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A study on the spatial distribution and historical evolution of spirit road stone carvings in the ancient capital of Nanjing and its surrounding areas

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This study applies GIS-based spatial analysis and historical geographic methods to examine the spatial distribution and temporal evolution of spirit road stone carvings (SRSCs) in Nanjing and surrounding regions. Using data from dynastic chronicles and archaeological surveys, it identifies key natural and cultural factors influencing SRSCs placement. Results reveal a clustered distribution pattern, with Qixia and Xuanwu as core zones and Danyang as a secondary center. A spatial shift is observed from the Southern Dynasties to the early Ming period, with the centroid moving northwest by 52.27 km. Most SRSCs are located below 40 m elevation and within 10 km of rivers. Political centralization, family burial traditions, and feng shui beliefs significantly influenced site selection. This research contributes a novel spatial perspective to funerary heritage studies and supports the development of 3D modeling and VR applications, advancing digital heritage conservation.

Immovable cultural relics, defined as cultural heritage with a fixed location tightly integrated with the surrounding landscape and legally protected from relocation, typically include ancient cultural sites, ancient tombs, historic buildings, cave temples, stone carvings, murals, and other significant modern historical sites and representative architecture¹. Immovable cultural relics are of immense historical, artistic, and scientific value, representing the invaluable cultural heritage of the Chinese nation. Spirit road stone carvings (SRSCs), a type of stone-carved heritage, fall within this category. The term “spirit road” refers to the ceremonial road leading to a tomb, with the stone carvings placed symmetrically along its sides as markers of the burial site. By the Southern and Northern Dynasties, the establishment of spirit roads with flanking stone carvings on level ground before the burial mound had evolved into a standardized burial practice². As an integral part of immovable cultural heritage, SRSCs encompass various art forms, including sculpture, inscriptions, and calligraphy. They reflect the development and evolution of ancient Chinese burial practices, serving as evidence of cultural exchanges between China and ancient civilizations such as India, Assyria, and Greece³. The formation and development of SRSCs were influenced by ethnic integration and the localization of religions such as Buddhism and Zoroastrianism⁴. As a significant product of intercultural exchange and fusion in antiquity, SRSCs possess a high degree of global significance and value. In-depth research on these carvings not only aids in preserving and

promoting China’s rich cultural heritage but also fosters mutual trust, learning, and understanding between Chinese and foreign cultures, aligning with the broader goals of global integration⁵.

As an ancient capital of eleven dynasties (Eastern Wu, Eastern Jin, Song, Qi, Liang, Chen, Southern Tang, Ming, Southern Ming, Taiping Heavenly Kingdom and the Republic of China)⁶, Nanjing has preserved a substantial number of SRSCs, notably the stone carvings of the Southern Dynasties tombs and the early Ming dynasty officials’ tombs. These have formed a relatively complete and rich cultural and artistic system of SRSCs². Since 1923, when the French Jesuit Zhang Huang, once a vicar at Xujiahui, Shanghai, authored “*A Study on the Tombs of the Liang Dynasty*” in French, scholars like Zhu Xizu and his son, Teng Gu, Luo Zongzhen, Wang Huanbiao from China, as well as Kan Amakawa and Yasuyuki Fujii from Japan, have successively conducted research and written works in this field. These studies, from the perspectives of archeology and art history, have systematically summarized issues related to the origins, artistic lineage, attribution, conservation, and restoration of the SRSCs in front of the princely tombs of Nanjing’s dynastic periods as an ancient capital⁷. “*Survey Report on Six Dynasties Tombs*”, authored by Zhu Xizu and Teng Gu, is a landmark work in this field, laying the foundational framework for the development of art archaeology in China and establishing a basis for subsequent studies on SRSCs⁸.

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In recent years, Geographic Information Systems (GIS) have become indispensable tools in cultural heritage research, offering robust capabilities in spatial analysis, visualization, and data management. These technologies have significantly advanced the study of spatial distribution and spatio-temporal evolution of heritage resources. For example, Shen et al. (2024) utilized spatial analytical tools and the Geodetector model to explore the distribution patterns and influencing factors of national-level cultural heritage in China, highlighting the roles of geography, policy, and culture⁹. Chu et al. (2024) applied nearest neighbor index and standard deviational ellipse techniques to investigate the evolutionary characteristics of heritage sites in northern Fujian, emphasizing the correlation between cultural landscape distribution and environmental conditions¹⁰.

At the global level, spatiotemporal models such as kernel density estimation and center of gravity analysis have been used to visualize the migration trajectories and aggregation patterns of world cultural heritage sites, revealing macro-level diffusion processes over time¹¹. Regionally focused studies have also demonstrated the versatility of GIS methods. Zhengchen et al. (2025) built a comprehensive database of cultural heritage sites in Xinjiang, using spatial statistical analysis to investigate how topography, transportation infrastructure, and human settlement patterns shape the geographic heterogeneity of site distributions¹². Similarly, Xu et al. (2025) examined the spatial evolution of China's national agricultural heritage systems, employing multiple GIS-based indicators to assess regional disparities and policy relevance¹³.

Beyond spatial pattern analysis, GIS has also been applied in multi-disciplinary and integrative frameworks for heritage management. For instance, Hadjimitsis et al. (2024) combined GIS with satellite remote sensing to assess both natural and anthropogenic risks to cultural heritage in Cyprus, establishing a comprehensive environmental monitoring framework¹⁴. Santos et al. (2023) employed GIS to support inventory, conservation, tourism, and cultural dissemination of Portugal's traditional ceramic tile heritage, demonstrating its potential for both analytical and promotional functions¹⁵. Likewise, Campanaro et al. (2016) integrated 3D GIS technology with laser scanning, photogrammetry, and computer vision techniques to develop a digital preservation workflow, significantly improving the documentation and restoration efficiency at the Swedish "Pompeii" site¹⁶.

However, while these studies demonstrate the diverse applications of GIS in cultural heritage research, most have centered on architectural remains, archeological landscapes, or site-based risk assessments. Few have systematically applied GIS to the study of funerary monuments—particularly SRSCs—as spatially embedded cultural artifacts with ceremonial, political, and esthetic dimensions. Prior studies on spirit road carvings have primarily focused on stylistic lineage, iconography, and epigraphy, lacking a comprehensive spatial-temporal framework. In response to these gaps, this study applies an integrated GIS methodology—including nearest neighbor analysis, Gini coefficient, kernel density estimation, and standard deviational ellipse—to examine the spatial clustering, evolutionary trajectories, and environmental correlations of SRSCs in Nanjing and its surrounding regions. This approach contributes a data-driven, geographic perspective to the study of funerary heritage, offering new insights into the cultural landscape dynamics of the Jiangnan region.

Methods

Nanjing is a major central city in eastern China and the capital of Jiangsu Province. It is located in the southwestern part of Jiangsu, along the lower reaches of the Yangtze River (118°22'–119°14'E, 31°14'–32°37'N)¹⁷. Nanjing is one of the first 24 historical and cultural cities designated by the State Council, and it ranks alongside Xi'an, Luoyang, and Beijing as one of China's four great ancient capitals. It boasts a 500,000-year history of human civilization, a 2500-year history as a city, and over 1700 years as a capital. As the capital of various dynasties, Nanjing served as a political, economic, and cultural center, with the SRSCs at the tombs of emperors and nobilities reflecting the standards and historical value associated with each period. This study defines its temporal scope by focusing on the dynasties that established their capitals in Nanjing, including the Eastern Wu, Eastern Jin,

Song, Qi, Liang, Chen, Southern Tang, Early Ming, Southern Ming, Taiping Heavenly Kingdom, and the Republic of China⁶. Among these, Eastern Wu, Eastern Jin¹⁸, Southern Tang, Southern Ming¹⁹, and Taiping Heavenly Kingdom²⁰ left no extant SRSCs, and the Republic of China, not being an ancient feudal dynasty, had no corresponding tomb system or SRSCs²¹. The primary periods with extant and identifiable SRSCs are the Southern Dynasties (420–589)—specifically the Song, Qi, Liang, and Chen—and the early Ming period. Here, the early Ming period refers to the years from 1368, when the Hongwu Emperor Zhu Yuanzhang established his reign in Nanjing, to 1421, when the Yongle Emperor Zhu Di declared Beijing the capital²², totaling 53 years. Therefore, the temporal focus of this study encompasses the Southern Dynasties (Song, Qi, Liang, and Chen) and the early Ming period.

The spatial scope of this study includes locations within the defined temporal range where SRSCs are distributed. These primarily encompass areas under the jurisdiction of Nanjing, Jiangsu Province, and nearby areas such as Jurong and Danyang in Zhenjiang, Xuyi County in Huai'an, and Fengyang, Bengbu, and Feidong in Anhui Province.

Data sources

The data in this study primarily come from three sources, the first being the administrative divisions and basic geographic information data. This, including vector data on national and prefecture-level administrative boundaries, hydrography, and elevation maps of China, were obtained from the Geospatial Data Cloud (<https://www.gscloud.cn/sources/index?pid=1&type=1>).

The second data source is the vector data on SRSCs. According to the Law of the People's Republic of China on the Protection of Cultural Relics, the Jiangsu Provincial Bureau of Cultural Heritage has implemented a policy of "in situ protection" for immovable cultural relics, which mandates that existing SRSCs must be preserved at their original locations and not be relocated. Therefore, the SRSCs analyzed in this study were categorized into three types: (1) Preserved in situ with surviving remains. This includes sites where the carvings are still preserved at their original locations today (e.g., most cases represented by the Liu Yu Chuning Mausoleum carvings). For these sites, field investigations were conducted. Upon locating each site, the geographic coordinates were obtained using the Baidu coordinate picker, and additional data such as dimensions, preservation status, and condition were recorded using measuring tapes, laser rangefinders, drones, and 3D laser scanners. Information on administrative regions and protection levels was sourced from the official website of the Jiangsu Provincial Bureau of Cultural Heritage (<https://wlt.jiangsu.gov.cn/>). (2) Surviving carvings that have been relocated but with verifiable original locations. These include cases such as the Southern Dynasties Taiping Village unnamed tomb carvings, originally excavated in Taizi'ao, Taiping Village, Yanziji Town, Nanjing, and later moved to display halls in the Nanjing Museum. The original coordinates, administrative information, and protection levels were obtained from the results of the Third National Cultural Relics Census (hereafter referred to as the "Third Census"), which are archived at the Nanjing Municipal Museum and provided by the third author of this paper, Yingnan Li. (3) Excavated carvings with verifiable original locations but subsequently lost. Examples include the carvings from Tai'an Mausoleum of Emperor Gao of Qi (Xiao Daocheng) in Zhaojiawan, Wujiacun, Huqiao Town, northeast of Danyang, which were destroyed by local farmers in the 1960s, and carvings from Shiziba Village, Maqun Town, Qixia District, Nanjing, which were stolen after excavation. The original coordinates, administrative information, and protection levels for these cases were also sourced from archeological excavation records archived at the Nanjing Municipal Museum and provided by the third author, Yingnan Li. Finally, ArcGIS 10.3 software was used to process the geographic coordinate data and attribute data of SRSCs, generating the vector data necessary for spatial analysis.

The third data source is the historical data. The historical period data presented in this paper, such as the number of floods during the Eastern Jin, Southern Dynasties, and early Ming periods, as well as the migration routes of the Xiao family, are derived from the analysis and compilation of official

Fig. 1 | Distribution of SRSCs in Nanjing and its surrounding areas. This map shows the spatial distribution of SRSCs across several regions in Jiangsu and Anhui Provinces, including Nanjing, Zhenjiang, Chuzhou, Hefei, Bengbu, and Huai'an. The markers represent different levels of heritage designation. Orange stars indicate National Cultural Heritage sites, blue crosses denote Provincial Cultural Heritage, green triangles represent City Key Cultural Heritage, magenta squares show City Cultural Heritage, yellow diamonds indicate District Cultural Heritage, and gray circles denote unclassified sites. The clustering of heritage sites is particularly notable in and around Nanjing, suggesting its historical prominence. Administrative boundaries, major cities, and scale are also depicted for geographic reference. All symbols are clearly labeled in the legend.

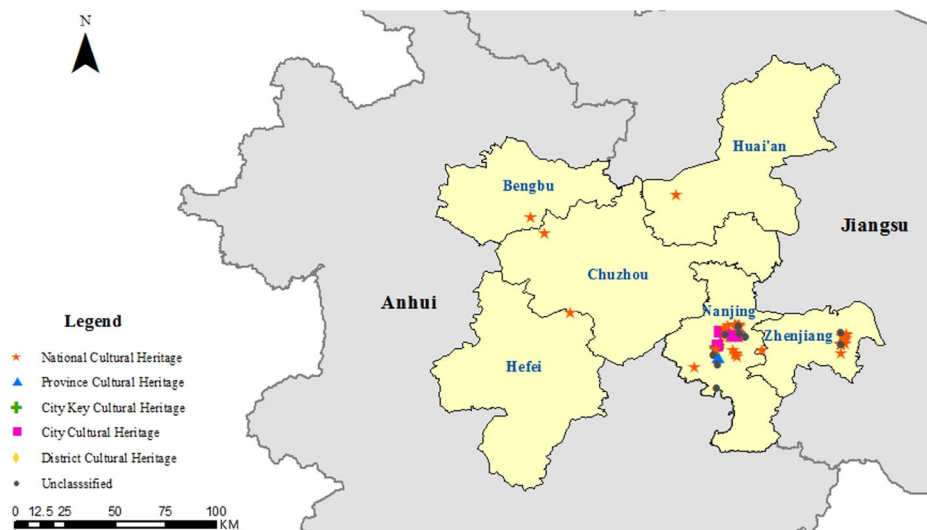


Table 1 | Survey registration table of SRSCs in Nanjing and its surrounding areas

Province /City	District	World cultural heritage	National cultural heritage	Province cultural heritage	City cultural heritage	District cultural heritage	Unclassified	Number
Jiangsu /Nanjing	Qixia	-	12	-	1	-	3	16
Jiangsu /Nanjing	Jiang ning	-	7	1	-	-	5	13
Jiangsu /Nanjing	Xuan wu	7	-	-	1	1	-	9
Jiangsu /Nanjing	Yuhua tai	-	3	-	2	-	1	6
Jiangsu /Nanjing	Gu lou	-	-	-	1	-	-	1
Jiangsu /Zhengjiang	Dan yang	-	11	-	-	-	2	13
Jiangsu /Zhengjiang	Ju rong	-	1	-	-	-	-	1
Jiangsu /Huai'an	Xuyi	-	1	-	-	-	-	1
Anhui /Chuzhou	Feng yang	-	1	-	-	-	-	1
Anhui /Bengbu	Long zihu	-	1	-	-	-	-	1
Anhui /Hefei	Fei dong	-	1	-	-	-	-	1

Chinese historical works, specifically the “Twenty-Four Histories.” These include the Records of the Grand Historian (Shiji), Book of Han (Hanshu), Book of Later Han (Hou Hanshu), Records of the Three Kingdoms (Sanguozhi), Book of Jin (Jinshu), Book of Song (Songshu), Book of Southern Qi (Nan Qishu), Book of Liang (Liangshu), Book of Chen (Chenshu), and History of Ming (Mingshi), as well as the chronological official annals Ming Shilu (Veritable Records of the Ming). The ten volumes from the “Twenty-Four Histories” series cited in this paper are based on the editions published by Zhonghua Book Company, Beijing, in January 2000 (ISBN: 9787101021288). The edition of Ming Shilu used is the one published by Zhonghua Book Company, Beijing, in January 2016 (ISBN: 9787101110906).

The distribution of these stone carvings includes 16 sites in Qixia District, 13 in Jiangning District, 9 in Xuanwu District, 6 in Yuhuatai District, and 1 in Gulou District, all in Nanjing, Jiangsu Province; 13 sites in Danyang City and 1 in Jurong City, Zhenjiang, Jiangsu Province; 1 in Xuyi County, Huai'an, Jiangsu Province; 1 in Fengyang County, Chuzhou, Anhui Province; 1 in Longzihu District, Bengbu, Anhui Province; and 1 in Feidong County, Hefei, Anhui Province. Among these sites, there are seven designated as World Cultural Heritage, 45 as national key cultural relics protection units (including the seven World Cultural Heritage sites), one as a provincial-level protected unit, five as city-level protected units, one as a district-level protected unit, and 11 sites with no official protection designation, totaling 63 sites (Fig. 1 and Table 1).

Research methods

The research methodology includes the following steps: (1) Using the nearest neighbor index to analyze the spatial distribution patterns and layout of the SRSCs. (2) Calculating the Gini coefficient to assess the imbalance in the number and density of SRSCs within district (county) level units and to determine whether there are spatial disparities among the carvings. (3) Applying the kernel density estimation tool to identify central areas within the spatial distribution of the SRSCs. (4) Using the standard deviational ellipse to analyze the centrality, distribution, directionality, and spatial range of the stone carvings' spatial distribution²³.

Using the nearest neighbor index to analyze the spatial distribution patterns and layout of SRSCs. SRSCs can be abstracted as point features, characterized by three types of spatial distributions: random, uniform, and clustered. In research, the nearest neighbor index (R) is commonly used to differentiate among these patterns²⁴. The formula for calculating the nearest neighbor index is given as follows:

$$R = \bar{r}_i / r_E \tag{1}$$

$$r_E = \frac{1}{2\sqrt{m/A}} = \frac{1}{2\sqrt{D}} \tag{2}$$

In this formula, \bar{r}_i represents the average distance from each point to its nearest neighbor; r_i is the theoretical nearest neighbor distance for a random distribution of point features; m represents the number of point features; A is the study area; and D is the density of point features per unit area. When $R = 1$, the point features tend to be randomly distributed; when $R > 1$, the point features tend to be uniformly distributed; and when $R < 1$, the point features tend to be clustered²⁵.

Using the Gini coefficient model to calculate the imbalance in the number and density of SRSCs within district and county units, and to determine whether spatial differences exist among these carvings. This analysis uses the imbalance index to reflect the distribution balance of SRSCs across selected districts and counties in Jiangsu and Anhui provinces²⁶. The calculation formula is as follows:

$$S = \frac{\sum_{i=1}^n Y_i - 50(n + 1)}{100n - 50(n + 1)} \quad (3)$$

In this formula: n represents the number of districts and counties, Y_i represents the cumulative percentage of the proportion of SRSCs in each district or county, sorted in descending order. S ranges from 0 to 1: when $S = 0$, the carvings are evenly distributed across all areas; when $S = 1$, all SRSCs are concentrated in a single district. The calculation of the Gini coefficient was performed using the default bandwidth settings in ArcGIS software, in which the bandwidth was automatically estimated based on the input data according to the Silverman bandwidth estimation method.

Using kernel density analysis to reflect the concentration and dispersion of SRSCs in Nanjing and its surrounding areas. Kernel density estimation calculates the density of point features around each output grid cell, directly reflecting the distribution characteristics of core areas of SRSCs²⁷. The formula is as follows:

$$F(x) = \frac{1}{Nd} \sum_{i=1}^n K\left(\frac{x - x_i}{d}\right) \quad (4)$$

In this formula, $F(x)$ is the estimated value of the kernel density, K is the Gaussian kernel function, x is the estimation point, x_i is the i th spirit road stone carving point, d is the search radius, and N is the number of spirit road stone carving points within the bandwidth²⁸.

The standard deviation ellipse can accurately reveal the overall spatial distribution characteristics of geographic elements²⁹. The centroid migration trajectory model can express the spatiotemporal evolution of geographic elements³⁰. The combination of these two methods has been widely used to study long-term series data and large-scale spatiotemporal patterns. The calculation methods are as follows:

$$\begin{cases} X = \sum_{i=1}^n x_i w_i / \sum_{i=1}^n w_i \\ Y = \sum_{i=1}^n y_i w_i / \sum_{i=1}^n w_i \end{cases} \quad (5)$$

Where X and Y represent the coordinates of the center of the standard deviation ellipse, X_i and Y_i represent the coordinates of pixel i , W_i is the weight, and N is the total number of pixels.

$$\tan \theta = \frac{\sum_{i=1}^n \bar{X}_i^2 W_i^2 - \sum_{i=1}^n \bar{Y}_i^2 W_i^2 + \sqrt{\left(\sum_{i=1}^n \bar{X}_i^2 W_i^2 - \sum_{i=1}^n \bar{Y}_i^2 W_i^2\right)^2 + 4\left(\sum_{i=1}^n \bar{X}_i \bar{Y}_i W_i\right)^2}}{2\sum_{i=1}^n \bar{X}_i \bar{Y}_i W_i} \quad (6)$$

Where θ is the azimuth angle, and X_i , Y_i is the coordinate difference between the spatial coordinates of the SRSCs within the study area and the center point (\bar{X}_w, \bar{Y}_w) .

$$\begin{cases} \sigma_x = \frac{\sqrt{2\sum_{i=1}^n (\bar{X}_i W_i \cos \theta - \bar{X}_i W_i \sin \theta)^2}}{n} \\ \sigma_y = \frac{\sqrt{2\sum_{i=1}^n (\bar{Y}_i W_i \sin \theta + \bar{Y}_i W_i \cos \theta)^2}}{n} \end{cases} \quad (7)$$

Where σ_x and σ_y represent the standard deviations along the X-axis and Y-axis, respectively, indicating the lengths of the X-axis and Y-axis, and n is the total number of pixels.

Methodological framework

This study establishes a comprehensive methodological framework integrating spatial statistical analysis with historical and environmental perspectives to systematically examine the spatial distribution patterns, temporal evolution, and environmental determinants of SRSCs in Nanjing and its surrounding areas. The methodological framework is structured in a sequential and complementary manner as follows: (1) The nearest neighbor index and Gini coefficient are first employed to evaluate the overall spatial distribution characteristics of SRSCs, identifying whether they exhibit random, uniform, or clustered patterns. These quantitative metrics serve as a foundational step for understanding macro-level spatial tendencies. (2) Kernel density estimation is used to visualize and analyze local spatial concentrations and to detect hotspot areas of SRSCs. This method helps reveal fine-scale variations and areas with significant cultural or political importance. (3) The standard deviational ellipse and center of gravity migration analysis are applied to explore directional distribution tendencies and track spatial shifts across different historical periods. These analyses illustrate how political events, such as the Disaster of Yongjia and capital relocation during the Ming dynasty, influenced the spatiotemporal evolution of SRSCs. (4) Spatial overlay analysis was conducted to examine the relationship between the distribution of SRSCs and environmental factors, particularly topographic constraints, using digital elevation models (DEM). In addition, historical climate and environmental data were primarily derived from official Chinese historical works mentioned in the data sources section above. These sources document climate conditions, natural disasters, and other environmental information, providing essential data support for understanding how considerations of flood prevention and construction convenience influenced site selection for SRSCs and the associated tombs.

The selection and integration of these spatial analytical methods are theoretically grounded in spatial statistics and historical geography. The analysis of clustering and directional patterns draws upon Tobler's First Law of Geography, which emphasizes the inherent spatial dependence of cultural phenomena. Furthermore, the incorporation of environmental overlay analyses is inspired by cultural landscape theory (Sauer, 1925), which underscores the mutual shaping of human activities and natural environments. By combining quantitative spatial metrics with historical documentary sources, this approach ensures that empirical findings are not only statistically robust but also theoretically anchored within the interdisciplinary framework of cultural heritage studies.

Results

Spatial distribution characteristics

At the district (county, including county-level cities) level, the geographic locations of SRSCs can be considered as point elements and represented by coordinate points. Based on the nearest neighbor index for SRSCs in Nanjing and its surrounding areas, the actual nearest neighbor distance is 5.02 km, while the theoretical nearest neighbor distance is 10.3 km. Analysis shows a nearest neighbor index of 0.48, which indeed indicates a clustered distribution pattern. Based on our GIS analysis results, this value is statistically significant. Specifically, the corresponding Z-score is -7.92 (p value < 0.001), which strongly indicates that the observed pattern significantly deviates from a random distribution at a 99% confidence level. Thus, the clustering tendency of the SRSCs is statistically confirmed rather than arising by chance (Fig. 2).

The imbalance index can be used to study the degree of balance in the distribution of point elements across different regions. Based on the Gini coefficient model, calculations in Excel yield an imbalance index of 0.568253968. Since the imbalance index is less than 1, this indicates an uneven distribution of spirit road stone carving points across the entire area.

Fig. 3 | Lorenz curve of SRSCs. This figure displays the Lorenz curve (red line) compared to a line of uniform distribution (green line) to assess the spatial distribution of SRSCs among administrative regions. The x-axis represents different regions, including Qixia, Danyang, Jiangning, Xuanwu, Yuhuatai, Feidong, Fengyang, Gulou, Jurong, Longzihu, and Xuyi, arranged in cumulative order. The y-axis indicates the accumulated percentage of SRSCs. The Lorenz curve shows significant deviation from the uniform distribution line, indicating that the carvings are unevenly distributed across regions, with a concentration in specific areas such as Qixia, Danyang, and Jiangning. This inequality suggests a strong spatial clustering tendency, reflecting historical and cultural preferences in site selection for spirit roads.

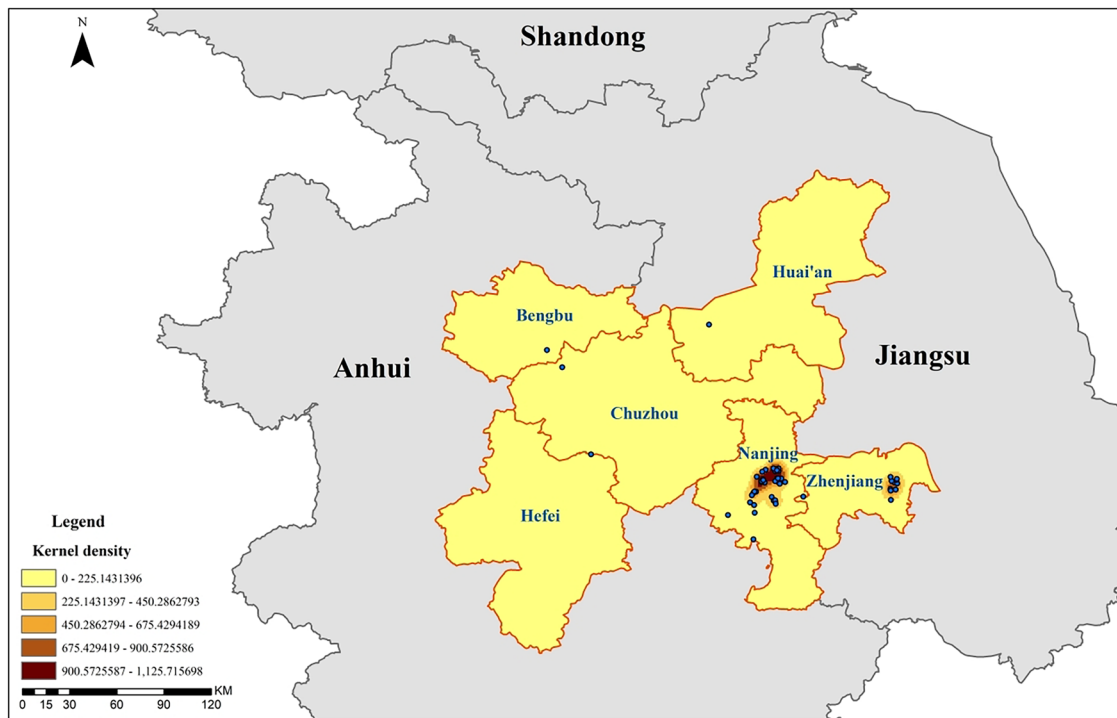
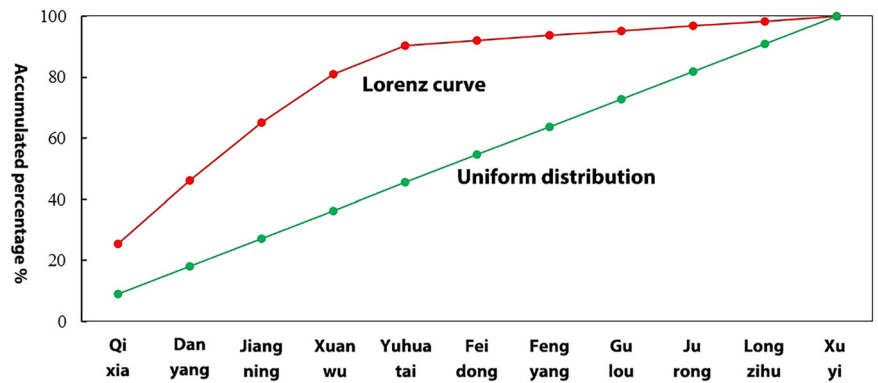


Fig. 4 | Kernel density map of SRSCs. This map illustrates the spatial distribution intensity of SRSCs based on kernel density estimation. The study area covers parts of Jiangsu and Anhui Provinces, including major cities such as Nanjing, Zhenjiang, Chuzhou, Bengbu, Hefei, and Huai'an. The color gradient—from light yellow to dark brown—represents five density levels, with darker shades indicating higher concentrations of stone carvings. The highest density range (900.57–1125.72) is

primarily concentrated in Nanjing and parts of Zhenjiang, signifying these areas as key cultural and historical centers. Each blue point represents an individual spirit road stone carving location. The visualization reveals a clear clustering pattern around Nanjing, validating the region's historical significance in funerary traditions during imperial China. Administrative boundaries and city names are labeled for reference, and a scale bar is included for distance measurement.

and revealing one primary cluster center and one secondary cluster center with distinct clustering boundaries. Among them, Qixia and Xuanwu are high-density areas, forming the primary cluster center with a certain degree of continuity. Danyang is a relatively high-density area, serving as the secondary cluster center. The Jiangning area is adjacent to the primary cluster center but has relatively lower clustering. Other areas show very low clustering, with a scattered distribution pattern.

Characteristics of spatiotemporal evolution

Using the Directional distribution ellipse tool within the Spatial statistics module in ArcGIS software, the stone carving data within the study area was processed to generate two different kernel density maps and a directional distribution ellipse. The ellipse's major axis represents the data distribution

direction and maximum dispersion direction, while the minor axis represents the data distribution range and minimum dispersion direction; the rotation angle indicates the dominant direction of distribution (Fig. 5)³¹.

The analysis results of the standard deviation ellipse show that the distribution pattern of SRSCs shifts from an east-west orientation to a northwest-southeast orientation across different periods. During the Southern Dynasties, the SRSCs exhibit an east-west orientation with clear directional characteristics; the area of the standard deviation ellipse is 21,274.02 km² (Table 2), with a major-to-minor axis ratio of 3.19, indicating a relatively clustered spatial distribution of the carvings. In this period, the primary locations of SRSCs were in Qixia, Danyang, and Jiangning (Fig. 6a). During the early Ming period, the SRSCs exhibited a northwest-southeast orientation. Although fewer in number, their distribution expanded in scale,

Fig. 5 | Standard deviation ellipse

distribution map. This map illustrates the spatial distribution trends of SRSCs during two historical periods using standard deviational ellipses. The orange ellipse represents the Southern Dynasty, while the blue ellipse represents the Ming Dynasty. Each ellipse visualizes the directional trend, spatial extent, and concentration orientation of the stone carvings for the respective period. The Southern Dynasty ellipse is more compact and oriented along an east-west axis, indicating a more centralized and regionally focused distribution pattern. In contrast, the Ming Dynasty ellipse is broader and tilted northwest-southeast, suggesting a wider and more dispersed distribution range. The comparison reveals a significant spatial shift and expansion in the location of SRSCs from the Southern Dynasty to the Ming Dynasty, reflecting changes in political centers, burial practices, and cultural influence over time. A scale bar is provided for distance reference.

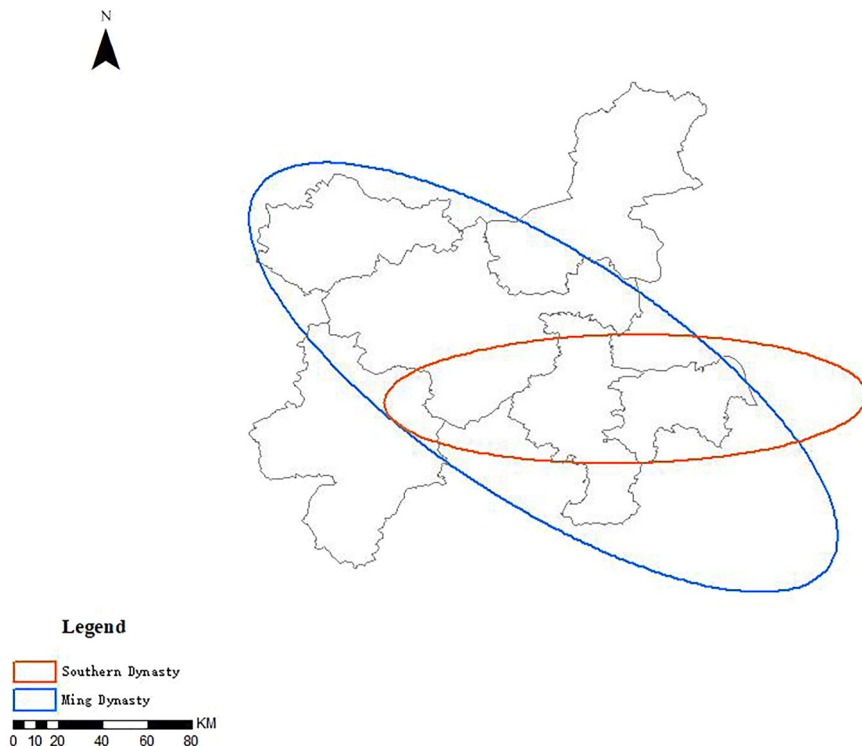


Table 2 | Standard deviation ellipse analysis results

Dynasty	Center X	Center Y	Ellipse area/km ²	Short axis length /m	Long axis length/m	Rotation angle/°	Flattening ratio
Southern Dynasties	119.121	32.042	21274.02	46058.22	147056.12	89.25	0.52299534
Early Ming	118.593	32.184	58279.23	84121.25	220557.48	130.24	0.60844414

primarily concentrated in Xuanwu District and Yuhuatai District (Fig. 6b). The rotation angle increased compared to the Southern Dynasties, and the ratio of the long axis to the short axis of the standard deviation ellipse was 2.62, indicating a reduction in directional characteristics compared to the Southern Dynasties. The area of the standard deviation ellipse reached 58,279.23 km² (Table 2), which is 2.74 times the area of the standard deviation ellipse for the Southern Dynasties stone carvings, reflecting a more dispersed spatial distribution and an increased level of spatial dispersion.

In summary, the spatial distribution of SRSCs in Nanjing and its surrounding areas during the Southern Dynasties and early Ming periods exhibited distinct directional characteristics, displaying east-west and northwest-southeast orientations, respectively. The spatial dispersion gradually increased, with the trend of dispersed expansion evolving from an east-west to a northwest-southeast orientation.”

Centroid migration analysis is a comprehensive and representative statistical method. Changes in the location of the centroid of SRSCs can indicate the overall spatial distribution trend of the carvings at that time or indirectly reflect the migration process of the center³².

By analyzing the evolution trend across the two historical stages, it was found that the SRSCs exhibited a southeast-to-northwest progression pattern (Fig. 7). During the Southern Dynasties, the center of SRSCs was located in Jurong City (119.121°E, 32.042°N). In the Ming period, the center shifted to Pukou District, Nanjing (118.593°E, 32.184°N), moving 52.27 km northwest from its location in the Southern Dynasties.

Discussion

Topographical factors are an objective natural influence and one of the main factors affecting the distribution of SRSCs in Nanjing and its surrounding areas. By overlaying the distribution map of SRSCs in Nanjing and its

surrounding areas with the regional topographic elevation map, data show that these carvings are mainly concentrated in mountainous and hilly terrains such as the Zhongshan area, Mufu Mountain area, Qixia Mountain area, Yuhuatai area, and Danyang Hills. Most SRSCs are located at elevations between 9 and 40 m. By overlaying the SRSCs with the digital elevation model (DEM) for analysis³³, elevation points for 63 SRSCs were obtained (Fig. 8).

Among them, 29 SRSCs are located at an elevation of 9–20 m, accounting for 46% of the total; 25 are at an elevation of 21–40 m, accounting for 40%; eight are at an elevation of 40–60 m, accounting for 13%; and one is at an elevation of 61–70 m, accounting for 0.02% of the total.

By period, in the Southern Dynasties, 28 sites are located at an elevation of 9–20 m, accounting for 44.4% of the total; 11 are at an elevation of 21–40 m, accounting for 17.5%; and four are at an elevation of 40–60 m, accounting for 0.06% (Fig. 9a).

During the early Ming period, 1 spirit road stone carving is located at an elevation of 9–20 m, accounting for 0.02% of the total; 14 are at an elevation of 21–40 m, accounting for 22.2%; 4 are at an elevation of 40–60 m, accounting for 13%; and 1 is at an elevation of 61–70 m, accounting for 0.02% (Fig. 9b).

Nanjing and its surrounding areas are located in the Ningzhen-Yang Hills region, part of the Jiangnan hilly zone in southern China. Low mountains, hills, and undulating uplands account for ~60.8% of the city’s total area¹⁷. The widespread hilly terrain across Nanjing provided favorable natural conditions for the selection of elevated sites for tombs and their associated SRSCs.

Precipitation and the frequent occurrence of floods are also among the main climatic factors influencing the distribution of SRSCs in Nanjing and its surrounding areas. The middle and lower reaches of the

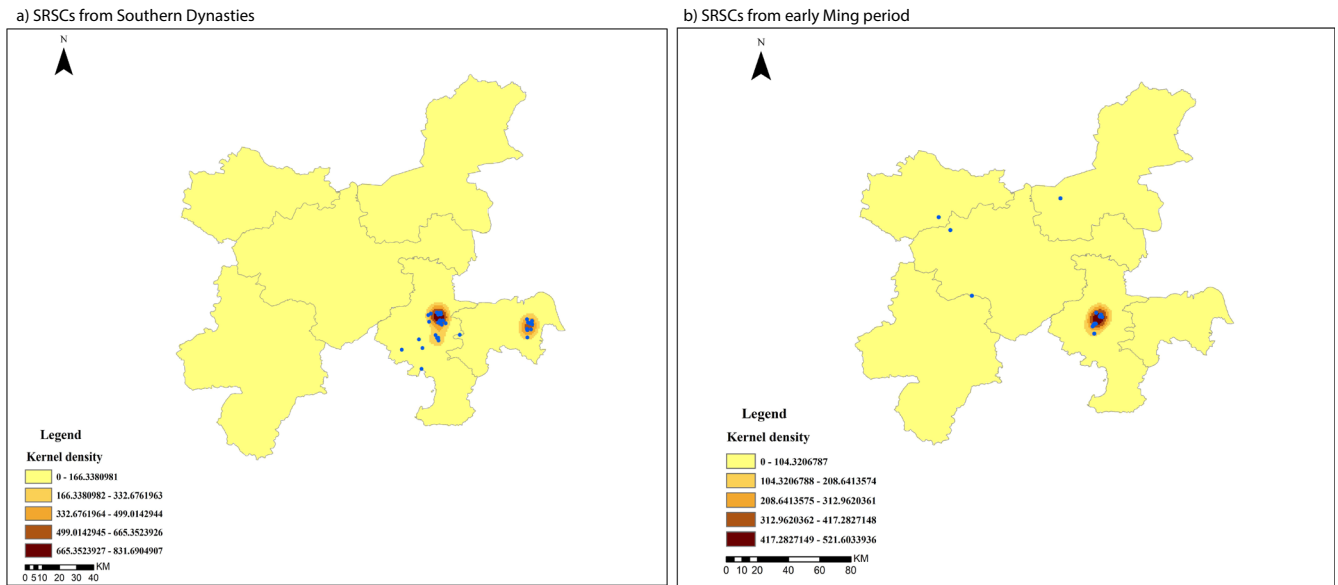


Fig. 6 | Kernel density map of SRSCs from Southern dynasties and early Ming period. This figure consists of two kernel density maps illustrating the spatial concentration of SRSCs during two distinct historical periods: **a** the Southern Dynasties and **b** the early Ming period. The maps cover the same geographic region, allowing for visual comparison of distribution changes over time. In panel (a), the SRSCs from the Southern Dynasties show a relatively dispersed yet dual-core pattern, with high-density clusters observed in both the central area near present-day Nanjing and a secondary cluster to the east. The kernel density values range from 0 to 831.69, with darker shades indicating higher spatial concentrations. Panel (b)

displays SRSCs from the early Ming period, revealing a more centralized and intensified clustering pattern primarily around Nanjing. The density range spans from 0 to 621.60, and the concentration appears more compact compared to the Southern Dynasties. The comparison indicates a historical evolution in burial site selection, suggesting political centralization and changes in ritual practices during the Ming dynasty. Each map includes administrative boundaries, city markers, and a color-coded legend to indicate the density ranges. A scale bar is also provided for distance reference.

Fig. 7 | Evolution map of SRSCs cluster centers.

This map illustrates the spatial migration of the central distribution point of SRSCs between two historical periods. The red dot represents the mean center of SRSCs from the Southern Dynasties, while the blue dot indicates the mean center for the Ming Dynasty. A black arrow connects the two centers, symbolizing the directional shift over time. The arrow points from east to west, reflecting a notable westward relocation of the spatial center of burial sites. This directional movement suggests changes in political geography, cultural priorities, and burial practices between the Southern Dynasties and the early Ming period. The map includes administrative boundaries for geographic reference and a scale bar for distance measurement. The visual representation provides clear evidence of spatial dynamics in heritage distribution across historical eras.

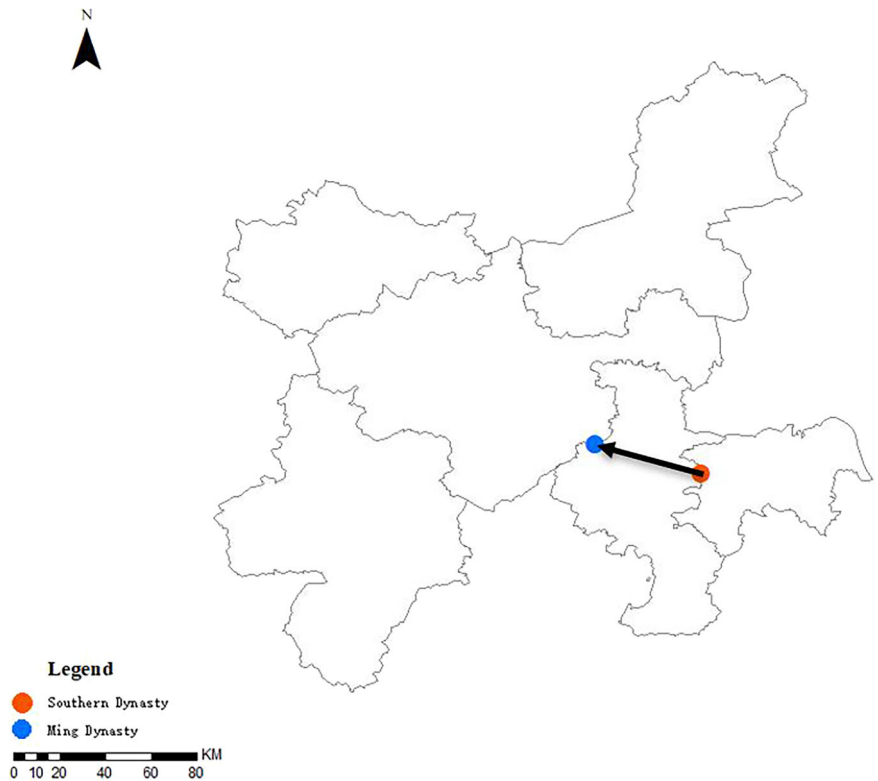


Fig. 8 | Elevation map of SRSCs. This figure presents a digital elevation model (DEM) of Nanjing and its surrounding regions, illustrating topographic variation and the altitudinal context of SRSCs. The background color gradient represents elevation in meters, ranging from dark green (lowest elevation, 0–17 m) to dark red (highest elevation, 213–602 m). The black diamond symbols indicate the locations of documented SRSCs. The map reveals that most of these carvings are distributed along low to moderate elevation zones (~35–144 m), primarily concentrated in the southern and southeastern parts of the study area. This spatial relationship suggests a preference for specific topographic conditions in burial site selection, aligning with traditional feng shui principles that favor locations at the foot of mountains and near water sources. The map includes administrative boundaries, a scale bar for distance reference, and a clearly defined legend indicating elevation ranges.

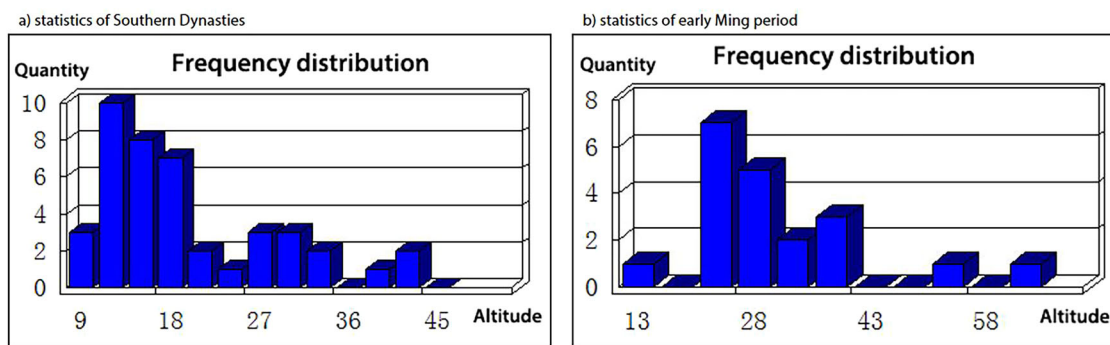
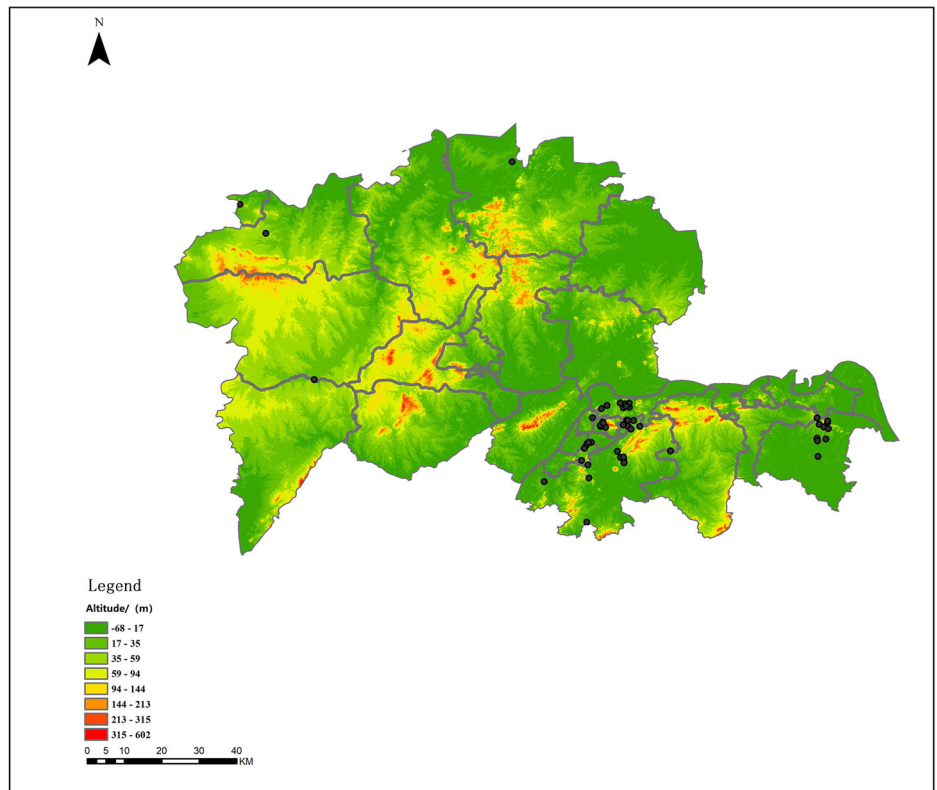


Fig. 9 | Altitudinal frequency distribution of SRSCs from the Southern Dynasties and the early Ming period. This figure presents two histograms comparing the elevation preferences of SRSCs from **a** the Southern Dynasties and **b** the early Ming period. The x-axis represents elevation (altitude in meters), while the y-axis indicates the quantity of SRSCs within each altitude range. Panel (a) shows that SRSCs from the Southern Dynasties are concentrated in low-altitude zones, particularly between 9–18 m, suggesting a strong preference for flat, river-adjacent terrain. In contrast,

panel **b** reveals that SRSCs from the early Ming period shift slightly toward higher elevations, with most sites distributed between 13 and 43 m, indicating a broader altitudinal tolerance and potential changes in site selection criteria over time. These frequency distributions reflect evolving burial practices and highlight the influence of geographical and cultural factors in the spatial planning of spirit roads across different dynastic periods.

Yangtze River, where Nanjing and its surrounding areas are located, belong to the subtropical monsoon climate zone, characterized by warm and humid conditions with distinct seasons. Historical and modern climatic records indicate that the annual precipitation in this region generally ranges from 800 to 1600 mm, while nearby hilly areas receive over 1600 mm per year. This persistent pattern of high precipitation has historically led to elevated groundwater levels and frequent seasonal flooding³⁴.

Official historical chronicles in ancient China systematically recorded meteorological disasters. By examining official historical records from the Eastern Jin, Southern Dynasties, and Ming Dynasty, this study identified 76 flood events in Nanjing and its surrounding areas between 317 and 589 CE, and 31 flood events between 1368 and 1450 CE, totaling 109 flood events

across these two periods, with an average occurrence of approximately once every 3 years (Table 3).

In ancient Chinese tomb construction, preventing water infiltration was always regarded as a primary consideration for site selection and structural design, as water penetration could lead to the decay of coffins, damage to burial objects, and collapse of burial chambers, causing severe destruction to the tombs. Based on the historical data, it is evident that frequent flooding in Nanjing and its vicinity would pose significant risks to tombs built at lower elevations. Therefore, given the widespread hilly terrain in this region, selecting higher-altitude hills and mountain slopes naturally became the preferred strategy for tomb placement.

Soil and lithological factors jointly influence the formation of the distribution of SRSCs in Nanjing and its surrounding areas. The soil types in

Table 3 | Historical Flood Events in Nanjing and its surrounding areas

Serial number	Calendar years	Dynasty	Number of flood events	Data source
1	317–420 CE	Eastern Jin	41	Book of Jin
2	420–479 CE	Liu-Song dynasty	10	Book of Song
3	479–502 CE	Southern Qi	6	Book of Southern Qi
4	502–557 CE	Liang dynasty	10	Book of Liang
5	557–589 CE	Chen dynasty	9	Book of Chen
6	1368–1398 CE	Ming (Hongwu era)	21	Ming Veritable Records
7	1399–1450 CE	Ming (Yongle era)	10	History of Ming, Ming Veritable Records

Nanjing are mainly divided into two categories: zonal soils and cultivated soils. In the northern and central parts of Nanjing, zonal soils are predominantly yellow-brown soils, while in the southern areas bordering Anhui Province, red soils are more common. Cultivated soils, formed through long-term agricultural activities, are mainly paddy soils, along with some yellow paddy soils and vegetable garden soils¹⁷.

These soils share common characteristics, including fine texture, poor structure, heavy and compact consistency, and poor water retention and permeability, making them prone to waterlogging and soil erosion³⁵. Based on the aforementioned climatic factors, it can be inferred that constructing tombs by deep excavation in low-elevation plain areas of Nanjing would inevitably lead to water seepage into burial chambers due to soil properties. Therefore, soil conditions further encouraged the selection of tomb sites on hilly terrains in Nanjing and its surrounding areas, to avoid structural damage caused by water infiltration.

The materials used for carving SRSCs are primarily limestone (CaCO_3), a type of sedimentary rock with a hardness of 2.7, which makes it easy to quarry. This type of stone typically occurs in block form, making it suitable for producing large-scale stone sculptures. Its fine crystalline structure provides resistance to weathering, facilitates precise detail carving, and ensures the clarity and durability of the carvings³⁶. Limestone is widely distributed in mountainous areas around Nanjing, such as Zhong Mountain, Mufu Mountain, and Yang Mountain. The distribution of SRSCs within these mountain ranges facilitated convenient material sourcing, transportation, and on-site carving operations, effectively reducing production costs and providing strong support for the construction of these stone carvings.

In summary, the tomb site selection practices in the Nanjing region can be compared with those in dynasties that established their capitals in present-day Xi'an, such as the Qin and Han dynasties. Xi'an is located in the Guanzhong region, with the urban area situated on the second terrace of the Weihe Plain at an elevation of 400–700 m, characterized by deep soil deposits. The soils of the Weihe Plain are mainly yellow-brown and brown soils, featuring deep layers and compact texture³⁷. Additionally, Xi'an has a continental monsoon climate with lower precipitation than Nanjing, resulting in minimal soil seepage risk.

Consequently, during the Qin and Han periods, imperial and noble tombs were often built in expansive areas and excavated deeply underground, with burial chambers connected to surface-level entrances via downward-sloping passages³⁸. In contrast, for dynasties that established their capitals in Nanjing, the soil's high permeability and the region's frequent flooding events eliminated the feasibility of deep underground excavation for tomb construction³⁹. However, the extensive hilly terrain in the area provided favorable natural conditions for constructing tombs on elevated sites (Table 4). As a result, tomb site selection in Nanjing adapted to local conditions by utilizing hilly landscapes, positioning tombs against hillsides and facing open plains. This led to the development of a distinctive system that evolved from the Qin and Han burial traditions, innovatively replacing underground tomb passages with above-ground spirit roads. According to historical records, the spirit road typically extends ~1000 m from the tomb entrance, following the natural terrain and topography. As a result, it is often not a straight line but rather curved, and the tomb and the

spirit road are usually not aligned along a single central axis⁴⁰. This indicates that imperial tombs in Nanjing and its surrounding areas were generally located on mountain foothills, slopes, or summits, while the spirit road extended from the foot of the mountain to the tomb entrance. The SRSCs, as above-ground architectural elements marking the beginning of the spirit road and symbolizing the tomb owner's status and rank, were usually placed at a certain distance from the burial chamber on relatively flat terrain (Fig. 10).

Consequently, the elevation of the SRSCs is lower than that of the tomb entrance, generally situated on relatively flat ground at elevations between 9 and 40 m, with a particular concentration between 9 and 20 m.

Hydrological factors play an indispensable role in the formation of the distribution of SRSCs in Nanjing and its surrounding areas. Using ArcGIS software, a multi-ring buffer analysis was conducted on level-5 and above water systems in Jiangsu and Anhui provinces, with buffer distances set at 5, 10, 15, and 20 km. The buffer area of rivers was calculated and overlaid with the distribution of SRSCs. Results show that 85.7% of SRSCs are located within 10 km of a river, and 93.7% of the total are within 15 km. As shown in Fig. 11, most SRSCs are distributed along river systems, mainly concentrated along the Nanjing section of the Yangtze River, the Qinhuai River, and the Danyang section of the Grand Canal. This pattern indicates that water sources, essential natural resources for human society's production and livelihood, were a significant factor in selecting the locations for imperial tombs and SRSCs. In ancient times, proximity to water systems supported daily life and production needs, providing favorable conditions for the construction, maintenance, and visitation of SRSCs.

For example, the stone materials used in spirit road carvings or completed stone beasts, which are large and heavy, could be transported via waterways to their destination. According to a Chinese classic ancient book, "*Book of Southern Qi Volume 22*", the stone beasts, stone pillars, and related materials for Emperor Wen's Changning Tomb were transported from Xiangyang, Hubei, to Nanjing by Emperor Xiaowu⁴¹. Although the transport method is not specified, both Xiangyang and Nanjing are located along the Yangtze River, making water transport the most feasible method for moving such heavy materials. It can be inferred that the Yangtze River played a crucial role in the transportation involved in creating SRSCs. During the Southern Qi and Liang periods, imperial funeral processions and noble visits to tombs began by boarding ships at Fangshan in the southern suburbs of Nanjing, entering the Yangtze River, then traveling via canal to the Xiao Liang River, and finally heading north to the tombs in Danyang. This also highlights the importance of river systems as transportation routes for visiting and maintaining SRSCs.

Human factors have also jointly influenced the formation of the distribution of SRSCs in Nanjing and its surrounding areas, and can be divided into political and cultural factors. The political factors mainly include three aspects: (1) The capital city, as a political center, often exhibits a clustering effect of imperial tombs. As the capital of 11 dynasties, Nanjing served as the political and cultural center of the entire southern region for an extended period. Consequently, emperors and nobles who established their capitals in Nanjing selected tomb sites near the capital, facilitating the construction, management, and ritual offerings associated with the tombs and their SRSCs. The concentration of tombs near the capital also functioned as a

Table 4 | Comparison of natural conditions between Nanjing and Xi'an

Region	Topography	Soil	Dynasties	Total duration (years)	Total number of flood events	Frequency of flood events	Data sources
Nanjing	Low elevation (avg. 8.9 m), dominated by low mountains, hills, and uplands	Mainly yellow-brown and red soils	Eastern Jin, Southern Dynasties, Early Ming	356	109	Approx. once every 3 years	Book of Jin, Book of Song, Book of Southern Qi, Book of Liang, Book of Chen, History of Ming, Ming Veritable Records
Xi'an	Weihe Plain at an average elevation of 400–700 m	Mainly yellow-brown and brown soils	Qin, Western Han, Eastern Han	441	15	Approx. once every 29 years	Records of the Grand Historian, Book of Han, Book of the Later Han, Records of the Three Kingdoms

means for the ruling class to display their power and authority to the populace. This phenomenon is common throughout Chinese history. Xi'an, Luoyang, Beijing, and Nanjing are collectively known as China's "Four Great Ancient Capitals," each having served as the capital for multiple dynasties. As a result, large numbers of imperial tombs are distributed around these cities (Table 5), with even more tombs belonging to princes, nobles, and high-ranking officials.

(2)The "Disaster of Yongjia," a significant political upheaval that marked the end of the Jin dynasty, occurred in 311 CE. Following this event, invasions by northern nomadic groups into the Central Plains led to large-scale social unrest and mass population migrations. To escape the warfare, many people migrated southward across the Yangtze River. According to official historical records (Book of Jin, Book of Song), it is estimated that from 311 to 479 CE, approximately 900,000 people migrated southward, accounting for about one-sixth of the 5.4 million registered households in the Southern Dynasties and approximately one-eighth of the total northern population at that time.

The migration primarily involved aristocrats, scholars, and dependent commoners from the Central Plains, who often moved as family clans, forming so-called "qiaoxing" (migrating surname) groups. Prominent aristocratic families such as Wang, Xie, Yuan, and Xiao were representative of this southward migration. Among these, more than 220,000 migrants settled in Jingkou (present-day Zhenjiang, Jiangsu) and Jinling (present-day Changzhou, Jiangsu)⁴². The founder of the Liu-Song dynasty, Liu Yu, and the Xiao imperial family of the Southern Qi and Liang dynasties were notable representatives. Taking the Xiao family as an example, their ancestral home was in Lanling, Donghai (present-day Linyi, Shandong Province). Due to the turmoil, they migrated south with the Jin court, first settling in Jingkou (present-day Zhenjiang), and later moving to and permanently residing in Danyang (present-day Danyang, Zhenjiang)⁴³. During the Southern Qi and Liang periods, the Xiao family rose to become the imperial household, gradually transforming from a northern migrant clan into a newly established southern aristocratic power (Fig. 12).

The imperial tombs of the Xiao family were distributed in two main areas: one group of 14 tombs was constructed near Jiankang (present-day Nanjing) due to the political centrality of the capital, while another group of 14 tombs (including one in Jurong) was built in Danyang, their settlement after migration. This made Danyang, besides Nanjing, another major area with a concentrated distribution of SRSCs (Table 6).

(3) Alternative capital city. Fengyang was the hometown of Zhu Yuanzhang, the founding emperor of the Ming Dynasty. The Ming Imperial Mausoleum, the joint burial site of Zhu Yuanzhang's parents, is located in Fengyang, Anhui Province (present-day Fengyang County, Chuzhou City, Anhui Province). In the second year of the Hongwu reign (1369), Fengyang was designated by Zhu Yuanzhang as "Zhongdu" (the Central Capital), and at one point it was considered a potential alternative capital for the Ming Dynasty⁴⁴. During the three construction phases of the Ming Imperial Mausoleum from 1366 to 1379, its location remained in Fengyang without relocation. One important reason for this was that, as a designated alternative capital, Fengyang needed prominent royal infrastructure projects to assert its political status. This also illustrates how political factors influenced the siting of SRSCs⁴⁵.

In addition to political factors, cultural factors also jointly influenced the distribution of tombs and their SRSCs. The cultural factors include three aspects: traditional funerary beliefs, the continuity of burial systems, and the influence of feng shui culture. In traditional Chinese culture, there is a strong emphasis on the concept of being buried in one's hometown after death and the burial practice of family members being interred together in family clusters. Taking the Xiao family as an example, after the "Disaster of Yongjia," they migrated south to Danyang for political asylum and eventually settled and flourished there. After death, family members could no longer return to their original hometown of Lanling, Donghai (present-day Lanling County, Linyi City, Shandong Province) for burial. Instead, they were buried in Danyang, their "second hometown" after migration, following the family practice of "burial by clan"⁴⁶. This was an important factor,

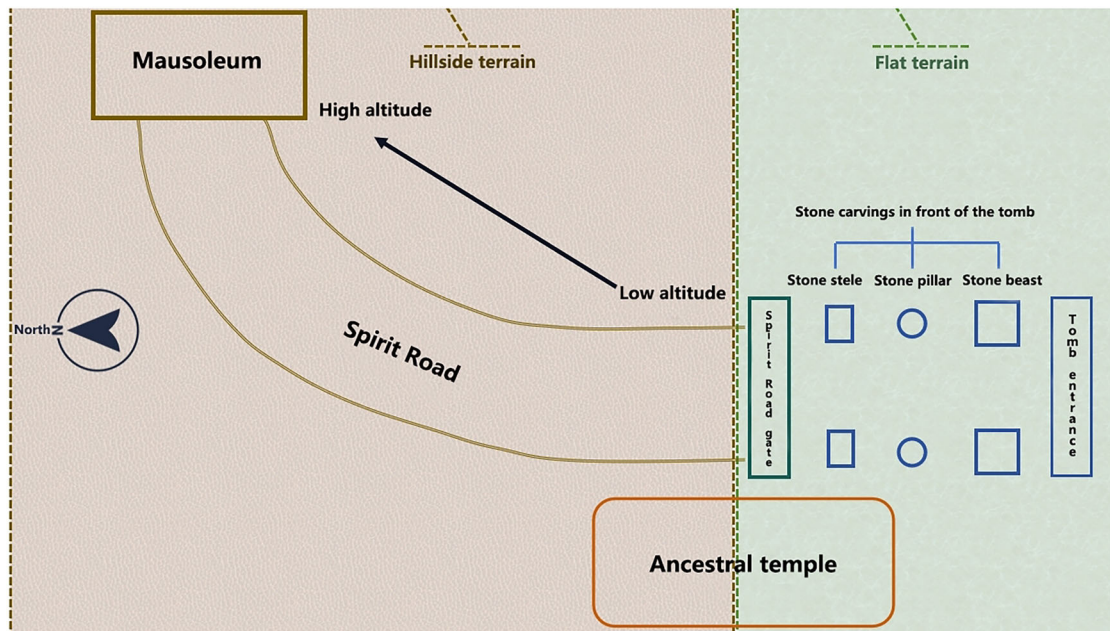


Fig. 10 | Plan layout of tombs and SRSCs. This diagram illustrates the typical spatial configuration of a traditional spirit road (shen dao) tomb complex, including the relationship between natural terrain, architectural elements, and stone carvings. The layout is divided into two topographic zones: the western section is hillside terrain with higher elevation, where the mausoleum is typically located; the eastern section is flat terrain at lower elevation, which houses the spirit road gate, ancestral temple, and ceremonial stone carvings. The spirit road curves upward from the spirit road gate toward the mausoleum, following a symbolic progression from low to high

ground. Along the spirit road, a sequence of stone elements is positioned symmetrically in front of the tomb entrance, including stone steles (square), stone pillars (circular), and stone beasts (rectangular), which are integral components of traditional funerary architecture. The layout reflects geomantic (feng shui) principles, emphasizing elevation, cardinal orientation, and ritual symmetry. A north arrow provides directional reference, and all components are clearly labeled for interpretive clarity.

Fig. 11 | Water system distribution map of SRSCs. This map displays the distribution of cultural heritage sites (represented by red dots) in relation to the region’s hydrological features, including rivers and lakes (shown in blue), across multiple administrative districts (outlined in gray). The spatial clustering of cultural heritage sites near major water systems, particularly around the Yangtze River and its tributaries, is evident.

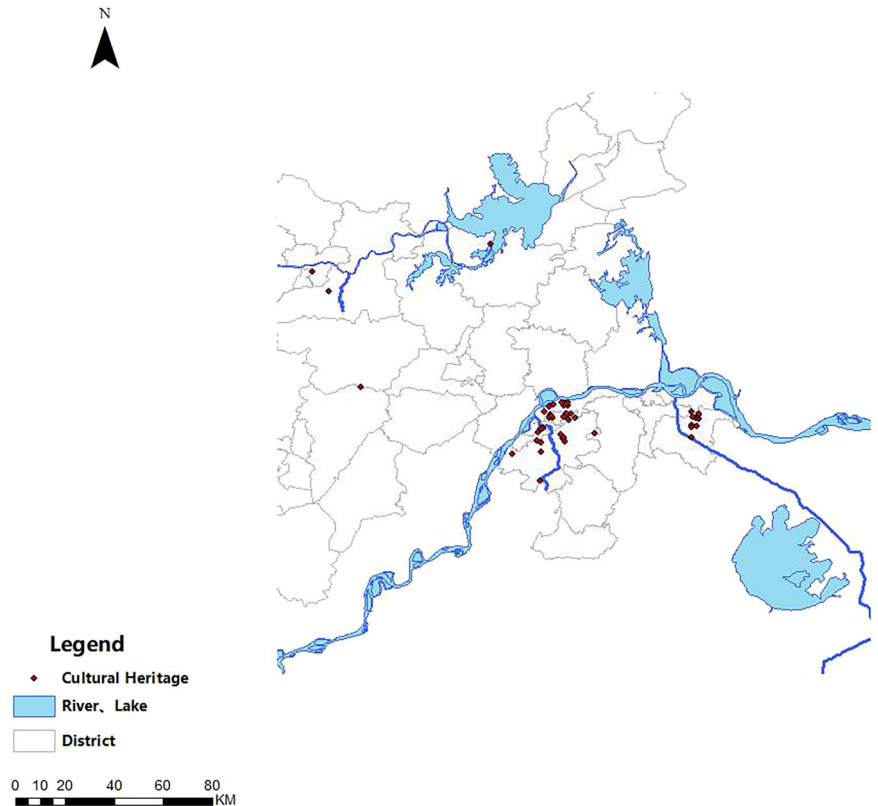


Table 5 | Comparison of the number of imperial tombs and dynasties among the four great ancient capitals

City	Number of imperial tombs	Number of ruling dynasties
Nanjing	22	11
Xi'an	79	13
Luoyang	24	13
Beijing	21	6

aside from political considerations, contributing to Danyang becoming a major cluster area for SRSCs in the Jiangnan region. Many similar examples existed in the early Ming period as well. Fengyang, the site of the Ming Imperial Mausoleum, was the hometown of Emperor Zhu Yuanzhang and the burial place of his parents. The Ming Zuling Mausoleum, located at Yangjiadun north of Sizhou City (present-day Xuyi County, Jiangsu Province), was the residence and burial place of Zhu Yuanzhang's grandfather, Zhu Chuyi. Among the founding ministers of the Ming Dynasty, Tang He's tomb was located in his hometown, Donghu Village, Fengyang (present-day Longzihu District, Bengbu City, Anhui Province), while Wu Fu's tomb was located in his hometown, Liang County (present-day Xiaoxu Township, Feidong County, Anhui Province). Most of the hometowns of Emperor Zhu Yuanzhang and his founding ministers were in present-day Anhui Province. This explains why SRSCs are scattered across Anhui as well.

According to official historical records, starting from Liu Jiao, King Yuan of Chu in the Western Han Dynasty, there was already a practice of constructing tombs by carving into mountains⁴⁷. This burial system was subsequently adopted by Emperor Wen of Han and later further developed by Emperor Wen of Wei, Cao Pi, who advocated the burial method of "using mountains as tombs"⁴⁸. After the "Disaster of Yongjia," the Jin imperial family migrated eastward, and northern people moved south. When these northern migrants and their descendants became rulers in the Jiangnan region (such as the emperors of the Eastern Jin and Southern Dynasties), they brought with them the concept and burial system of "using mountains as tombs." Meanwhile, in ancient Jiangnan, particularly in the Wu and Yue regions, various forms of primitive worship were prevalent, among which mountain and river worship was especially prominent. Archeological findings from the Liangzhu culture, which represents ancient Wu and Yue culture, reveal numerous elevated altars built on high platforms, used as burial sites. The underlying reason was that ancient people hoped that by building altars on higher grounds, they could shorten the distance between humans and heaven, facilitating communication with the heavens⁴⁹. Burying tombs at such locations symbolized the deceased's aspiration for their soul to ascend quickly to heaven, thereby reinforcing their earthly power and status. The integration of the mountain and river worship beliefs of indigenous Jiangnan culture with the northern migrants' burial ideology of "using mountains as tombs" became a significant basis for selecting mountain areas as burial sites for Southern Dynasties aristocrats. This cultural synthesis explains why SRSCs in Nanjing and its surrounding areas are distributed along mountain foothills such as Zhong Mountain, Mufu Mountain, and Jubao Mountain. Chinese feng shui culture has a long and profound history. It originated during the Xia dynasty approximately four to five thousand years ago, developed during the Shang and Zhou periods, took shape during the Qin and Han dynasties, and reached a more mature form during the Wei and Jin periods, eventually flourishing in the Ming and Qing dynasties. Specialized works on feng shui include Qing Nang Jing (The Classic of the Green Satchel), Zang Shu (The Book of Burial), and Yangzhai Sanyao (Three Essentials of the Living House)⁵⁰. Although most official historical records do not explicitly state that emperors and aristocrats selected tomb sites in mountainous areas due to feng shui considerations, there are exceptions. For example, Records of the Grand Historian (Shiji, "Biography of Chuli Zi") and Records of the Three Kingdoms (Sanguozhi, "Biography of Guan Lu") explicitly mention events where feng shui influenced tomb site selection. The publication of specialized feng shui texts and

these historical accounts are sufficient to demonstrate the significant impact of feng shui on ancient Chinese society. Feng shui theory posits that the feng shui of ancestors' tombs can influence the fortune of their descendants, while the feng shui of emperors' tombs can impact the fate of the entire state. Regarding site selection, feng shui emphasizes the principle of "relying on mountains and facing water," meaning that tombs should be built backed by high mountains, facing water, and enclosed by lower hills on both sides, ideally in a semi-enclosed area on the mountainside or in a mountain valley⁵¹. A typical example is the Book of Burial authored by Guo Pu during the Eastern Jin period, which is considered the foundational text of feng shui culture. It systematically elaborates on feng shui theory and was the first to formally introduce the term "feng shui." The text clearly states that tombs should have high mountains at the back, protective hills on both sides, and an open area in front to block strong winds and create an environment conducive to accumulating and preserving "qi"⁵². Nanjing, historically known as Jinling, is characterized by mountainous and hilly terrain, offering numerous sites that meet the "relying on mountains and facing water" requirements of feng shui for tombs. Additionally, during the early Ming period, Emperor Zhu Yuanzhang once considered relocating the Ming Imperial Mausoleum from Fengyang to Nanjing. However, officials advised that relocating the mausoleum might cause the loss of spiritual energy accumulated in the original mountain and river setting, potentially affecting the fate of the dynasty ("时有言改葬恐泄山川灵气者,乃不复改")⁵³. Zhu Yuanzhang accepted this suggestion, and the mausoleum ultimately remained in Fengyang. This is another example demonstrating how feng shui theory influenced the site selection of SRSCs. Based on these feng shui texts, historical records, and the objective topographical conditions of Nanjing's hilly landscape, it is reasonable to infer that the distribution of tombs and their SRSCs in hilly areas during the Southern Dynasties and the early Ming period was influenced by feng shui culture.

This study systematically analyzed the spatial distribution and spatiotemporal evolution characteristics of SRSCs in Nanjing and its surrounding areas by employing Geographic Information Systems (GIS) and historical-geographical methods, extracting historical data from official historical records. It identified natural factors as objective influences and cultural factors as subjective influences, jointly shaping the spatiotemporal distribution and evolution of SRSCs. The key findings include: (1) SRSCs exhibit significant clustered distribution, forming a spatial structure centered primarily around Qixia and Xuanwu districts of Nanjing, with Danyang as a secondary center. Other areas exhibit scattered distributions, showing an overall density gradient evolving from the west and northwest towards the southeast. (2) The distribution of SRSCs is spatially uneven. During the Southern Dynasties period, carvings were predominantly concentrated in Qixia District, Jiangning District in Nanjing, and Danyang City in Zhenjiang, collectively accounting for 63.5% of the total. During the early Ming Dynasty, the main distribution shifted northwestward by 52.27 km, focusing primarily in the Xuanwu and Yuhuatai districts of Nanjing. (3) Natural factors are predominant objective determinants for the distribution of SRSCs, resulting in most carvings being situated at elevations below 40 meters. Above this elevation, the quantity of carvings decreases with increasing altitude. Additionally, 85.7% of SRSCs are located within 10 km of rivers. (4) Political and cultural factors significantly influenced the distribution patterns of SRSCs. These factors do not act independently but rather intertwine and interact with natural conditions to shape the spatial arrangements of SRSCs. The innovations of this study are highlighted in three aspects. Firstly, SRSCs represent a crucial yet relatively understudied component of the Chinese burial system, with previous research largely confined to archeological and art historical fields, leaving geographical analyses of their spatial characteristics and formation mechanisms largely unexplored. Secondly, this study innovatively integrates GIS-based spatial analysis with historical text mining, overcoming the disciplinary limitations of traditional SRSCs studies, thereby elucidating the spatial patterns and evolution rules driven by combined natural and cultural factors. Lastly, based on the methodology and findings of this research, the author further developed preliminary 3D digital modeling and virtual reality presentations

Table 6 | Detailed distribution of the Xiao family's SRSCs

Serial number	Name of tomb and carvings	Dynasty	Location	Heritage designation	Region
1	Stone carvings of Xiao Xiu, Prince Kang of Ancheng	Southern Liang	Entrance of Ganjiaxiang Primary School, Yaohua Gate, Qixia District	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Nanjing)	Nanjing
2	Stone carvings of Xiao Dan, Prince Zhongwu of Shixing	Southern Liang	East part of the newly renovated park, Ganjiaxiang West, Qixia District	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Nanjing)	Nanjing
3	Stone carvings of Xiao Jing, Marquis Zhonghou of Wuping	Southern Liang	Intersection of Qixia Avenue and Xinxian East Road, Qixia District	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Nanjing)	Nanjing
4	Stone carvings of Xiao Hui, Prince Zhonglie of Poyang	Southern Liang	Inside the community park, Ganjiaxiang West, Qixia District	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Nanjing)	Nanjing
5	Stone carvings of Xiao Hong, Prince Jinghui of Linchuan	Southern Liang	East side of Yingtian College, Xianlin University Town, Xianhemen, Qixia District	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Nanjing)	Nanjing
6	Stone carvings of Xiao Rong, Prince Jian of Guiyang	Southern Liang	North of Nanjing Refinery Primary School, east of Nanlian Third Village, Qixia District, Nanjing	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Nanjing)	Nanjing
7	Stone carvings of Xiao Wei, Prince of Jian'an Commandery	Southern Liang	Intersection of Hengfei Road and Hengtai Road, Qixia District, Nanjing	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Nanjing)	Nanjing
8	Stone carvings of Xiao Ying, Marquis Kuan of Xinyu	Southern Liang	Dongjiabian Village, Qixia Town, 50 m west of Lianxi Road, Qixia District, Nanjing	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Nanjing)	Nanjing
9	Stone carvings of the unidentified tomb in Xujiacun	Southern Liang	Within the first chemical plant area of Jmling Petrochemical Company, Yanziji Town, Qixia District, Nanjing	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Nanjing)	Nanjing
10	Stone carvings of the unidentified tomb in Beijiaodian	Southern Liang	Beijiabian, Wulong Village, Yaohua Street, Qixia District, Nanjing	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Nanjing)	Nanjing
11	Stone carvings of the unidentified tomb in Shenxiang	Southern Liang	No. 100, Shenxiang, Qixia Avenue, Qixia District, Nanjing	District-level Cultural Relic Protection Unit	Nanjing
12	SRSCs of the unidentified tomb in Taiping Village	Southern Liang	Excavated from Taizi'ao, Taiping Village, Yanziji Town, Nanjing	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Nanjing)	Nanjing
13	Stone carvings of the unidentified tomb in Shiziba Village	Southern Liang	Vegetable plot next to Shiziba Village, Maqun Town, Qixia District, approximately 500 m north of Shanghai-Nanjing Expressway	Nanjing Municipal Cultural Relic Protection Unit	Nanjing
14	Stone carvings of the unidentified tomb in Zhangku Village	Southern Liang	Fairland in Zhangku Village, Yaohua Town, Qixia District, approximately 500 m north of Xiao Hong's tomb carvings	None	Nanjing
15	Entrance stone carvings of Southern Qi and Liang tombs in Danyang	Southern Qi and Liang	Both sides of Xiaoliang River, 0.5 km southeast of Lingkou Town, Danyang; behind the New Century Shoe Factory, Danyang	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Danyang)	Danyang
16	Stone carvings of Emperor Xuan of Qi, Xiao Chengzhi's Yong'an Mausoleum (or Emperor Gao of Qi, Xiao Daocheng's Tai'an Mausoleum)	Southern Qi	260 m southeast of the intersection of 001 Township Road and Gujing Road, Danyang	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Danyang)	Danyang
17	Stone carvings of Emperor Wu of Qi, Xiao Ze's Jing'an Mausoleum	Southern Qi	East of Tianjia Village, Yunyang Town, Danyang, less than 100 m along a north-south road	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Danyang)	Danyang

Table 6 (continued) | Detailed distribution of the Xiao family's SRSCs

Serial number	Name of tomb and carvings	Dynasty	Location	Heritage designation	Region
18	Stone carvings of Emperor Jing of Qi, Xiao Daosheng's Xiu'an Mausoleum	Southern Qi	300 m east of the intersection of Menlou Road and Township Road 003, Danyang	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Danyang)	Danyang
19	Stone carvings of Emperor Ming of Qi, Xiao Luan's Xing'an Mausoleum (or Emperor Jing of Liang, Xiao Fangzhi's tomb)	Southern Qi / Liang	0.5 km northeast of Sancheng Lane, Jinglin Town, eastern Danyang; north of Huning Expressway; northwest of Jiangsu Wallace Suit Factory; in a paddy field, 60 m south of Emperor Wen of Liang's Jian Mausoleum	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Danyang)	Danyang
20	Stone carvings of Emperor Wen of Liang, Xiao Shunzhi's Jian Mausoleum	Southern Liang	Northeast of Sancheng Lane, Jinglin Town, eastern Danyang; about 60 m north of the spirit road carvings of Xiao Luan's Xing'an Mausoleum	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Danyang)	Danyang
21	Stone carvings of Emperor Wu of Liang, Xiao Yan's Xiuling Mausoleum	Southern Liang	Paddy field in Sancheng Lane, Jinglin Town, eastern Danyang; about 360 m north of Emperor Wen of Liang Xiao Shunzhi's Jian Mausoleum carvings, near Liu Family Village, Sancheng Lane	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Danyang)	Danyang
22	Stone carvings of Emperor Jianwen of Liang, Xiao Gang's Zhuangling Mausoleum	Southern Liang	Paddy field in Sancheng Lane, Jinglin Town, eastern Danyang; about 60 m north of Xiao Yan's Xiuling Mausoleum carvings	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Danyang)	Danyang
23	SRSCs of the unidentified tomb in Jinwangchen (possibly Emperor Houfei of Qi, Xiao Baojuan's tomb)	Southern Qi	South of Hugao Road, west of Chenjia Village, Houxiang Town (formerly Jianshan Township, Jinwangchen Third Village), Danyang; in paddy fields among Jin Family Village, Wang Family Village, and Chen Family Village	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Danyang)	Danyang
24	Stone carvings of the unidentified tomb in Lanshilong (possibly Emperor Qianfei of Qi, Xiao Zhaowen's tomb)	Southern Qi	Lanshilong, Houxiang Town, Danyang (formerly Lanshilong, Jianshan Township); about 600 m south of Xiao Zhaoye's tomb carvings; 5 m west of Jianpi Road; nearest streetlight post number 'Shengyan0032'	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Danyang)	Danyang
25	Stone carvings of the unidentified tomb in Shuiling Mountain (possibly Emperor Houfei of Qi, Xiao Zhaowen's tomb)	Southern Qi	Southeast of Shuiling Mountain Village, Picheng, Yangshi, Danyang; about 5 m east of Jianpi Road; nearest streetlight post number 'Shengyan0057'	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Danyang)	Danyang
26	Stone carvings of the unidentified tomb in Sancheng Lane	Southern Qi / Liang	Excavated in Sancheng Lane, Jinglin Town, eastern Danyang; now in Fenghuang Lake Park	None	Danyang
27	Stone carvings of Emperor Gao of Qi, Xiao Daocheng's Tai'an Mausoleum (or Emperor Xuan of Qi, Xiao Zhaozhi's Yong'an Mausoleum)	Southern Qi	West of Yong'an Mausoleum, commonly known as Huang(wang)fen Mountain, near Zhaojiban and Wujia Village, Huqiao Town, northeastern Danyang; destroyed by local farmers in the 1960s	Destroyed	Danyang
28	Stone carvings of Xiao Ji, Prince Jian of Nankang	Southern Liang	Vacant lot southeast of Shishigou Village, Huayang Town, Jurong	National Key Cultural Relic Protection Unit (Southern Dynasties Tomb Stone Carvings in Danyang)	Jurong

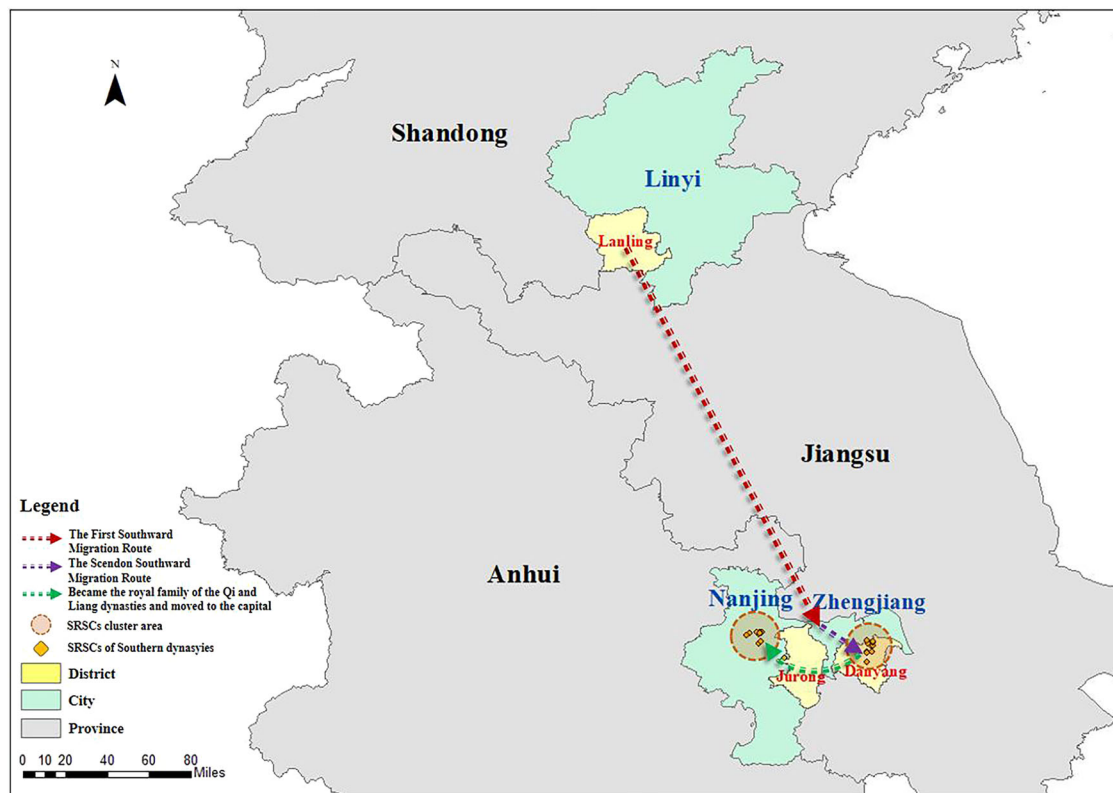


Fig. 12 | Map of the migration routes of the Xiao family and the distribution of their SRSCs. This map illustrates the historical migration routes of the Xiao family from the Lanling region in present-day Linyi, Shandong Province, to the southern capital area of Nanjing and Zhenjiang in Jiangsu Province. The dashed red arrow indicates the first major southward migration, while the dashed green arrow represents a secondary migration route. The orange circular symbols mark SRSCs cluster areas associated with the Southern Dynasties, particularly in Jurong and Danyang, where descendants of the Xiao family established tombs. These regions

later became important burial grounds for members of the royal family during the Qi and Liang dynasties. Administrative divisions are outlined by different color shades: city-level units in yellow, provincial boundaries in green, and district borders in gray. The map emphasizes the correlation between historical family migration patterns and the spatial distribution of their monumental funerary SRSCs, shedding light on the political and cultural shifts of the period. A scale bar is provided for distance reference.

of SRSCs, achieving digital innovations in heritage conservation and dissemination, and demonstrating the research’s value and potential (Fig. 13). Moreover, integrating GIS analysis with various natural disaster risk datasets can provide technical support for disaster risk assessment, early warning systems, and emergency responses for SRSCs. Multidimensional digital technologies centered around GIS offer novel perspectives and methodologies for the protection and preservation of immovable cultural relics exemplified by SRSCs.

Data availability

The data in this study primarily come from three sources, the first being the administrative divisions and basic geographic information data. This, including vector data on national and prefecture-level administrative boundaries, hydrography, and elevation maps of China, were obtained from the Geospatial Data Cloud (<https://www.gscloud.cn/sources/index?pid=1&type=1>). The second data source is the vector data on SRSCs. According to the Law of the People’s Republic of China on the Protection of Cultural Relics, the Jiangsu Provincial Bureau of Cultural Heritage has implemented a policy of “in situ protection” for immovable cultural relics, which mandates that existing SRSCs must be preserved at their original locations and not be relocated. Therefore, the SRSCs analyzed in this study were categorized into three types: (1) Preserved in situ with surviving remains. This includes sites where the carvings are still preserved at their original locations today (e.g., most cases represented by the Liu Yu Chuning Mausoleum carvings). For these sites, field investigations were conducted. Upon locating each site, the geographic coordinates were obtained using the Baidu coordinate picker, and additional data such as dimensions, preservation status,

and condition were recorded using measuring tapes, laser rangefinders, drones, and 3D laser scanners. Information on administrative regions and protection levels was sourced from the official website of the Jiangsu Provincial Bureau of Cultural Heritage (<https://wlt.jiangsu.gov.cn/>). (2) Surviving carvings that have been relocated but with verifiable original locations. These include cases such as the Southern Dynasties Taiping Village unnamed tomb carvings, originally excavated in Taizi’ao, Taiping Village, Yanziyi Town, Nanjing, and later moved to display halls in the Nanjing Museum. The original coordinates, administrative information, and protection levels were obtained from the results of the Third National Cultural Relics Census (hereafter referred to as the “Third Census”), which are archived at the Nanjing Municipal Museum and provided by the third author of this paper, Yingnan Li. (3) Excavated carvings with verifiable original locations but subsequently lost. Examples include the carvings from Tai’an Mausoleum of Emperor Gao of Qi (Xiao Daocheng) in Zhaojiawan, Wujiacun, Huqiao Town, northeast of Danyang, which were destroyed by local farmers in the 1960s, and carvings from Shiziba Village, Maqun Town, Qixia District, Nanjing, which were stolen after excavation. The original coordinates, administrative information, and protection levels for these cases were also sourced from archeological excavation records archived at the Nanjing Municipal Museum and provided by the third author, Yingnan Li. Finally, ArcGIS 10.3 software was used to process the geographic coordinate data and attribute data of SRSCs, generating the vector data necessary for spatial analysis. The third data source is the historical data. The historical period data presented in this paper, such as the number of floods during the Eastern Jin, Southern Dynasties, and early Ming periods, as well as the migration routes of the Xiao family, are derived from the analysis and



Fig. 13 | Results of 3D digital modeling and VR display of SRSCs. This figure presents the final results of the 3D digital modeling and virtual reality display of SRSCs. The top left shows the 3D modeling render of Southern Dynasty SRSCs. The bottom left displays the 3D digital modeling process of early Ming Dynasty SRSCs.

The top right is a screenshot of the virtual panoramic tour interface for the early Ming SRSCs, while the bottom right is a screenshot of the virtual panoramic tour interface for the Southern Dynasty SRSCs.

compilation of official Chinese historical works, specifically the “Twenty-Four Histories.” These include the Records of the Grand Historian (Shiji), Book of Han (Hanshu), Book of Later Han (Hou Hanshu), Records of the Three Kingdoms (Sanguozhi), Book of Jin (Jinshu), Book of Song (Songshu), Book of Southern Qi (Nan Qishu), Book of Liang (Liangshu), Book of Chen (Chenshu), and History of Ming (Mingshi), as well as the chronological official annals Ming Shilu (Veritable Records of the Ming). The ten volumes from the “Twenty-Four Histories” series cited in this paper are based on the editions published by Zhonghua Book Company, Beijing, in January 2000 (ISBN: 9787101021288). The edition of Ming Shilu used is the one published by Zhonghua Book Company, Beijing, in January 2016 (ISBN: 9787101110906).

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Conceptualization, C.G. and W.Z.; methodology, C.G.; software, C.G. and L.J.; validation, C.G., L.J., and Y.n.L.; formal analysis, C.G., Y.n.L., and W.Z.; investigation, C.G. and Y.n.L.; resources, C.G. and Y.n.L.; data management, C.G.; manuscript writing, C.G. and L.J.; revision, C.G., L.J., and W.Z.; submission, C.G. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interests.

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