periods, exhibiting the largest values in NNI and Z-score. The NNI of the Pre-Sui Dynasty is greater than 1 (1.2010), and it does not pass the significance test (p is 0.1657; z is 1.3863), indicating it is a random distribution. The NNI in the Sui and Tang Dynasties is greater than 1 (1.2857), and given the Z-score of 2.2538, it passes the significance test, indicating it is a dispersed distribution. The NNI of Five Dynasties to Song Dynasty is 0.9368, which fails to pass the significance test (p is 0.5299; z is − 0.6282), showing it is a random distribution. The NNI statistics of cultural heritage sites in the Yuan and Ming Dynasties, Qing Dynasty, and Modern Times are all smaller than 1, and given their z-scores and p-values, they did not pass the significance test. The above data show that the distribution types in these three periods are all clustered, and the clustering degree increased from the first period to the third, showing an obvious inheritance relationship of clustering degree.

Analysis results of kernel density

This part shows the kernel density analysis of cultural heritage sites according to the six historical periods and traces the evolution of the spatial aggregation characteristics (Fig. 5). From the Pre-Sui period to the Modern Times, the distribution of sites gradually shifted from a concentrated layout to a more scattered layout, and the number of high-density groups changed from one to two. This trend indicates that the interconnection between the sites became weaker, and the high-density core in the ancient city grew to stretch out to smaller clusters spanning along the Grand Canal water system, which is consistent with the reconstruction process of the Grand Canal water system. This trend also shows the increasingly important role of the Shantang District

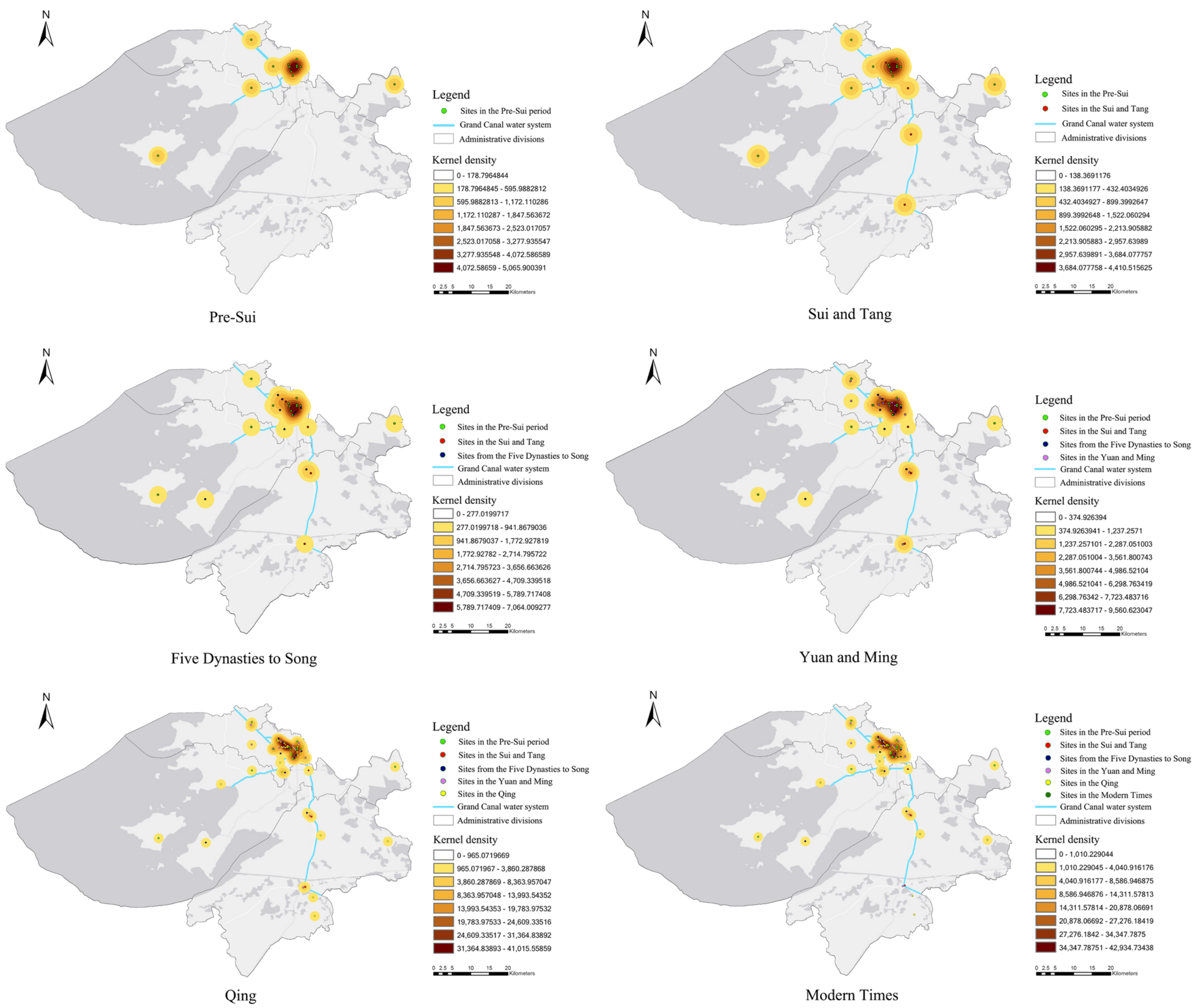


Fig. 5 Kernel density maps of cultural heritage sites in the Pre-Sui Period, Sui and Tang Dynasties, Five Dynasties to Song Dynasty, Yuan and Ming Dynasties, Qing Dynasty, and the Modern Times

and Shantang Canal as a commercial center in Ancient Suzhou City in the Ming and Qing Dynasties, with many shops, guild halls and temples built along the street blocks [8].

By the end of the Pre-Sui Period, there was one high-density circle located in Ancient Suzhou City. Three sub-high-density circles were initially formed along the Grand Canal water system, which were Hushuguan Town, Mudu Ancient Town and Hanshan Temple. In the Sui and Tang Dynasties, the high-density circle extended to the southeast of the ancient city because of the construction of the Precious Belt Bridge [8]. There were two new sub-dense areas scattered along the southern part of the Grand Canal, and the Canal acted as an axis from northwest to southeast for the distribution belt of cultural heritage. From the Pre-Sui period to the Five Dynasties to Song Dynasty, the ancient city had been the unique core of cultural heritage sites, which was a result of its administrative role in political, social, and cultural affairs [31]. It was not until the Yuan and Ming Dynasties that the high-density area started to stretch northwest towards the Shantang Canal. This is because the Stone Stupa of the Rev. Bai Causeway was built by the Shantang Canal and the Xiajin Bridge and Lingering Garden were constructed by the Shangtang Canal.

The sites showed a more concentrated aggregation in the ancient city, and the six sub-dense areas along the Grand Canal became denser. In the Qing Dynasty, the high-density core dissolved into one high-density circle extending from the Chang Gate to the Shantang Canal,

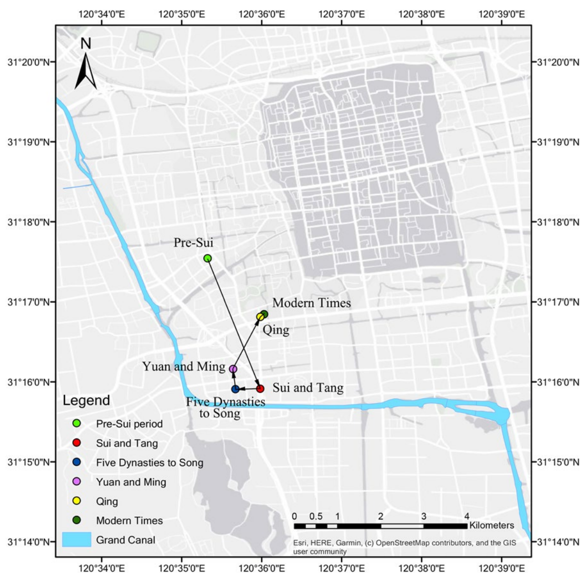


Fig. 6 Movement of center of gravity of the six historical periods

Table 5 Location and movement of the center of gravity in six historical periods

Period	Longitude	Latitude	Move distance/ meters
Pre-Sui	120.588774	31.292330	37.204
Sui and Tang	120.599721	31.265210	5.735
Five Dynasties to Song	120.594570	31.265112	5.487
Yuan and Ming	120.594071	31.269324	15.457
Qing	120.599764	31.280201	1.094
Modern Times	120.600518	31.280742	N/A

N/A means "not applicable" in the table

and one diagonal sub-high-density stretch leading to the southwest part of the ancient city. The density of sites along the Shantang Canal increased more than four times compared to the previous historical period, and the distribution pattern has been determined since then. The sub-high area expanded from the Pingjiang Historical District towards the Pan Gate and the southwest city moat of Suzhou, which was not only the economic and cultural center, but also the main passage for regional boats [1]. In Modern Times, the sub-high-density circle shifted southwest, because four recent buildings were built in the south and west sides of the ancient city.

Analysis results of center of gravity

According to Fig. 6 and Table 5, the movement of the centers of gravity of the six periods shows a trend of southeast-west-northwest-northeast-northeast, and the center moved 64.977 m in all. From the Pre-Sui period to the Sui and Tang Dynasties, the centroid moved 37.204 m along the Grand Canal, and both centers of gravity are located east of the Grand Canal. This migration is the result of the construction of three water conservancy projects along the southern section of the Suzhou Canal, including the Precious Belt Bridge, Ande Bridge, and the Track Road of Wujiang [8]. The centers of gravity of all these six periods are located between the Grand Canal and the southwestern section of the city moat. This indicates that the Grand Canal was the dominant factor affecting the migration of the centers of gravity. The center of gravity of Yuan and Ming moved 5.487 m northwest, because the sites were added in the northern section of the Suzhou Canal, Shantang Canal and Shangtang Canal. The center of gravity of the Qing Dynasty presented a movement trend towards the ancient city, which is consistent with the strengthened infrastructures in the ancient city [34].

Analysis results of standard direction ellipse

The standard direction ellipse is used to show the differences of distribution of sites in the six periods and to analyze the directional characteristics of the sites in each period. The ratio of the long and short axes of the ellipse determines the directionality; and the size of the

Table 6 Statistics of the ellipses in the six historical periods

Period	X-Axis Length (m)	Y-Axis Length (m)	Elliptical Area (m^2)	Rotation Angle (∘)
Pre-Sui	176.535	71.191	39481	70.72
Sui and Tang	157.519	129.589	64124	59.12
Five Dynasties to Song	146.447	111.198	51157	49.21
Yuan and Ming	113.913	135.908	48635	16.79
Qing	90.140	128.312	36334	168.45
Modern Times	88.471	125.648	34921	168.53

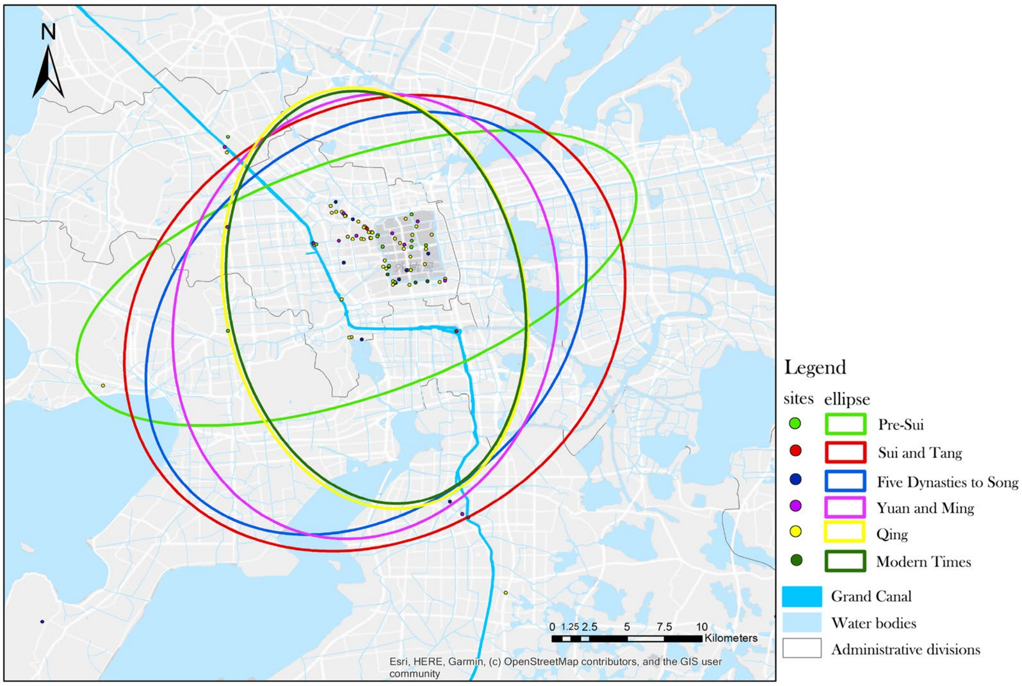


Fig. 7 Elliptical distribution of cultural heritage in the six historical periods

area of the ellipse can reflect the range of site distribution [30]. Table 6 presents the statistics of the long axis, the short axis, the elliptical area, and the rotation angle. The results show that the ellipses from the Pre-Sui to the Yuan and Ming Dynasties all show a southwest-northeast distribution trend, which spanned across the ancient city and Grand Canal water system. The ellipses of the Qing Dynasty and Modern Times presented a southeast-northwest distribution trend, which is consistent with the flow direction of the Suzhou Canal (Fig. 7). The Grand Canal has played a substantial role in shaping the direction of the layout after the Qing Dynasty. From the Pre-Sui Dynasty to the Qing Dynasty, the ellipse rotated counterclockwise, and the overall rotation angle of the ellipse was 97.81°. The elliptical direction of the Qing tended to be stable, and the present distribution pattern has taken shape since then. The ellipse of Modern Times has the smallest distribution range and the most obvious distribution directionality.

Influencing factors for evolution

To analyze the evolution of cultural heritage distribution, it is important to investigate the geographical and hydrological environment around the Suzhou Canal, and study the economic, political, and cultural developments in their specific historical context. The influencing factors on the distribution of Suzhou's cultural heritage can be classified into two categories: natural and human [30, 45]. Factor detection on GeoDetector is performed to explore the statistical relationship between the cultural heritage sites and several influencing factors, including elevation, canal, population, water transportation, and ICH.

Natural factors

Suzhou is in the middle of the Yangtze River delta and the Taihu plain, and 54.8% of the total area is plain [34]. Suzhou belongs to the northern subtropical humid monsoon climate zone, and the climate in Suzhou is warm and humid with abundant precipitation [31], which is suitable for farming and planting [33]. In addition, Suzhou is adjacent to Tai Lake in the west and the Yangtze River in the north. These water systems provide good irrigation conditions for fisheries and rice cultivation, thus driving the economic development of Suzhou and its surrounding cities [5]. The unique geographical and hydrological characteristics surrounding the canal system in Suzhou have laid the foundation for the cultural heritage [1].

With ArcGIS 10.8, the DEM dataset was superimposed on the sites, and the DEM elevations were extracted to point shapefiles. The elevation of each of the 96 sites was calculated, and the number of the sites in each elevation level was counted (Fig. 8). According to the DEM data about cultural heritage sites, the lowest elevation is -3 m, and the highest elevation is 42 m. The elevation of cultural heritage sites is divided into six levels: level 1 is – 10–10 m, level 2 is 10–30 m, level 3 is 30–50 m, level 4

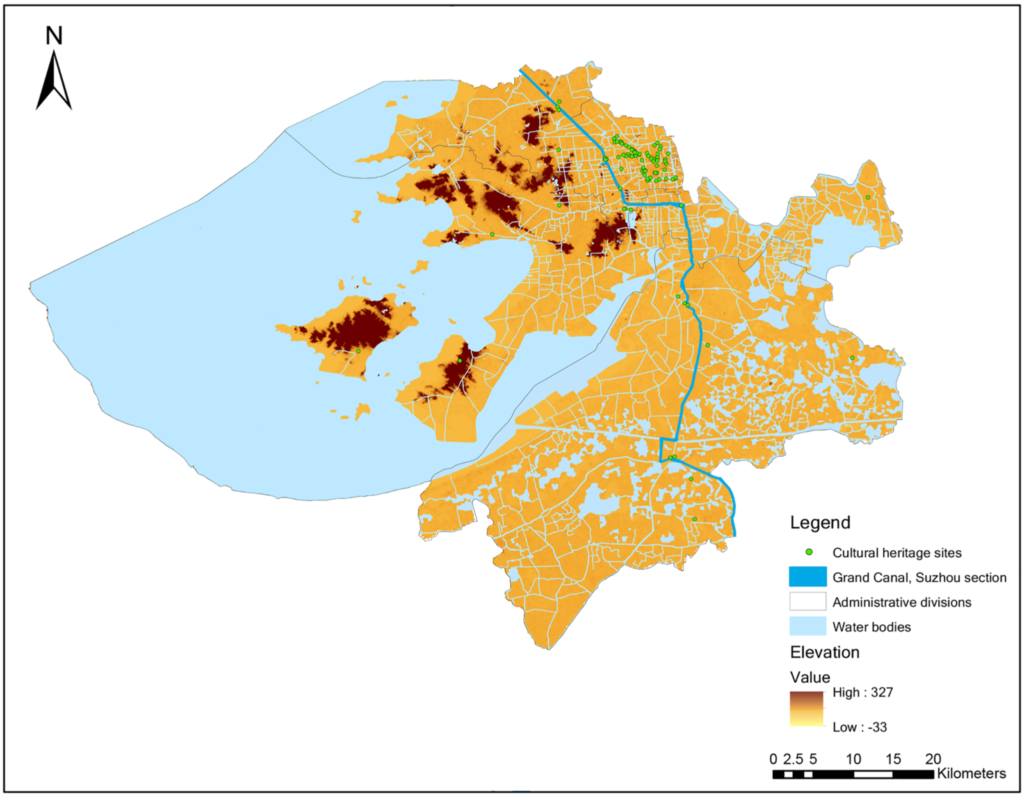


Fig. 8 Elevation of cultural heritage sites

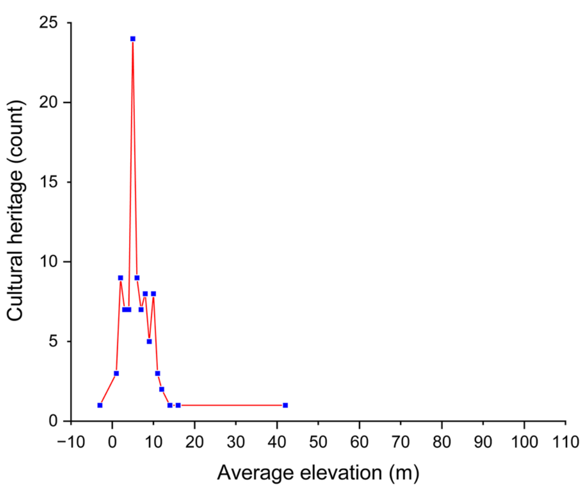


Fig. 9 Change curves of the cultural heritage sites with different elevation levels

is 50–70 m, level 5 is 70–90 m, and level 6 is 90–110 m. The change curves of the sites in different elevation levels were plotted to investigate the influence of elevation on distribution of the sites (Fig. 9). According to Table 7, 84.4% of the sites are distributed in the elevation range of – 10–10 m, and 14.6% of the sites are distributed in the elevation range of 10–30 m. The results show that the elevation had a definite influence on the distribution.

Human factors

The evolution of the Grand Canal water system and its associated cultural heritage sites are affected by the political, social, economic, and cultural aspects in Suzhou's history. During the Spring and Autumn Period, Suzhou was the capital and economic center of the State of Wu and has been the political and military center in the Jiangnan region since then [34]. The

Table 7 Altitude of cultural heritage sites

Altitude (m)	– 10 ~ 10	10 ~ 30	30 ~ 50	50 ~ 70	70 ~ 90	90 ~ 110
Number of sites	81	14	1	0	0	0
Percentage of sites	84.4%	14.6%	1.0%	0	0	0

Emperors of Wu ordered the construction of the canal system to transport troops and food and compete with the surrounding states [8]. The economic prosperity produced a specific cultural and art context in Suzhou [5], which became the cultural center in the southern part of China [35]. Since 514 BCE, Suzhou has been one of the most prosperous cities in regions south of the Yangtze River, serving as the production and trade center of grain and commerce [1]. From the Sui Dynasty to the Yuan Dynasty, the country's economic center moved southward, fueling the prosperity of Suzhou's commerce and the diversification of citizens' lives [33]. The Tang government strengthened water management regulations and issued the first "water law" in China to control the canals, water transportation, and water conservancy facilities [34]. During the Tang and Song Dynasties, Suzhou was transformed into the industrial and commercial center south of the Yangtze River, and the economic strength of the Yangtze River delta began to surpass that of the north [5, 34]. The Yuan government published an open policy with foreign businessmen who could gather at Liujia Port and travel via the Lou Canal, contributing to sea transport of grain and overseas commerce [8, 34]. During the Ming and Qing Dynasties, Suzhou was the economic center in China for production and trade of silk, cotton, and printed materials, and the transportation center for import and export of commodities and materials [36]. In the Qing Dynasty, Suzhou was the capital of Jiangsu, and the government set up the Customhouse of Suzhou to regulate foreign trade along the Grand Canal [8]. The city was densely populated by citizens [33], which was in line with the sharp rise of the number of cultural heritage sites in the Qing Dynasty.

Because of the Grand Canal water system, Suzhou is not only a shipping center for the Jiangnan Canal to connect with surrounding cities, but also a transportation hub between the north and south [5]. Water transportation has been of high importance in all dynasties of Suzhou, and the digging of the Grand Canal connected the canal system in the ancient city, enriching Suzhou's water transportation network [37]. The transportation of food, merchandise, and other goods often relied on the wharves in the Grand Canal, and this gave rise to water marketplaces [4, 25]. The Grand Canal facilitated the water transportation of architectural materials, thus promoting the construction of cultural heritage in Suzhou.

After surveying registered ICH lists published by the China ICH network (www.ihchina.cn) and Suzhou ICH network (https://szfy.wglj.suzhou.com.cn), and reviewing

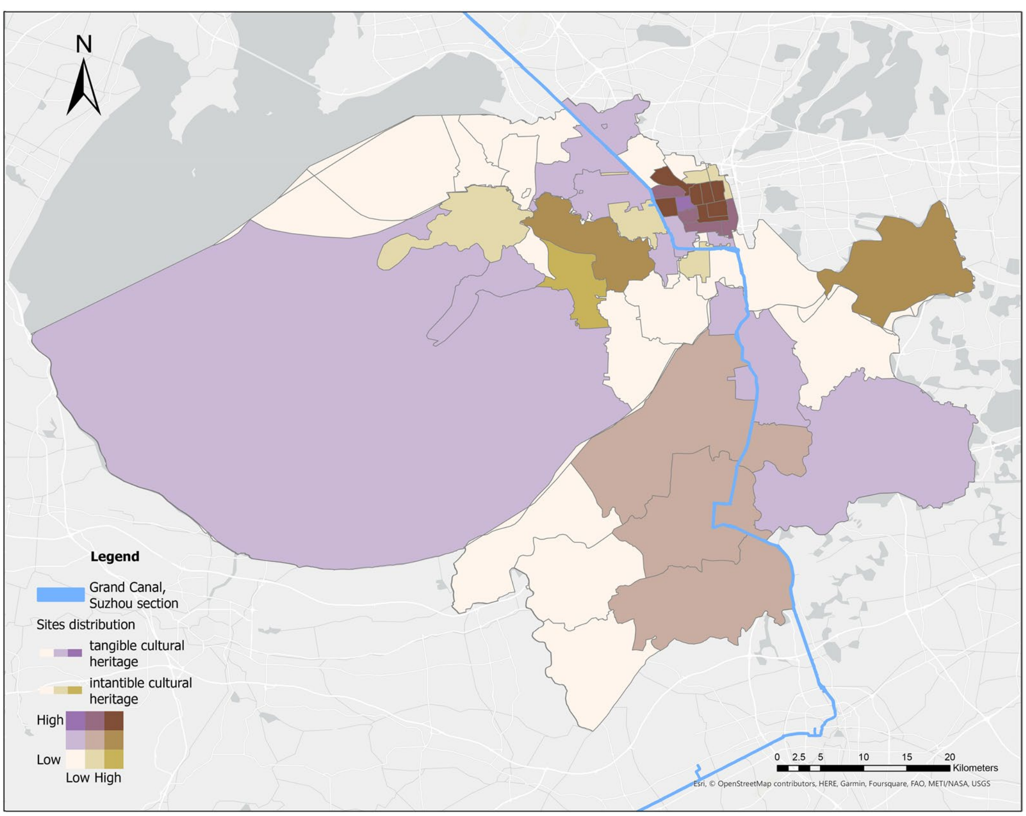


Fig. 10 Bivariate choropleth map of tangible cultural heritage in relation to ICH

several publications to clarify them [11, 40], this research selects a total of 54 categories of ICH related to the Suzhou Canal, including traditional theater, traditional dance, traditional music, traditional fine arts, traditional craftsmanship, traditional medicine, folklore, and folk literature. A bivariate choropleth map was made on ArcGIS Pro to determine if there are spatial correlations between tangible and intangible cultural heritage sites along the Suzhou Canal [46]. According to Fig. 10, denser heritage sites were seen spreading along the Grand Canal. Pockets with high density of ICH and low density of tangible cultural heritage were seen on the Tai Lake side of the Grand Canal. This is because fewer canal systems were distributed on the west side of the Grand Canal compared to the ancient city side. This map also highlighted the ancient city, the area around the Shantang Canal and the block on the southeast of the Shangtang Canal and Grand Canal as having both high density of tangible and intangible cultural heritage sites. This may have been the result of the larger concentration of canals on the ancient city side of the Grand Canal.

Multivariate analysis of the influencing factors

GeoDetector, or Geographical Detector, is a multivariate statistical tool to detect and assess the causal factors for an observed development in spatial variation analysis [38]. The factor detector on GeoDetector was used to identify the possible determinants of the cultural heritage types in the evolution process and measure the spatially stratified heterogeneity of the variables [39]. This part used the elevation data from 4.1 to reveal the statistical relationship of the sites and the Canal. Near analysis on ArcGIS 10.8 was used to calculate the nearest distance between the cultural heritage sites and the water system composed of the Grand Canal and canal system. Besides, the weight of goods transported via water and the population development of Suzhou in the six historical periods were collected from the historical volumes [23]. Among the 54 categories of ICH in 4.2, the count of ICH in each of the six historical periods was calculated.

In this research, the q-statistic method measures the degree of impact of each influencing factor on the heritage type in the six historical periods, and the statistics on elevation, nearest distance to the Canal, population, weight of goods transported via water, and ICH in a time series were obtained and imported into the calculator interface on GeoDetector. The q and p values of all influencing factors in this research were calculated and could support the assumption that these factors contribute to the evolution (Table 8). The q value is within 0 to 1, and the larger the q value is, the higher impact this explanatory variable exerts on the dependent variable; if the p value is smaller than 0.05, then the determinant power is obvious [41]. The q value of the canal factor is 1, which is significantly bigger than that of the other determinants; the p value of Canal is 0. The results suggest that the Canal has the paramount influence on the evolution of cultural heritage. Conversely, the statistical relationship suggests that population, elevation, water transportation, and cultural and art factors show insignificant impacts on evolution.

Table 8 Influencing factors and their determinant values

	Elevation	Canal	Population	Water transportation	ICH
q statistic	0.18	1	0.2	0.15	0.15
p value	0.909	0	0.984	0.075	0.241

Discussion

Comparison with previous studies

It is valuable to explore the evolution and distribution of the heritage sites along the Suzhou section of the Grand Canal using GIS spatial analysis and discuss the main influencing factors. The findings in this research have proved the initial assumptions: (1) the historical development of the Suzhou Canal affected the spatial distribution of heritage sites; and (2) several factors, including elevation, canal, population, water transportation and ICH, contributed to the spatio-temporal evolution of site distribution. This research transformed waterways in historical maps into geospatial data on ArcGIS and calculated the lengths of the waterways in two parts: the Grand Canal water system and canal system. The analysis of the changes in the canal system is consistent with that of Zhang [42] and Wang [34]. The georeferencing method used in the calculation of the lengths of the canal system is comparable to that of Zhang, and the results in the lengths are also very close, with small deviations ranging from 0.4 km to 6.7 km [42] (Table 9). The canal system was the longest from the Song Dynasty to the Ming Dynasty, which corresponds to the prosperity of the waterways in the Song and Ming Dynasties according to Zhang [42]. The length of the canal system reached

Table 9 Comparison of the lengths of the canal system in Ancient Suzhou City

Year	Research findings in this study	Synthesis calculations in Zhang 2013	Deviation
1229	82.4 km	87.8 km	5.4 km
1639	86.3 km	79.6 km	6.7 km
1896	62.4 km	61.3 km	1.1 km
1950	60.4 km	60.8 km	0.4 km
1986	37.0 km	39.6 km	2.6 km

a peak in 1639 CE, which is in line with the first to third calculations before the synthesis calculation in Zhang [42]. The population and weight of goods transported via water in the Ming Dynasty were relatively high among the six historical periods, which could account for the rise in the length of canals. This is consistent with Wang's explanation that canals were dredged several times in the Ming Dynasty and their prosperity is closely related to the economic development [42].

The number, type, construction time and distribution patterns of heritage sites correlate with geographical environment, historical development, and economic strength [47]. The relationship between the 96 cultural heritage sites selected for this study and the Grand Canal is likely to be unique and complex, and may involve multiple layers of historical, cultural, and functional connections. This is compatible with the selection criteria of cultural heritage sites in Li and Zhu's research [21]. Li and Zhu selected 31 water conservancy projects and 28 historical sites as tangible cultural heritage along the Grand Canal, Suzhou section. This study used GIS to show the kernel analysis maps of heritage sites attached to Suzhou Canal and revealed the spatial aggregation patterns in different historical periods. Another comparable GIS study on the Grand Canal was carried out by Zhao et al. [14]. He collected tangible and intangible heritage data and overlapped the kernel analysis with GIS-sDNA analysis to find out the in-site phenotype of the settlement space along the Grand Canal, Tianjin section. The results in this study signify that the heritage sites were concentrated around the Shantang District in the Ming and Qing Dynasties, and there was one sub-high-density area surrounding Precious Belt Bridge in the Sui and Tang Dynasties and two sub-high-density circles around Pingjiang Historical District and Pan Gate in the Qing Dynasty and Modern Times. This is confirmed by Qiu's research which highlighted the Precious Belt Bridge, Pingjiang and Shantang Historic Districts, Pan Gate, and Wujiang ancient towpaths as five typical heritage areas along the Grand Canal, Suzhou section [43]. In terms of the influencing factors, the canals have the most profound impact on the distribution of heritage sites. The q value of the canal factor reveals the dominant role of canals in determining the heritage distribution and this accords with Wang et al.'s conclusion that important urban areas developed along the canals [34].

Overall, the results in this study are consistent with those in previous studies and are scientifically based.

Future research directions

The selection of influencing factors in this research was made after extensive literature review and data mining; then a systematic index system could be constructed for the influencing factors related to the site distribution [28, 48]. This research collected the historical data of the influencing factors in past dynasties, and further research will bring other geographical and socio-cultural factors into the overall analysis and address the limitations in this research.

With the modern development of industries, the Grand Canal is no longer the primary transportation line of industry, and the densest area of cultural heritage has gradually shifted from the ancient city area [6]. In the rapid urbanization today, resilient measures should be taken by heritage conservation institutions to strike a balance between heritage conservation and sustainable development [34], and the modern planning of the Canal development should be based on historical authenticity and cultural identity [44]. For example, with the dangers of climate change, cultural heritage sites are even more at risk and deserve careful observation and protection. To update the cultural-ecological system along the Canal, the historical resources of different periods in this study should be linked to the Canal, and should be registered, recognized, and reused with the cooperation of the departments of cultural heritage, water conservancy, and tourism, etc. [48]. The series mapping in this research displays a long period of cultural accumulation and regional change, thus offering valuable implications for landscape planning along the Suzhou Canal.

Conclusion

Using the multi-dimensional and multi-data framework, this study traces the evolution of the cultural heritage distribution along the Suzhou Canal and presents cultural mapping in a time-series of historical periods. The main conclusions of this research are as follows. (1) The construction of the Suzhou Canal began in the Spring and Autumn Period, flourished in the Sui dynasty, and continued in Modern Times. (2) Throughout this time scope of over 2500 years, the Suzhou Canal has always been the determinant axis for the layout of heritage sites, which are distributed in a belt along the Canal. The canal system affects the spatial evolution of cultural heritage sites. (3) The urban area surrounding Ancient Suzhou City was the high-density core and the geographic center for the distribution of heritage sites. (4) The statistical analysis tools show correlations between the evolution and influencing factors and verify the impacts of these factors.

The inclusion of the GCC in UNESCO's World Heritage List indicates its deep cultural significance in Chinese civilization and its appeal to international audiences. To honor this decision, historical, geographical, and cultural factors should be embodied in the canal protection strategy, and digital preservation techniques should be used for the cultural heritage. It is valuable to investigate the evolution of canals and cultural heritage for cultural development and promotion. By applying GIS spatial analysis methods that can be tailored to a variety of features, this article offers a scientific basis applicable for further research and provides a relevant model for future sustainable heritage conservation and urban planning work in many parts of the world.

Abbreviations

GIS	Geographical information system
GCC	Grand Canal in China
ICH	Intangible cultural heritage
UNESCO	United Nations educational, scientific and cultural organization
DEM	Digital elevation model
NNI	Nearest neighbor index

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Availability of data and materials
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Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
The authors declare that they have no competing interests.

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