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Mapping the past with historical geographic information systems: layered characteristics of the historic urban landscape of Nanjing, China, since the Ming Dynasty (1368–2024)

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Abstract

The layering process of the historic urban landscape (HUL) has spatial and temporal characteristics. With the help of digital technology, building a database to collect and manage spatial information on HUL is an effective research method. Taking Nanjing since the Ming Dynasty (1368–2024) as an example, our paper proposes a framework for constructing a historical geographic information system (HGIS) for HUL. The results show that (1) ancient Chinese historical archives have good potential for use in the construction of historical landscape databases. The HGIS can visualize the evolution of HUL and realize the storage, expression, querying, and analysis of information in different formats. (2) The Republic of China is a turning point in the evolution of Nanjing's HUL. In terms of spatial evolution, the main distribution areas of urban form and characteristic places, as well as the NACH (normalized angular choice) and NAIN (normalized angular integration) cores of the road network, all moved from the south to the north of the city. In terms of typological evolution, the urban form changes from a predominantly residential area to one that emphasizes residential, administrative, educational and industrial areas. The main types of characteristic places shifted from house gardens, temples and ancestral halls to scenic buildings and public gardens. (3) Political factors, urban planning, commercial ports, and land prices influence the layering process of the HUL. The constructed database guides the preservation of HUL from the digital heritage perspective and the construction of other historical databases with spatial characteristics.

Keywords Historic urban landscape (HUL), Historical geographic information systems (HGIS), Digital heritage, Spatiotemporal evolution, Nanjing

Introduction

The management of cultural heritage is a concern for governments around the world. The rapid development of digital technology offers new approaches to the preservation of cultural heritage [1]. In 1992, UNESCO's use of a computerized information management system to protect Angkor Wat was seen as the beginning of digital preservation [2]. Cultural heritage, such as buildings and archaeological sites, is the main target for the application of digital tools, while digital preservation in HUL still lacks pragmatic guidance [3].

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HUL, which is “an urban area where cultural and natural values have accumulated over time” [4] and contains a “layering” of historical periods and constituent elements [5], is an important research topic for cultural heritage. The fragmentation of information is a major obstacle to effective conservation. Heritage information is stored in different forms and formats in different institutions, resulting in the inability to adequately consider multilayered values when making management decisions [3]. In addition, there is a lack of digital recording systems for the maintenance and restoration of HUL. Existing management methods cannot track the dynamics of spatial evolution [6], resulting in the research and practice of HUL mostly focusing on a single historical period and ignoring the spatial connection of elements [7]. Therefore, new approaches for the preservation of HUL are urgently needed. Historical geographic information systems (HGISs) are spatial technology-based GIS platforms that integrate historical records; transform information with spatial characteristics into numerical graphical data [8]; and visualize elements and historical periods in “layers”, facilitating the documentation, management, analysis, and application of historical information, which is highly conducive to the preservation of HUL.

As a product of the digital era, the use of HGIS to preserve HUL has important application prospects and academic value. First, HGIS can improve the completeness and sharing rate of multiple historical materials of HUL [9]. The management, protection, and restoration of historic landscapes often require historical archives, and traditional manual access methods are inefficient and unable to integrate historical, spatial, and current information on morphological units, road networks, and characteristic places [10]. HGIS can use geographic information technology to integrate local records, historical archives, and historical maps to achieve digital management of documents [11]. Second, HGIS can improve the scientific nature of HUL conservation. The documentation of HUL is presented in chronological order, with temporal attributes, and the historical events described occur in space, which means that it has geographic and spatial information [12]. HGIS databases can visualize the spatial pattern of HUL [13] and define the scope of protection. The database is utilized to collect natural environment and humanistic information and is combined with topography, hydrology, geology, land use, and urban planning information to carry out thematic analyses [14]. The results can be used as a basis for the preparation of conservation planning and reduce the one-sidedness of subjective judgment. Third, HGIS can enhance public awareness of preserving HUL. The digital archive construction in Ballarat [15] and Bursa [16] showed that HGIS can enhance public understanding

and interest in urban history through interactive maps and visualization and increase the sense of conservation awareness.

In recent years, studies of HGIS applied to HUL in Limousin [17], Cuenca [18], and cities in Southwest China [19] have been published. On the basis of the idea of “element-carrier-rule-application” [20], HGIS is constructed by using historical documents and maps [21]. The system transforms the data model into layered spatial maps and constructs point databases such as characteristic places [14], line databases such as street networks [21], or surface databases containing urban units on the basis of Conzen’s theory [22]. Databases of thematic historic landscapes, such as Nanjing Zijin Mountain [23], Tibetan Buddhist monasteries [9], and the Ming Great Wall [24], also appear. Digital terrains, spatial overlays, and buffer zones are used to study the spatial patterns and spatiotemporal distributions of historical landscapes [25]. However, owing to the special characteristics of historical materials and ancient maps, the spatialization and digitization of historical data often have problems such as projection, error, and edge joining [26]. The high-precision and standardized processing of a large amount of spatial and attribute data leads to difficulty and high cost in database construction. In addition, the records of the HUL in ancient Chinese literature are very vague [27]. Uncertain expressions such as “south side”, “a few kilometers”, and “inside” are often used instead of precise coordinates to describe geospatial information [23]. Therefore, existing databases have focused mainly on the last 100 years, and relatively few studies have been conducted on the digitization of ancient documents. In summary, HGIS still has knowledge gaps in HUL research. (1) Existing studies rarely show in detail the process of HGIS database construction for HUL. The steps of data collection and acquisition, integration and preprocessing, digitization and geographicization, and spatial model construction have not yet resulted in a mature system, which may affect reproducibility and accuracy [9]. (2) The research time series needs to be further extended. Ancient documents are important materials for HUL research, but the records are rather vague. The lack of effective methods for digitizing ancient data has led to existing results focusing on periods with definite data for the last 100 years, and there has been a dearth of results for centuries [28].

To this end, our study poses two research questions: (1) How can we construct an HGIS database of HUL across a long time series and containing different data types? (2) What are the characteristics of the spatial and temporal evolution of Nanjing’s HUL under different political regimes? What factors affect its evolutionary process? Our study has three purposes: (1) Propose a construction

method for an HGIS of HUL spanning several centuries. (2) Explore the feasibility of building an HGIS in the absence of precise geospatial data or ambiguous

data in ancient times. (3) Analyze the evolution of the HUL, reveal its development law, and provide scientific protection.

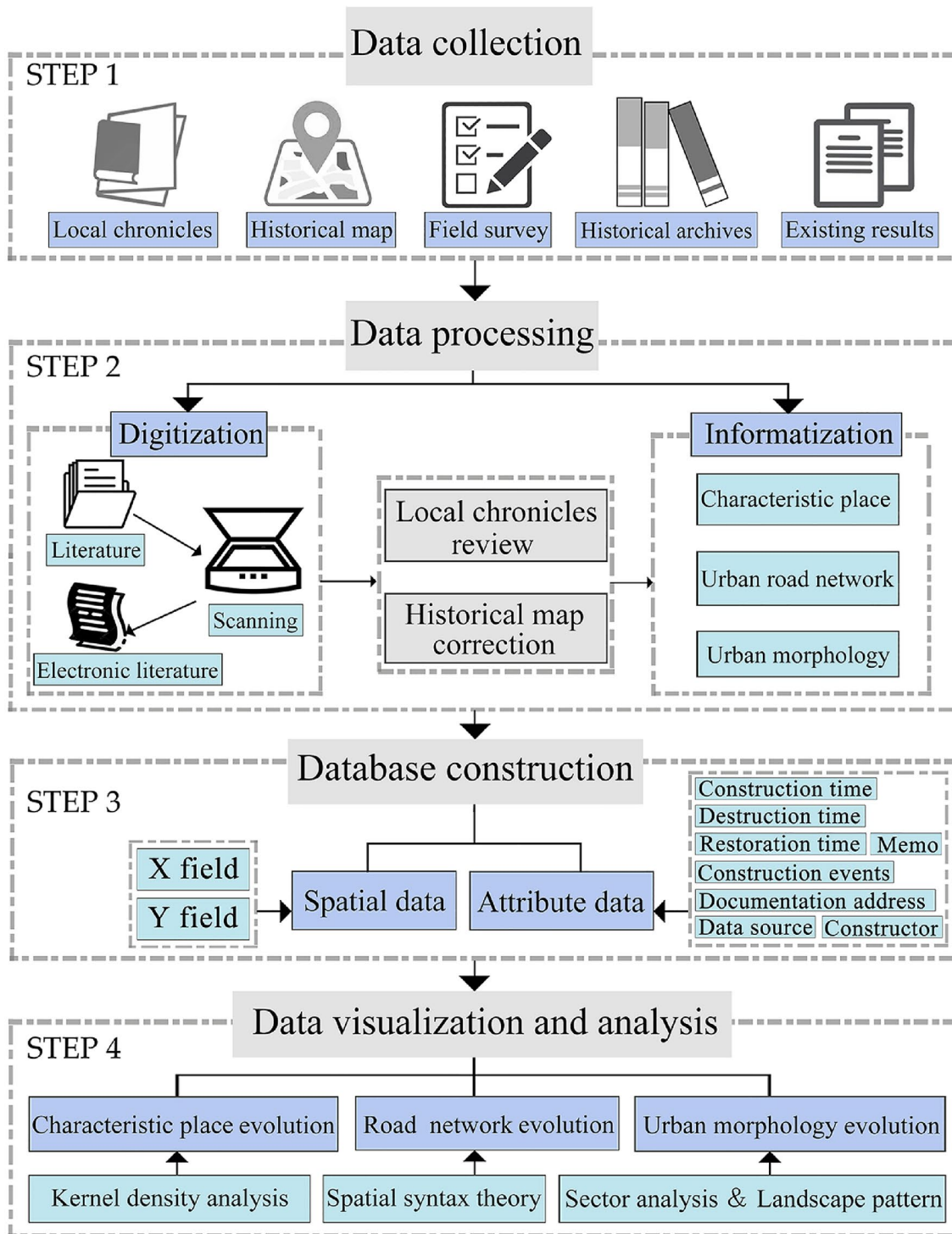


Fig. 1 Flowchart of building a HGIS for HUL

Construction of a historical geographic information system for HUL

The construction of the HGIS is divided into four steps (Fig. 1).

The data are collected from historical documents, such as local chronicles, historical archives, and ancient maps [29]. The data can be supplemented and verified via field surveys [9]. Additionally, basic geographic data, such as digital elevation model (DEM) data and water system data, must be collected.

Data processing consists of digitization and computerization of historical documents [30]. Digitization is the conversion of physical documents into electronic forms via machine-scan and recognition technology. Informatization involves importing the information contained in historical documents such as geographic location, time, and event records into a GIS after extraction for classification, statistics, analysis, and management. There is ambiguity and uncertainty in the recording of spatial information about parts of the HUL in local chronicles [31], and document cross-checking and information screening are important methods for obtaining high-quality spatial data [26]. Compared with modern maps, there are errors in the accuracy of historical maps. Adding more control points, such as street intersections, existing buildings, and river inflection points, to correct historical maps is an important way to obtain high-quality spatial data [32]. Inconsistencies in historical data standards need to be addressed in the digitization process. First, the uniformity of the data sources should be ensured. The selection of historical documents should preferably be of the same caliber, for example, by using official records of relatively high credibility, which can reduce the large differences in the number of records of HUL due to inconsistencies in the data sources [9]. Historical maps should be drawn with the same precision and be comparable. Second, ensure that the data have consistent definitions of names, coordinates, and information attributes. (1) Many historical landscapes have changed names during their evolution, and there may be different attribute fields or naming styles from different sources. Uniform toponymic vocabulary and description specifications need to be defined to address differences in toponymic expressions [33]. (2) Use a unified geographic coordinate system and projection to ensure that the spatial information of HUL elements can be correctly displayed and analyzed on the same map. The third is the standardization of semantic modeling [34]. (1) Adopt data structures commonly used in GIS, such as features and attribute tables, as the standard for data storage and exchange. (2) Ensure the geometric consistency of the data. In the GIS platform, topological relations are used to ensure the connectivity and consistency of the road

network. Buffer analysis and overlap analysis are used to calibrate the point and surface data.

The first step of data informatization involves presenting spatial and attribute data from different periods on the same electronic map and building a unified operating platform. The second step is the extraction of elemental information (Fig. 2). The locations of characteristic places in the historical records are geocoded and positioned on the map. Geocoding is a coding method based on spatial positioning technology that converts spatial geographic information into latitudinal and longitudinal coordinates [35]. Visual interpretation is a common method for extracting road network data. For the informatization of morphological units, the Conzen urban morphology method is the most widely used [36]. Characteristic places, road networks, and morphological units have been labeled on historical maps since modern times, while before modern times, they were inferred from historical records [37], following the principle of “from near to far, from whole to partial, accurate first and then fuzzy”, and extrapolating back to the previous period on the basis of later generations [38]. In terms of space, the general pattern is determined first and then refined step by step according to the functional space. In terms of elements, the locatable and accurate elements in the historical materials are identified first, and then the elements with ambiguous locations are speculated based on the literature. Before traditional Chinese cities were modernized, detailed changes were slow [39], providing the possibility of comparing and locating information on the HUL.

After the data were processed, the HGIS database was constructed. Finally, the layered characteristics of the HUL are analyzed, and the process of evolution is visualized in the form of maps.

Practice of the historic geographic information system in HUL

Study area

Nanjing, formerly known as “Nanking”, is the capital of Jiangsu Province. The old city of Nanjing was established in 1368, covering an area of approximately 43 km² (Fig. 3), and is listed on the tentative list of world heritage sites [21]. As the ancient capital of the Six Dynasties, Nanjing was an important political center in southern China, with a relatively developed economy and culture, forming a cluster of characteristic places. Although it was developed more than 600 years ago, its road network and urban morphology have remained relatively stable [21]. In addition, Nanjing is a famous historical and cultural city, and the historical literature on the HUL is abundant. Therefore, Nanjing is very typical as a practical case of an HGIS in the study of HUL.

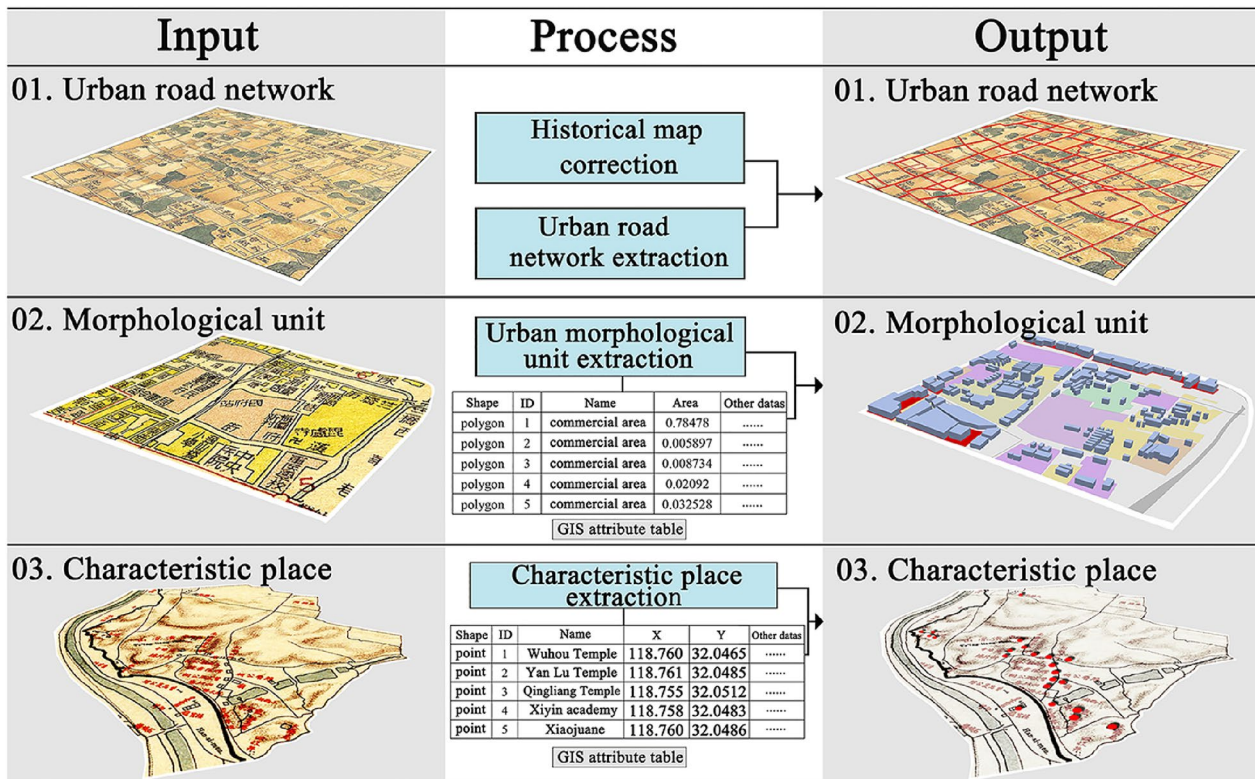


Fig. 2 Extraction process of historical map data

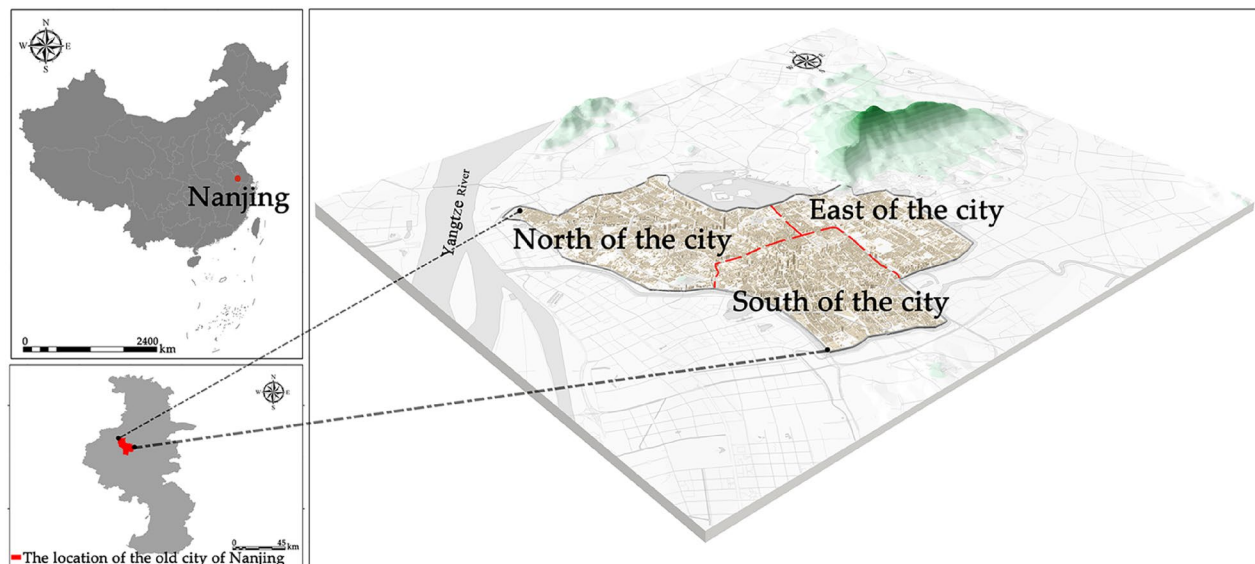


Fig. 3 Location of the study area

Considering the history of Nanjing and the level of detail of the relevant data, the study can be divided into six stages:

(1) During the Ming Dynasty (1368–1644), Nanjing was the capital and experienced less damage from war [40]. A comparison of surviving historical

documents from the early, middle, and late Ming Dynasties reveals that the HUL information is recorded more identically and with less change.

- (2) In the early to mid-Qing Dynasty (1645–1864). The Ming Imperial Palace area was severely destroyed and replaced by the “garrison city” (also called Manchu city) for the Eight Banners officers and soldiers. This led to significant changes in the HUL in the eastern part of the city.
- (3) In the late Qing Dynasty (1865–1911), after the Taiping War, the HUL was severely damaged.
- (4) Republic of China (1912–1949). Nanjing became the capital of the national capitalist era. The “Capital Plan” was implemented, and the HUL changed significantly.
- (5) Early New China (1950–1978). With economic development, the road network and characteristic places have changed considerably.
- (6) After the reform and opening periods (1979–2024), conservation plans for the HUL were successively introduced.

Data collection

(1) Historical documents

The historical documents include local chronicles, historical maps, and historical archives. The local chronicles included Hongwu Jingcheng Tu Zhi (洪武京城图志), Wanli Yingtianfu Zhi (万历应天府志), Jinling Shi Ji (金陵世纪), Jinling Gu Jin Tu Kao (金陵古今图考), Kangxi Jiangningfu Zhi (康熙江宁府志), Qianlong Shangyuan Xian Zhi (乾隆上元县志), Qianlong Jiangning Xin Zhi (乾隆江宁新志), Jiaqing Reprint Jiangningfu Zhi (嘉庆重刊江宁府志), Tongzhi Shangjiang Liang Xian Zhi (同治上江两县志), Yundu Daoqiao Xiao Zhi (迳溪道桥小志), Fenglu Xiao Zhi (凤麓小志), Zhongnanhuabei Qu Yu Zhi

(钟南淮北区域志), Boshan Zhi (盩山志), Jinling Garden Zhi (金陵园墅志), Jinling Guji Tu Kao (金陵古迹图考), and “Nanjing Construction Chronicle”. Table 1 shows the historical maps.

The historical archives are from the Nanjing Archives and the Nanjing Urban Construction Archives. The Nanjing Municipal Archives currently hold a relatively complete collection of urban construction archives from the Republic of China and the early years of New China. The archives of the Public Works Bureau and Land Bureau are utilized to supplement the determination of urban form. For example, the 1936 Draft City Zoning Plan, File No. 1001-3-126. The Nanjing Urban Construction Archives preserved many drawings of road construction at that time, which is very valuable for understanding the spatial evolution of the road network. For example, the 1929 Road Map of Zhuque Road, File No. E11-0042-0138.

(2) Field survey

A field survey was conducted from January 2022 to January 2024 to verify the spatial location and time of construction of the HUL on the list and integrate it with existing data.

(3) Existing results

Zhu Xie in the Republic of China compiled the “Jinling Guji Tu Kao” through a field survey and drew the “capital city map” and the “palace city map” of the Ming Dynasty. A series of results formed by Chen Gang, “Research on Urban Historical Geography Based on New Hypermedia GIS Technology-Taking Nanjing in the Six Dynasties as an Example”, and publications such as “Geospatial and Landscape Processes of the Ancient Capital of Nanjing”, have proven the location of some characteristic places. A study of the morphology of the house gardens on Yihe

Table 1 Basic information of the historical maps selected for the construction of the HGIS

Name	Author or publisher	Scale/Resolution (m)	Data source
“Map of Provincial Capital Jiangning” in the late Qing Dynasty (1850)	Deng Qixian	Ten li per square	Old Images and Maps of Nanjing
“New map of the capital city of Jinling” in 1910	Jiangnan Lu Shi Academy	1: 10,000	Old Images and Maps of Nanjing
“Latest Map of Nanjing” in 1938	Yoshizo Koyama (Japanese)	1: 20,000	Old Images and Maps of Nanjing
“Nanjing City District Map” in 1962	People’s Liberation Army Nanjing Military Command	1: 10,000	Nanjing Planning and Natural Resources Bureau
“Street map of Nanjing” in 1983	Nanjing Survey and Design Institute	1: 10,000	Nanjing Planning and Natural Resources Bureau
KH-9 Lower Resolution in 1975	U.S. spy satellites	6–9 m	EarthExplorer (usgs.gov)

Road provided building plan maps from 1931, 1953, and 1970 [41]. The “Yingtian Prefecture Map” from the “Nanjing Construction Chronicle” depicts the road network and urban form of the Ming Dynasty. The Nanjing Urban Planning Compilation and Research Center has simulated the urban form since the Ming Dynasty [42], which provides a more scientific information reference.

Data processing

Historical map correction and alignment

The historical maps screened were geographically aligned to ensure that the maps of different periods were all in the same coordinate space and comparable [32]. The historical maps of 1910, 1937, and 1983 are taken as examples. First, 10 coordinate points were selected as control points and gealigned with 2020 Landsat-7 ETM+ data to check the error range of the historical maps (Table 2). Second, the 1937 historical map was used as an example. After 100 control points are selected for calibration, the error is approximately 7.74 m, which is controlled within one pixel. Overlaying the corrected historical maps with Landsat-7 ETM+ images revealed that the lakes and roads matched perfectly (Fig. 4). The remaining historical maps were then geographically aligned one by one following this method.

Data informatization of HUL elements

(1) Characteristic place

The acquisition of latitude and longitude coordinates for characteristic places consists of two groups. The first is the clear address, which can be directly located by local chronicles, historical maps, and existing results. The second is the ambiguous address, and according to historical

documents on the location, our study proposes three methods of localization: azimuthal, topological, and distance relationships.

① Azimuthal relationship

The azimuthal relationships include east–west, up–down, and left–right. Historical documents usually describe the spatial information of characteristic places, such as mountains, water, and streets. For example, the “Chen Gong Ancestral Hall” is described in the Jiaqing Reprint Jiangningfu Zhi as “Chen Gong Ancestral Hall, north of the Wende Bridge”.

② Topological relationship

The topological relationship refers to the spatial structure between characteristic places, covering adjacency, association, and containment. For example, Yu Di Zhi reported that “Zhengyang and Linguang Halls were built in Beiyuan”. If we know of Beiyuan, we can determine the approximate locations of Zhengyang and Linguang Hall, but we still need to combine it with other information to judge.

③ Distance relationship

The qualitative distance is usually described as “on the side of”. For example, it is recorded in Wanli Yingtianfu Zhi: “two wells, one in Shizigang, one on the side of the Baoen Temple”. The qualitative distance can be determined on the basis of the “azimuthal relationship” and the “topological relationship”. The quantitative distance is often recorded as “eight miles east of the city” or “approximately 100 paces west”. For example, it is recorded in Wanli Yingtianfu Zhi: “The Confucius temple was 30 paces east of the old county government”. The quantitative distance can be determined by referring to the

Table 2 Margin of error for Nanjing historical maps

No	Reference point	Location in the map		TM/ETM+ remote sensing image location		Error range (m) of 1910, 1937, 1983
		Longitude (°E)	Latitude (°N)	Longitude (°E)	Latitude (°N)	
1	Xinjiekou	118.779	32.0439	118.7789	32.0438	27.3004/10.318/2.9415 m
2	Stone Goddess of Mercy	118.789	32.0098	118.7892	32.0095	29.1357/10.3565/5.1931 m
3	Gulou	118.7771	32.061	118.7768	32.0608	49.2381/20.318/5.454 m
4	Longbozi	118.8184	32.0606	118.8179	32.0602	61.8523/29.5014/1.8742 m
5	Taiping Gate	118.8087	32.06	118.8085	32.0606	67.8288/29.1806/7.341 m
6	Zhongshan Gate	118.8229	32.041	118.8226	32.0410	41.0057/25.7443/5.5453 m
7	Yixian Bridge	118.7992	32.0425	118.799	32.0424	61.383/52.8935/2.6053 m
8	Zhonghua Gate	118.7762	32.0139	118.7764	32.0143	57.5097/25.7443/9.4801 m
9	Fucheng Bridge	118.7967	32.0349	118.7964	32.0348	46.2347/33.9873/7.4618 m
10	Hanxi Gate	118.7607	32.0448	118.7607	32.0448	35.9108/38.3324/8.3066 m

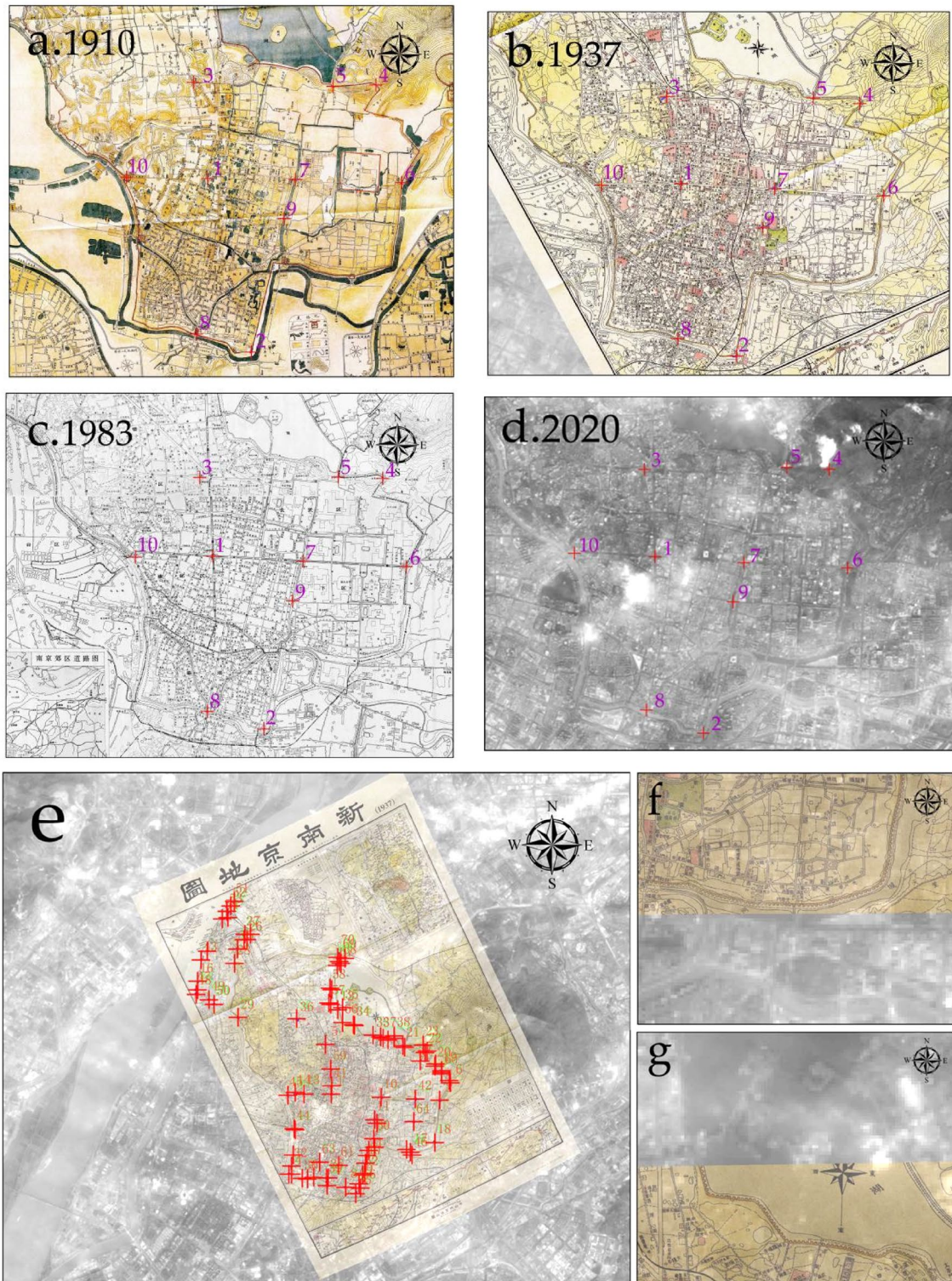


Fig. 4 **a–c** Positions of the 10 coordinate points in the historical maps of 1910, 1937, and 1983, respectively; **d** Positions of the 10 coordinate points geo-aligned by Landsat-7 ETM+; **e** Positions of the control points of the corrected historical maps. **f, g** Comparison maps after calibration

“Conversion Table of Weights and Measures of All Ages” compiled by Huang Shengzhang after conversion.

The Ginkgo Garden and the Lingying Temple are taken as examples. The steps are as follows:

First, the name and the construction time are determined. The Lingying Temple and Ginkgo Garden were built in the Ming and Qing Dynasties, respectively.

Second, spatial information is extracted from historical documents. Jinling Garden Zhi recorded “Ginkgo Garden, on Mingyang Street. There is a very tall ginkgo tree, branches and leaves reach the side streets.” Boshan Zhi recorded “Lingying Temple, which was rebuilt when Sangen built the Wuhou Ancestral Hall. It is at the foot of Snake Mountain”.

Finally, the latitude and longitude coordinates are determined on the basis of the spatial relationship between the characteristic places to be located and the reference point. The location of Snake Mountain was determined for the Lingying Temple. According to Boshan Zhi, “Wuhou Ancestral Hall is at the foot of Snake Mountain and it is in the same building as the Lingying Temple”, which shows that they are adjacent to each other. The Wuhou ancestral hall is marked on the 1910 Republic of China historical map, so the coordinates of the Lingying Temple are 118.7609 and 32.0465 (Fig. 5a). Regarding the Ginkgo Garden, the location of

Mingyang Street has not changed compared with today, and the general area of Ginkgo Garden can be inferred. Yuyuan Zhi noted that “there is a ginkgo tree with an enormous crown, which can shade Yuyuan’s Fenyin pavilion”. The Ginkgo Garden is adjacent to the Yuyuan Garden, and the “Fenyin pavilion” is located in the northwest corner of the Yuyuan Garden. Therefore, Ginkgo Garden is located north of Yuyuan Garden, and its coordinates are 118.7689 and 32.01979 (Fig. 5b).

(2) Urban network

The first Nanjing map with coordinates of latitude and longitude was the “city map of Jiangning” drawn by the French priest Fontaine in 1898 [43]; thus, the data of the road network after the Republic of China can be extracted from the measured historical maps as a reference. The first step is to extract the road network data for the period for which latitude and longitude coordinate maps are available, including the late Qing Dynasty (1865–1911), the Republic of China (1912–1949), and the founding of early New China (1950–1978). The large number of alleys greatly affects the accuracy of road network data. However, owing to the influence of factors such as the scale of maps in different periods, the drawing accuracy, and the use of cartographers, the number

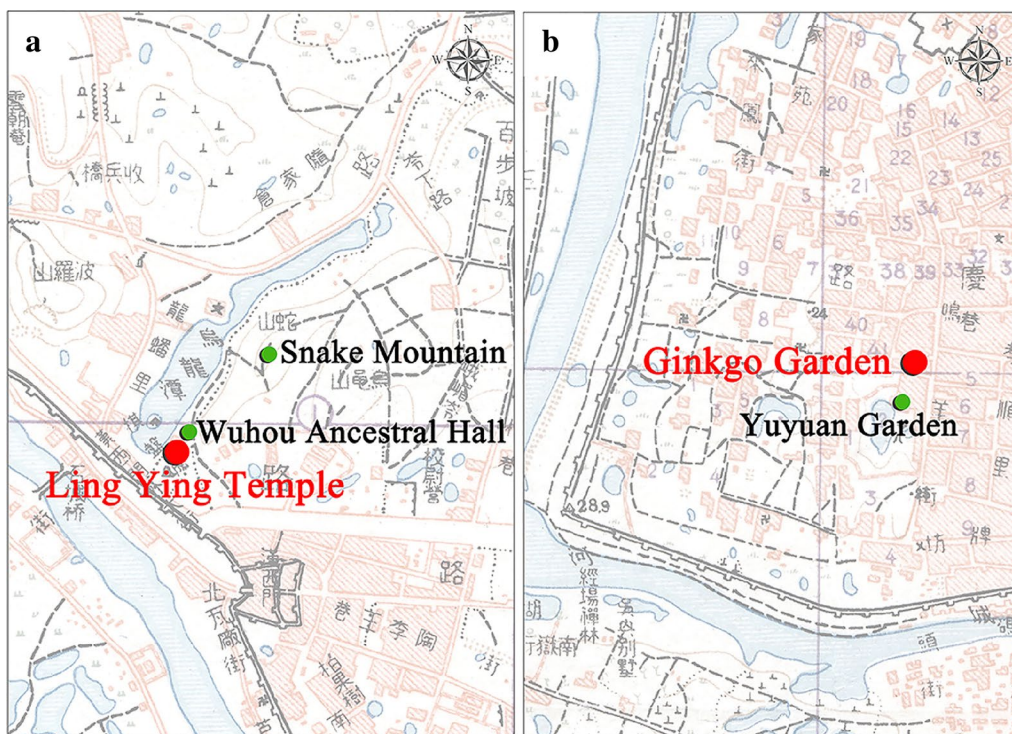


Fig. 5 Coordinates of Ling Ying Temple (a) and Ginkgo Garden (b)

of road networks in some years is often described in great detail, whereas others are more vague. In particular, some maps omit some small alleys, resulting in discrepancies with the actual situation. The historical maps of 1910, 1937, and 1983 selected for our paper were all drawn by officials with relatively high accuracy, so does the above situation exist? Can the road networks in each period be compared?

We can use the following methods for verification. First, we can compare the scale of the maps, which directly affects the accuracy of the drawing. Second, several alleys that are far from the main roads, with narrower road widths, and in residential areas were selected. If these alleys are drawn, the accuracies of these maps are similar and can be compared. The alleys are distributed in Mendong, Menxi, and Nanbuting, and 10 alleys with narrower widths and lower grades, such as Zhangjiaqiao and Taojiaxiang, are selected for comparison. The results show that these alleys were all drawn in the historical maps of 1910, 1937, and 1983, so the accuracy of the materials selected in our research is more consistent and can be compared (Fig. 6).

The second step is to extract the road network during the period when there were no latitudinal or longitudinal

mapping maps, including the Ming and early Qing Dynasties, which needs to be speculated on the basis of historical documents. The Jiangning Provincial City Map, drawn in the early Xianfeng period, depicts the shape of the road network before the Taiping War [44]. The map reads: “Since the war of 1853, Nanjing has been severely damaged, and many places have been reduced to ruins, so I redrew the Old Street Map of the Capital City of Jinling that I have preserved (自1853年甲寅久罹浩劫, 行且荡为瓦砾矣, 爰就家藏金陵省会城垣街巷旧图重付剖剗)”. Zhong and Chen believe that the “Old street map of the capital city of Jinling” was drawn at the beginning of the Qing Dynasty; therefore, the base map used in the “Jiangning provincial city map” was created during the early Qing Dynasty [43, 44]. According to the “Ancient Road History of Nanjing”, “the road network has not changed much from Hongwu in the Ming Dynasty to Guangxu in the Qing Dynasty”. Therefore, the Jiangning Provincial City Map shows the road network in the early Qing Dynasty and has important reference value for the Ming Dynasty. Existing historical documents on the road network of the Ming Dynasty include the official compilations of Hongwu Jingcheng Tu Zhi, Wanli Yingtianfu Zhi, and Chen Yi’s compilation of Jinling Shi Ji.



Fig. 6 Alleys in 1910, 1937, and 1983 historical maps

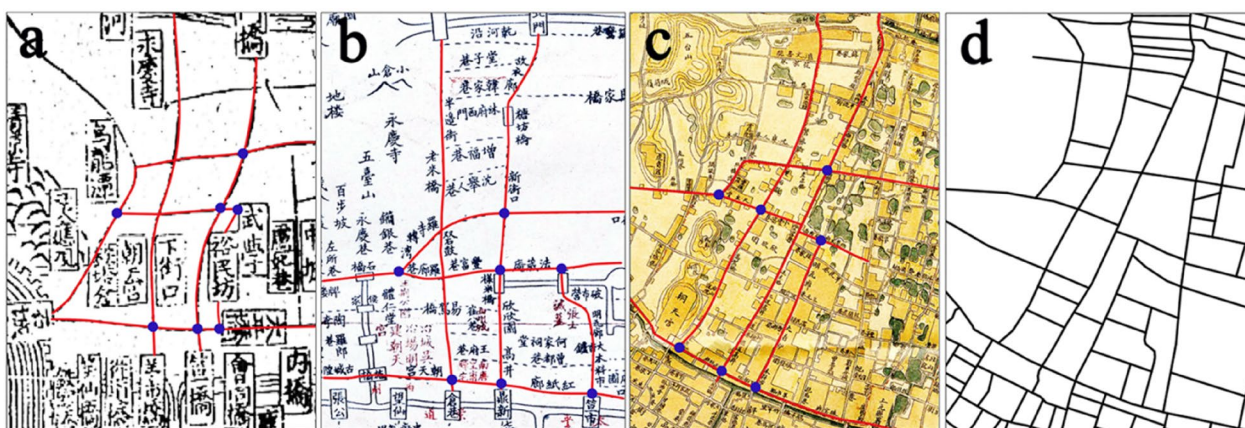


Fig. 7 Extraction examples of road network in Nanjing central region during the Ming Dynasty (**a** “Capital city map” during the Ming Zhengde Period; **b** Road Network from the 1850 “Map of Jiangning provincial capital”; **c** Historical map from 1910; **d** Digitized road network from the “Capital city map” during the Ming Zhengde Period)

The Hongwu Jingcheng Tu Zhi records the road network of the early Ming Dynasty. Wanli Yingtianfu Zhi records the road network in the middle of the Ming Dynasty. The Jinling Shi Ji is a very detailed record of the road network in the late Ming Dynasty, including 48 alleys and 38 streets. The “capital map” in Jinling Gu Jin Tu Kao of the Zhengde period draws the main streets, which can provide information for the restoration of the Ming Dynasty street network. By comparing the Ming Dynasty road network data with those of the Qing Dynasty and the Republic of China, the road network can be categorized into three types: “unchanged”, “changed”, and “completely disappeared”.

Therefore, the steps to map the road network in the Ming Dynasty are as follows (Fig. 7). The first step is to draw streets with unchanged names according to the maps of the Qing Dynasty and the Republic of China. The general structure of the road network is

determined on the basis of unchanged roads and intersections. The second step is to determine the ancient and modern names and locations of the “changed” road networks. These road networks accounted for 27.4% of the total network, which is highly important for accuracy. The main sources for identifying these “changed” road networks are Kangxi Jiangning Xian Zhi, Tongzhi Shangjiang Liangxian Zhi, Qianlong Jiangning Xin Zhi, Qianlong Shangyuan Xian Zhi and Nanjing Toponymic Encyclopedia, which recorded the old names of the road networks in the Ming Dynasty (Table 3). To the east of the city in the Ming Dynasty was the Imperial City, which changed much compared with the current road network. In the Republic of China, Zhu Xie drew a “capital city map” and a “palace city map”, which provided a reference for the restoration of the road network.

Table 3 Example of the evolution of street names in Nanjing

Number	Names in the Ming Dynasty	Names in the Qing Dynasty	Names in the Republic of China	Description in historical literature
1	Chang’an Street	Babao Street	Babao Street	(Ming) Wanli Shangyuan Xian Zhi recorded: “Chang’an Street, east of Dazhong Bridge, straight to the West Chang’an Gate”
2	Datong Street	Tongji Street	Banbian Street	(Ming) Hongwu Jingcheng Tu Zhi recorded: “Datong Street, south of the Tongji Gate, north of the bamboo Bridge”
3	Liren Street	Tongji Alley	Zhongzheng Street	(Ming) Hongwu Jingcheng Tu Zhi recorded: “Liren Street, in the west of Dazhong Bridge”
4	Chongli Street	Xiaomen Street	Daguang Street	(Qing) Daoguang Shangyuan Xian Zhi recorded: “Chongli Street, in the west of the Zhengyang Gate, straight to the Dazhong Bridge”
5	Xiyi Street	Daban Alley	Daban Alley	(Qing) Tongzhi Shangjiang Liang Xian Zhi recorded: “Xiyi Street commonly known as Daban Alley”
6	Bamboo Street	Mie Street	Tangfang Corridor	(Ming) ZhaoYu Zhi recorded: “Bamboo Street, the old salt market in this, commonly known as Mie Street”

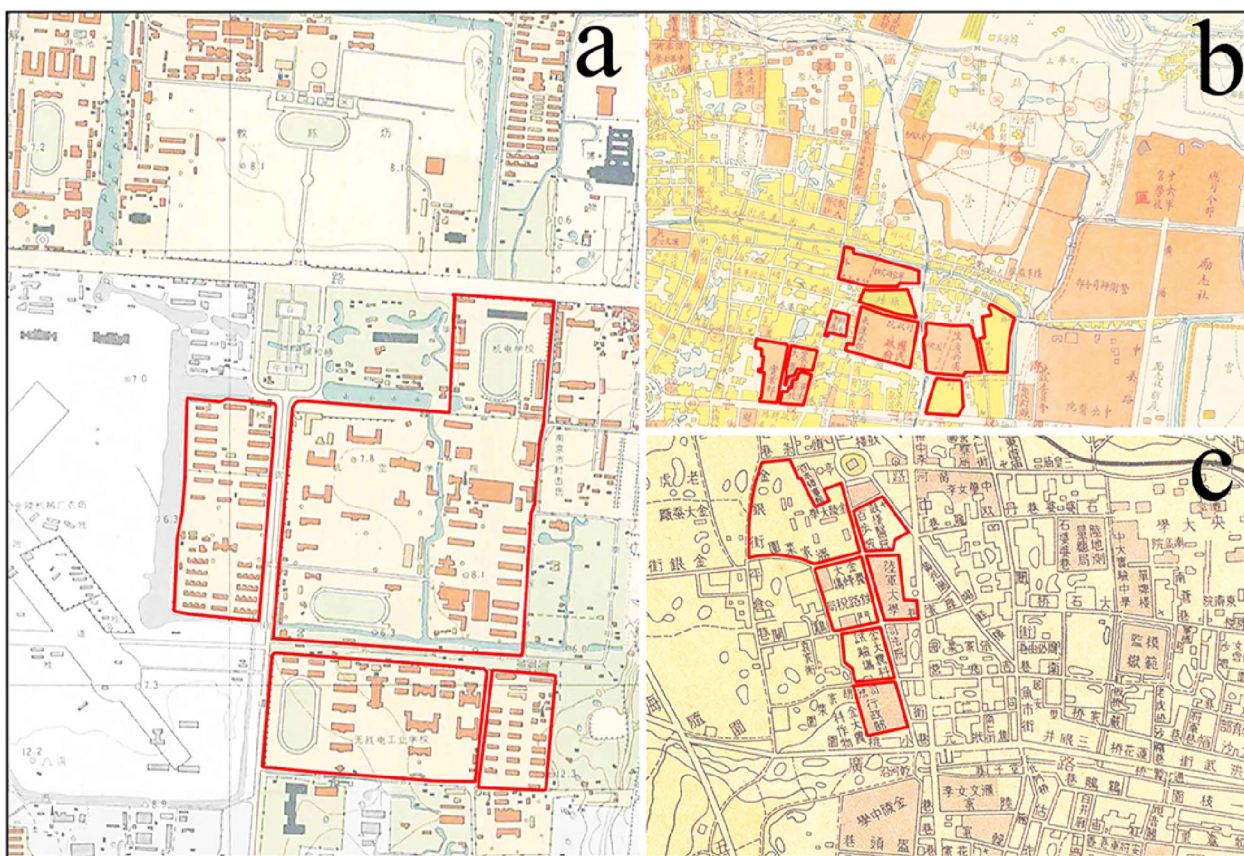


Fig. 8 Land use in historical maps of Nanjing (a 1962 map of Nanjing city area, b 1930 map of Nanjing city, c 1937 new Nanjing map)

(3) Urban morphology

Research on the urban morphology of ancient Chinese cities often uses GIS platforms to vectorize historical maps [45]. To further refine changes in morphological units, related studies in Qianxian [46] and Pingyao [47] have classified land use in more detail. After the late Qing Dynasty, Nanjing’s historical maps used different color blocks to denote urban morphology, such as commercial areas and education areas (Fig. 8), which can be directly vectorized.

Data on the urban morphology of the Ming and early Qing Dynasties were obtained from the Nanjing Construction Chronicle compiled by the Nanjing Local Chronicles Committee. This archive contains maps from the Ming and Qing Dynasties and indicates the built-up areas in each period in brown. The book was officially compiled and is extremely valuable as a reference. In ancient China, the evolution of urban morphology was characterized by slow changes in detail and long-term consolidation of land use, which ensured the stability of urban morphology due to this “historical resilience” [39]. The “land use map of Jinling city”, drawn in 1908, reflects

the morphological units at the end of the Qing Dynasty, and the map was drawn relatively close to the early Qing and Ming Dynasties, so it can be used as a basis for restoration. Furthermore, previous results have shown that morphology units such as governments, schools, and militaries were built on “official land”. Later generations continued to build on the same land as the previous generations did, and there was little change in the land use type during later generations.

Therefore, for the acquisition of morphological unit data in the Ming and early Qing Dynasties, our study proposes the following steps. First, the built-up area and the road network need to be extracted. The road network divides the built-up area into several units, which is informative for the determination of morphological units. Second, the morphological unit information is extracted from historical documents. For example, during the Ming Dynasty, Kezuo Zhui Yu defined the locations of commercial areas. “From Sanshan Street west to Doumen Bridge, its name is called the fruit area. ... Copper and iron are in the iron workshop; the drum store is at the mouth of Sanshan Street; wood is south of Chaoku Street, north is a carpenter

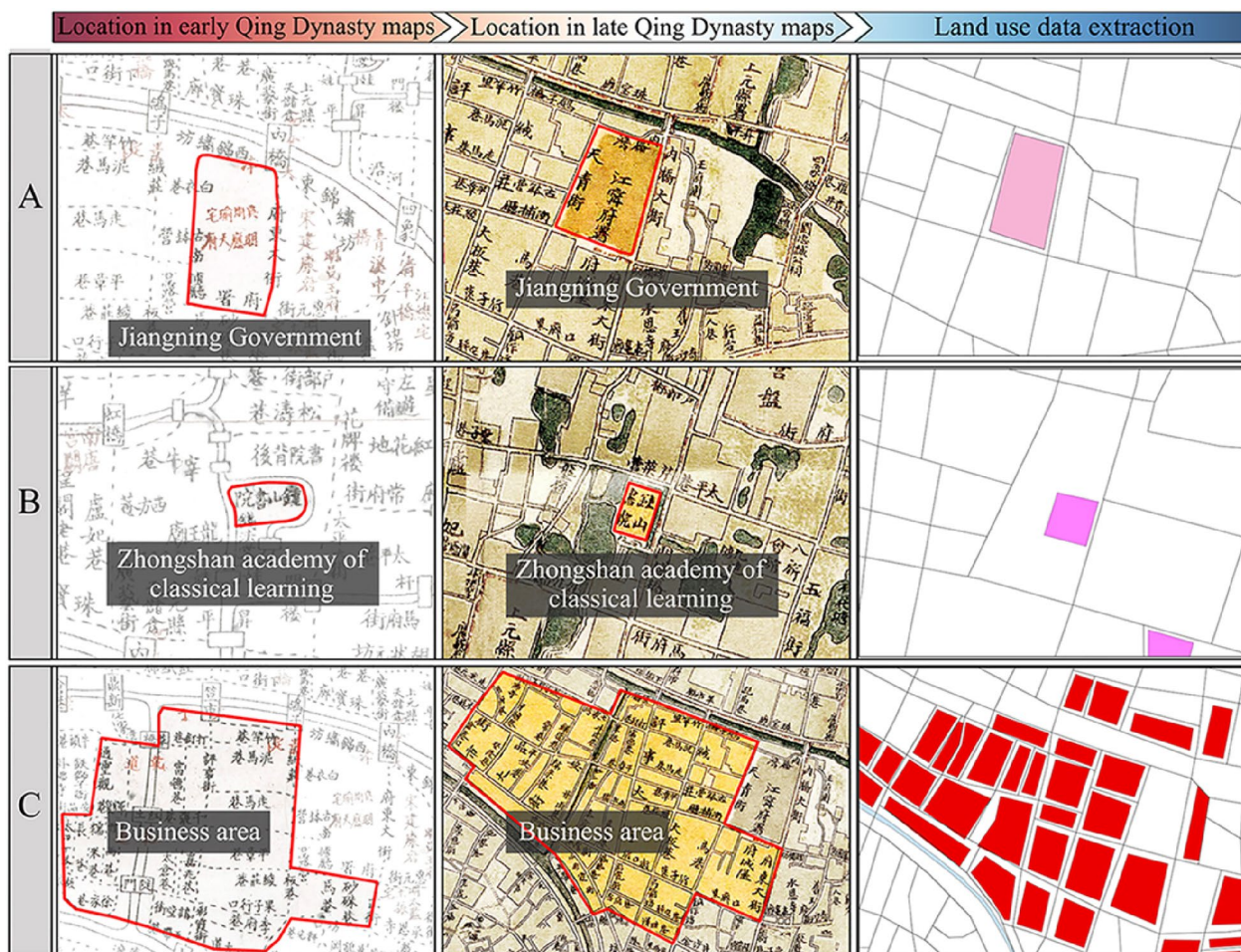


Fig. 9 Examples of the process of identifying urban form units

camp”. Third, the location of the morphological units of “official land”, such as administrative, educational, and warehouse areas, should be determined. For example, the record of the administrative area in Wanli Yingtianfu Zhi states, “In the early years of Hongwu, the government was moved to the west side of Jinxiu Fang, which is located in the southwest of Nei Bridge”. The government in the Qing Dynasty was not in a moving location, so later generations determined the location of the Ming Dynasty (Fig. 9a). As another example of an educational area, Qianlong Shangyuan Xian Zhi reported that the “Zhongshan Academy of Classical Learning was located at Qianchang Bridge in the northeast of the county government”. The academy was destroyed in the war of 1853 and later rebuilt at the same site, so the location in the early Qing Dynasty can be determined on the basis of the information in the historical maps of later generations (Fig. 9b). Fourth, the location of the morphological units of

“civil land”, such as residential and commercial areas, should be determined. The commercial area in the official records includes “bazaars” and “workshops”. In the Ming Dynasty road maps, the streets in the southwest are labeled with names such as “Bow and Arrow Workshop”, “Copper Workshop”, and “Hat Alley”. Consequently, the location of the commercial area can be determined (Fig. 9c). Apart from the religious and commercial areas in the “official land” and “civil land”, the remaining area is residential, which is the largest area.

Construction of databases

On the basis of the geodatabase data model, our database converts HUL data from text to point (characteristic places), line (road network), and surface (urban form) data with latitude and longitude coordinates, and each subdatabase stores corresponding attributes and spatial data.

Layered characteristics of the HUL

Research methods

Layered characteristics of urban form

(1) Sector analysis

This method enables the investigation of both the direction and the pace of urban form expansion [48]. New circular surface data are created with the geometric center of the ancient city and a radius of 6 km (which can cover the built-up area). These circular surface data were divided into 16 equally spaced sectors with the same area and a radius of 22.5°. The area of each urban form period within the sector was calculated to present the direction and pace in the form of a radar map.

(2) Landscape pattern metrics

To reveal the completeness and agglomeration of the urban form, we used the compactness index. To illustrate the fragmentation, complexity, and connectivity of the urban form, we used indicators such as the landscape shape index and fractal dimension index (see Table 4) [21, 49].

Layered characteristics of the road network

On the basis of the spatial syntax, two syntactic parameters, integration and choice, are used to analyze the evolution of the road network. Integration is a measure of the proximity of any street to other streets and can be considered topological accessibility. Choice is a measure of the probability that any street is crossed by the shortest topological distance path of two other streets [50]. Streets in the top 20% of integration or choice are considered foreground networks, and those in the top 5% of streets are considered core networks.

On the basis of the standardized minimum corner distance method proposed by Hillier, the street network is analyzed via the standardized degree of integration (normalized angular integration, NAIN) and the degree of choice (normalized angular choice, NACH), taking into

account the topological connectivity and angular variations between different street segments [50]. The formulas are as follows:

$$NAIN = \frac{n^{1.2}}{\sum_{i=1}^n d(x, i)} x \neq i \tag{1}$$

$$NACH = \frac{\log\left(\frac{\sum_{i=1}^n \sum_{j=1}^n \sigma(i, x, j)}{(n-1)(n-2)} + 1\right)}{\log(\sum_{i=1}^n d(x, i) + 3)}, i \neq x \neq j \tag{2}$$

In the formula, n represents the number of roads. $d(x, i)$ represents the minimum distance from road x to corner i , whereas $\sigma(i, x, j)$ denotes the minimum distance from road i through x to corner j .

Layered characteristics of the characteristic place

(1) Kernel density

We used the kernel density method based on ArcGIS to analyze the spatial distribution characteristics. It is useful for visualizing data and estimating probability density [51].

$$f(x, y) = \frac{1}{nh^2} \sum_{i=1}^n k\left(\frac{d_i}{h}\right) \tag{3}$$

In the formula, k is the kernel function, h is the bandwidth (km), n is the number of cities, and d_i denotes the distance (km) from the valuation point to the i th observation location.

(2) Nearest neighbor index

The nearest neighbor index is used to determine the distance between the centroid of each point within a spatial unit and the centroid position of its nearest neighbor object point. The index is essential for studying the spatial distribution type (e.g., uniform, random, or clustered).

$$E = \frac{\bar{r}_1}{r_E} = \sqrt[2]{D} \tag{4}$$

Table 4 Landscape pattern metrics and their definitions

Metrics	Abbreviations	Equations	Descriptions
Compactness index	CI	$CI = 2 \times \frac{\sqrt{\pi \times A}}{P}$	The CI value ranges from 0 to 1, and a larger value indicates a more compact urban form
Landscape shape index	LSI	$LSI = 0.25E/\sqrt{A}$	LSI evaluates the fragmentation, intricacy, and connectivity of urban morphology [49] LSI ≥ 1 , when LSI increases without limit and the landscape shape becomes more irregular
Fractal dimension index	FRAC	$FRAC = \frac{2 \times \ln(P/4)}{\ln(A)}$	FRAC quantifies the irregularity of urban morphology, with values ranging from 1 to 2 A higher value indicates a more intricate shape for the urban boundary [49]

A represents the area, P denotes the perimeter, and E signifies the total length of edges within the landscape

In the formula, r_1 is the average nearest neighbor distance between elements, rE is the theoretical average nearest neighbor distance between elements, and D denotes the point density. When $E > 1$, the point elements tend to be uniformly distributed. When $E < 1$, the point elements are clustered in a distribution [52].

(3) Standard deviation ellipse analysis

The standard deviation ellipse can be used to express spatial features such as central and directional trends of geographic elements [28]. Its calculation formula is as follows:

$$C = \frac{1}{n} \begin{pmatrix} \sum_{i=1}^n x_i^2 & -2 \sum_{i=1}^n x_i y_i & - \\ \sum_{i=1}^n x_i y_i & \sum_{i=1}^n y_i^2 & - \\ - & - & -2 \end{pmatrix}, \left\{ \begin{pmatrix} x_i - \bar{x}' \\ y_i - \bar{y}' \end{pmatrix} \right\} \quad (5)$$

In the formula, X_i and Y_i are the coordinates of element i , (\bar{X}', \bar{Y}') denotes the mean center of the element, and n is the total number of elements.

Results

Layered characteristics of urban form

(1) Changes in area and direction

During the Ming Dynasty, the built-up area was concentrated in the southern part of the city (Table 5). In the early Qing Dynasty, the imperial city was replaced by the Eight Banners Garrison City. The garrison soldiers lived on the north side of Xihua Gate, other areas were school yards and camps, and the built-up area was reduced in size. At the end of the Qing Dynasty, the commercial port of Xiaguan gradually rose. The built-up area began to spread to the north of the city, and Hehui Street became an important educational area, such as the Marine Division School and the Land Division School. In the Republic of China, to bury Sun Yat-sen on Zijinshan Mountain, Zhongshan Road, was built on the southern side of Jiangning Road. Owing to improved transportation conditions

and low land prices in the northern part of the city, the built-up area grew the fastest. First-class universities such as Central University, new-style residences, and government buildings appeared. The Republic of China was the first important growth period of urban form, with an average annual growth of 0.22 km². The period of 1949–1978 was the second most important growth time, with the built-up area growing from 20.61 km² in 1949 to 36.33 km² in 1978. The southern part of the city was saturated, and the built-up area expanded to the east and north of the city. The built-up area in the north of the city surpassed that in the south for the first time, changing the pattern of Nanjing for nearly a thousand years.

A radar map of the intensity of urban form expansion is obtained via the sector analysis method (Fig. 10). The built-up area grew mainly to the south in the early Qing Dynasty and to the southeast in the late Qing Dynasty, which was caused by the movement of the Eight Banners garrison city from Toutiao Lane to Babao Street after the war of the Taiping Heavenly Kingdom. In the Republic of China, the northwest became the main direction of expansion. After New China, it grew in both the northwest and east directions.

1) Changes in contour and shape

From the Ming Dynasty to the end of the Qing Dynasty, the compactness index increased and then decreased, while the landscape pattern index showed the opposite trend, and the fractal dimension did not change much. This indicates that the built-up area expanded outward, but it was looser, and the outline was extremely irregular. In the Republic of China, the built-up area expanded outward but became compact and rounded, and the contour became regular. After 1949, the compactness increased from 0.337 to 0.557, and the LSI and FRAC decreased. Owing to the limited space within the Ming city wall, the built-up area had a more compact shape and a regular and stable contour (see Table 6).

Table 5 Changes in the urban form indicators of Nanjing since the Ming Dynasty

Year	1577	1850	1910	1949	1978	2024
Total build-up area (km ²)	10.79	8.22	12.32	20.61	36.33	40.71
Perimeter (km)	41.54	31.78	46.27	47.66	56.51	40.62
South of the city (km ²)	6.16	7.51	7.67	11.24	12.73	13.00
East of the city (km ²)	2.98	0.41	1.50	2.41	7.94	9.63
North of the city (km ²)	1.65	0.30	3.15	6.96	15.66	18.08

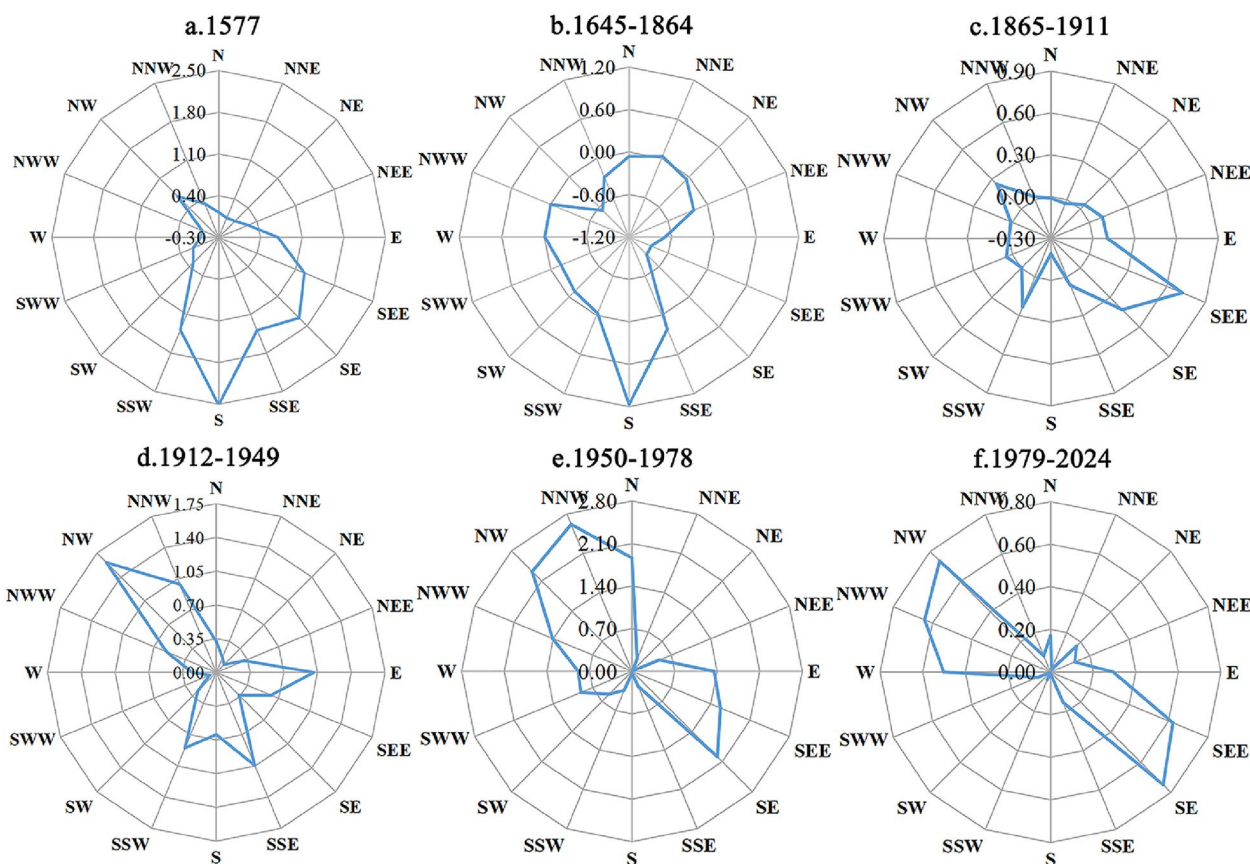


Fig. 10 Radar map of the intensity of expansion of urban form in different directions since the Ming Dynasty

Table 6 Indicators of changes in the contour and form of Nanjing since the Ming Dynasty

Year	1577	1850	1910	1949	1978	2024
Compactness (CI)	0.280	0.320	0.269	0.337	0.377	0.557
Landscape Shape Index (LSI)	3.161	2.771	3.296	2.625	2.349	1.592
Fractal Dimension Index (FRAC)	1.968	1.967	1.949	1.638	1.476	1.251

2) Changes in morphological unit

The morphological units in the Ming and Qing Dynasties were mainly residential areas, and commercial areas were concentrated in the Sanshan Street-Jewelry Gallery. The eastern part of the city included administrative areas such as the Imperial City during the Ming Dynasty and became military areas during the Qing Dynasty. From 1912 to 1949, commercial areas, such as the Central Road, Zhujiang Road, Zhongshan Road, and Taiping Road, expanded northward along the main roads. Xinjiekou became the commercial core. On

both sides of Zhongshan Road in the north were uniformly planned residential areas. The northern part of the city was also an important educational area. From 1949 to 1978, the urban morphology tended to be saturated, with little change in commercial and residential areas. A large number of industrial areas appeared in the north and east. After 1978, the morphological units stabilized, and the industrial areas were replaced by residential areas. The military areas changed relatively little and were stably located in the northeast of the city at Xiaoying and Huangpu Road (Fig. 11).

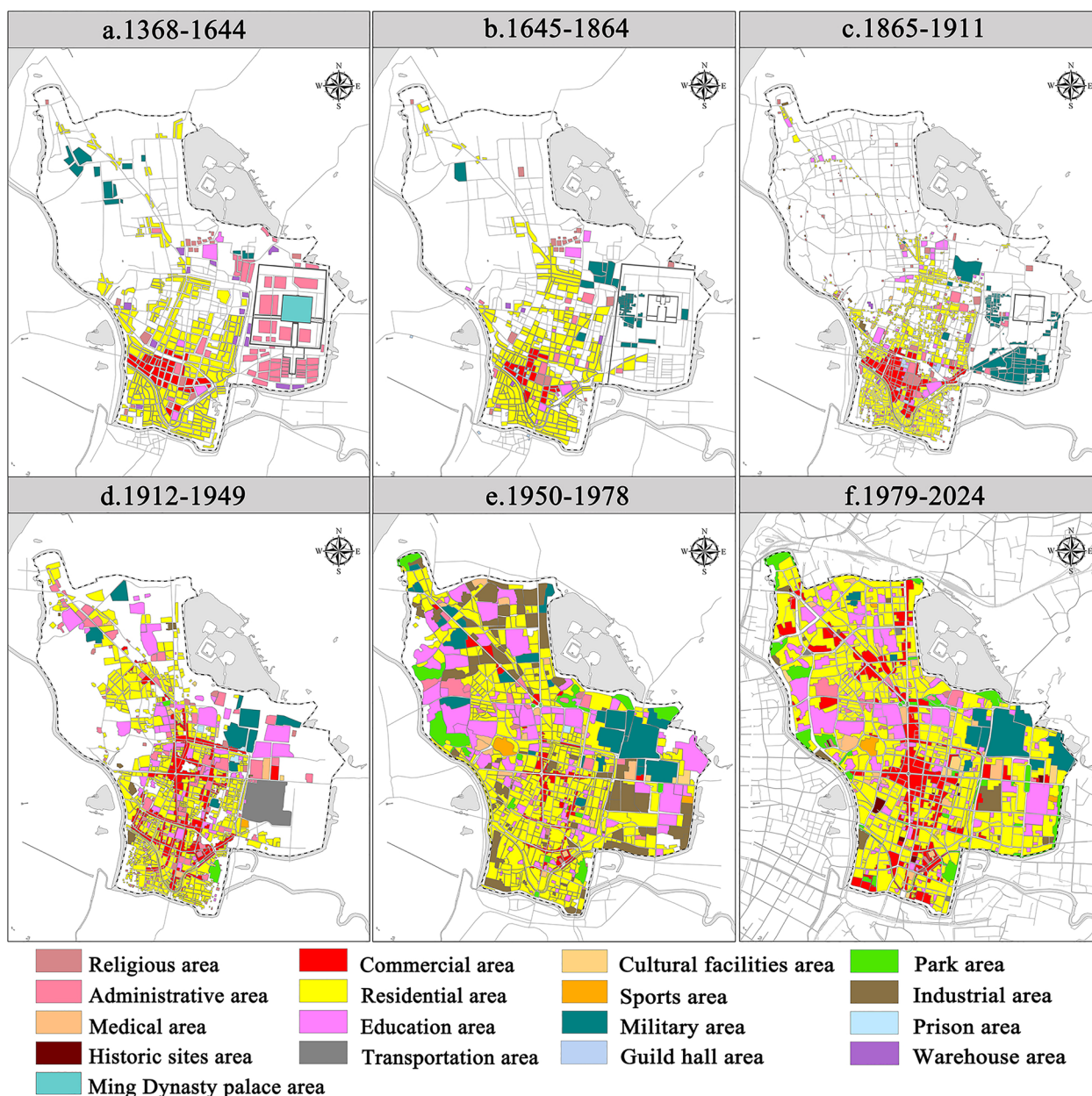


Fig. 11 Evolution of built-up areas and morphological units since the Ming Dynasty

Layered characteristics of the urban road network

In terms of NAIN, the core of the Ming and Qing foreground network is distributed in the densely populated and commercially concentrated areas in the south of the city, north and south of the “South Gate Street—Neiqiao”, “Pingshi Street—Caixia Street”, and east and west of the “Red Paper Corridor—Jewelry Corridor”. In the Republic of China, the road network changed. Zhongshan Road and Zhongyang Road became the new north-south axes. The core of NAIN first expanded

from the south to the north of the city, and the NAIN of the road network on both sides of Zhongshan East Road improved. After the founding of New China, large-scale road reconstruction led to changes in the NAIN, with the core shifting toward Gulou. The integration of Zhongshan North Avenue and the road network adjacent to Central Road, such as Majia Street, Tongjia Alley, and Lanjia Street, increased. After 1978, NAIN tended to stabilize. The NAIN indices of the main roads in the southern region, such as Jiankang

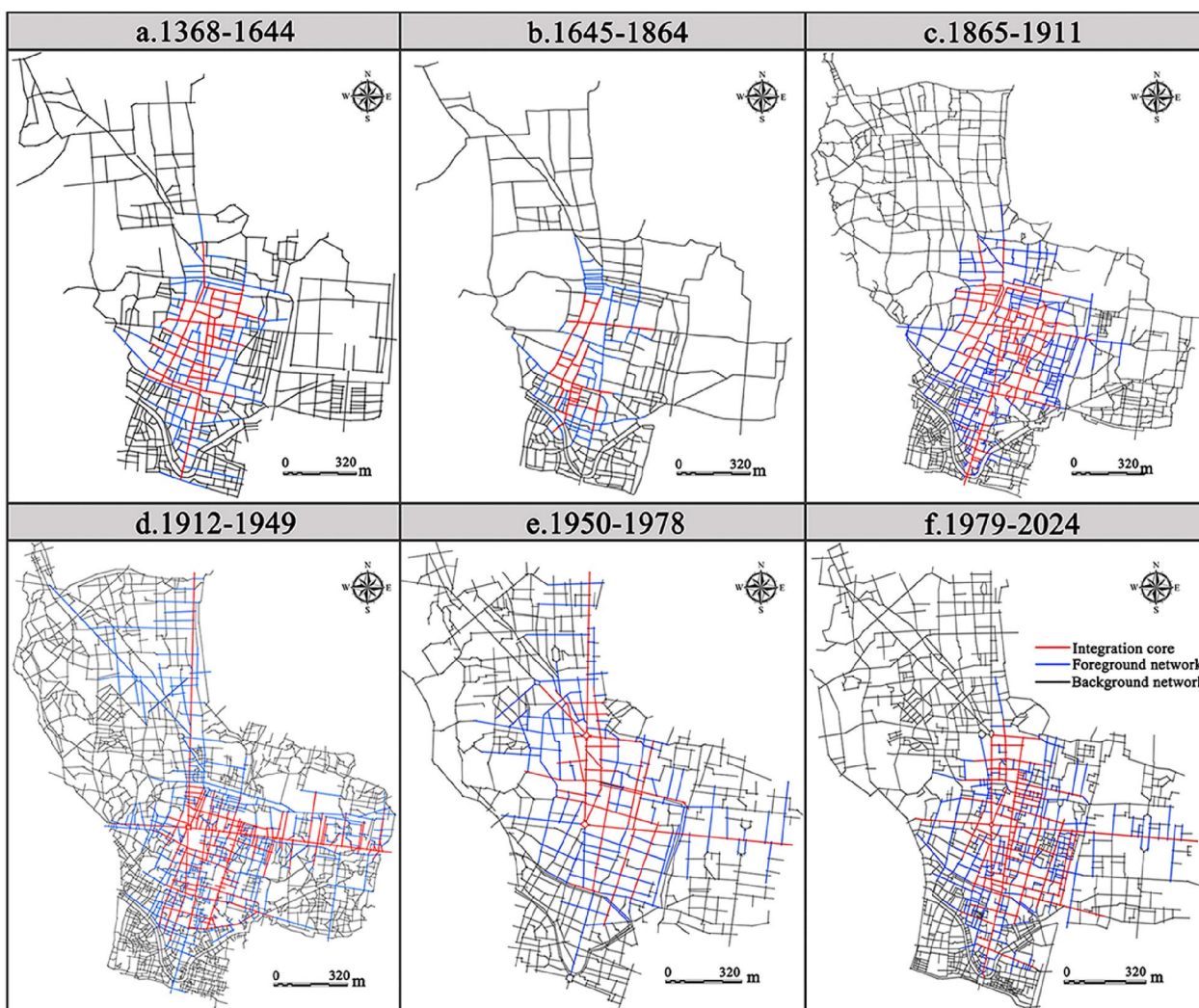


Fig. 12 Characteristics of the layer evolution of NAIN in the road network since the Ming Dynasty

Road, Changle Road, and Shengzhou Road, improved. The eastern part of the city did not have an effective road network until after the founding of New China, and Jiefang Road replaced Yudao Street as the foreground network (Fig. 12).

In terms of NACH, the structures of the NACHs in the Ming and Qing Dynasties were similar. The cores of the east–west direction are “Xiajiekou—Jewelry Gallery” and “Tujiekou—Daxinggong”, whereas the cores of the north–south direction are “Nammendajie—Neiqiao” and “Mingwalang—Caixia Street”. A stable road network with a low NACH index has not yet been developed to the north and east of the city. In the Republic of China, the NACH core began to move northward, and the two traditional east–west axes,

“Hanximen-Dazhongqiao” and “Shuiximen-Dazhongqiao”, which used to be located in the south, disappeared. Central Road, Zhongshan East Road, Hanzhong Road, Jiankang Road, and Taiping Road became the foreground cores of the NACH. After 1978, Zhonghua Road—Hongwu Road became the core of NACH from the south to the north of the city. The main structures were North Zhongshan Road, Central Road–South Zhongshan Road, and Hanzhong Road–East Zhongshan Road. The secondary structure consists of Changle Street and Jieqing Road in the southern region, Jiankang Road in the central region, and Zhujiang Road in the northern region. Traditional small-scale alleys form the tertiary road network (Fig. 13).

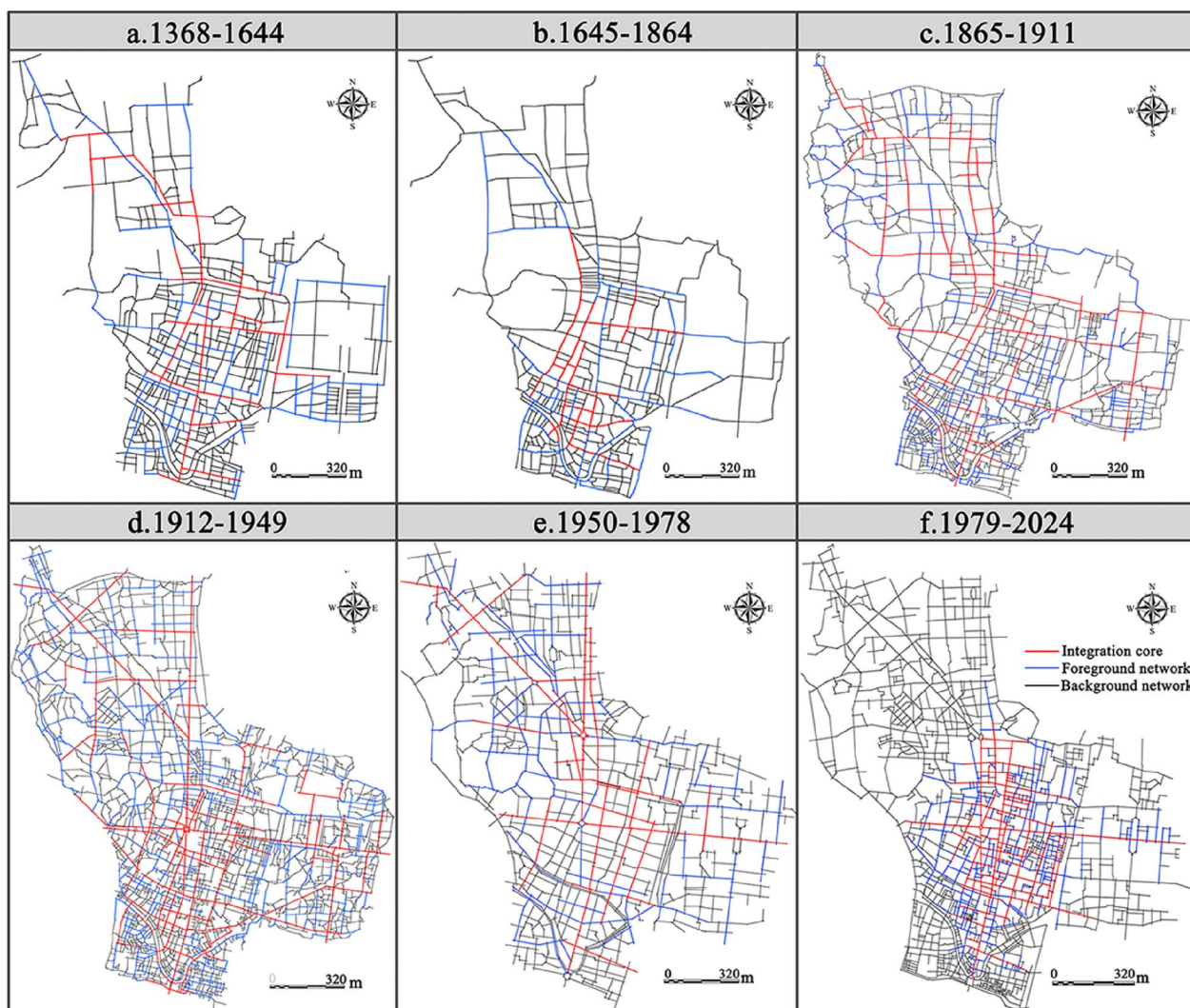


Fig. 13 Characteristics of the layer evolution of NACH in the road network since the Ming Dynasty

Layered characteristics of characteristic places

Ancient historical archives, especially local chronicles, recorded characteristic places, including governments, academies, ancestral halls, and temples, in the “Construction”, “Schools”, and “Scenic Spots” chapters. Our study categorizes them into 14 types according to the way they were recorded in the historical archives, including house gardens, scenic buildings, public gardens, temples, ancestral halls, government buildings, and educational buildings. This categorization method can be better connected with the social background of the historical landscape, reflecting ancient people’s perceptions of the historical landscape [53], and has been applied in the studies of Yanzhou and Wanzhou [54].

(1) Overall distribution characteristics

There were 328 characteristic places during the Ming Dynasty. The nearest neighbor index is $R=0.5378$, indicating an aggregated distribution. Menxi is the distribution core, and Confucius Temple, Qingliang Mountain, and Jilong Mountain are the secondary distribution cores (Fig. 14). At the beginning of the Qing Dynasty, there were 488 characteristic places, and the distribution area was not much different from that of the Ming Dynasty. At the end of the Qing Dynasty, there were 462 characteristic places. The nearest neighbor index is $R=0.6167$, and the distribution area begins to disperse. The Confucius Temple and Qingliang Mountain were the two major

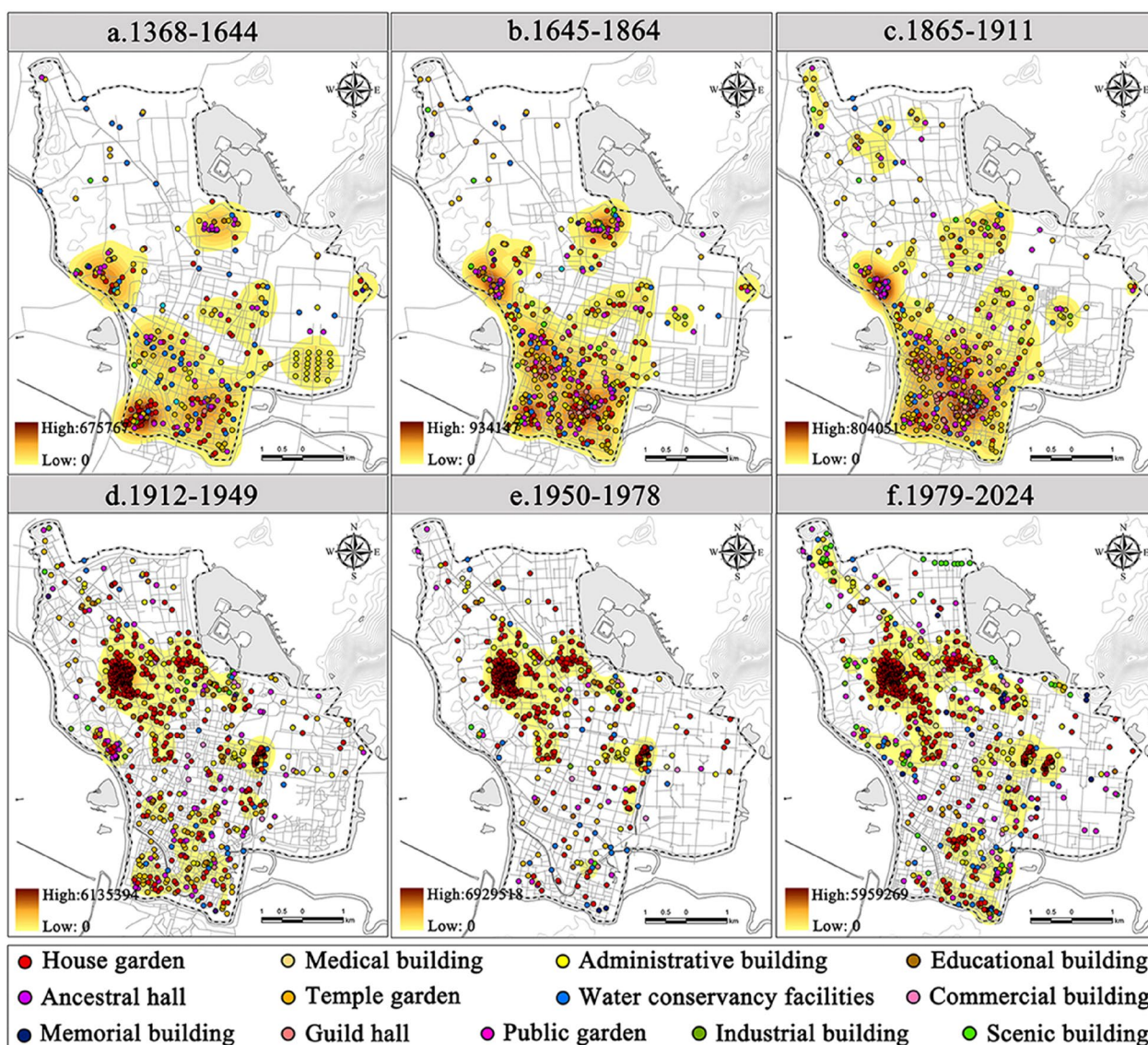


Fig. 14 Characteristics of the layer evolution of characteristic places since the Ming Dynasty

cores. Owing to improvements in transportation in the northern part of the city, temples and educational buildings began to sit on Hehui Street, and public gardens such as the Nanyang Commodity Exposition and the Lvyun Garden were sited on Dingjiaqiao. In summary, the characteristic places of the feudal period are concentrated in the southern part of the city. House gardens, temples, and ancestral halls always occupied the first three places. During the Ming Dynasty, house gardens were located in Menxi and Longpanli, and during the Qing Dynasty, they expanded to the center of the city, especially Nei-qiao Street, Sanshan Street, and Pingshi Street. Temples and ancestral halls were located in the southern part of the

city, with some dots in the northern part of the city, such as the Ma'an, Qingliang and Siwang Mountains.

In the Republic of China, the number of characteristic places increased to 960, and the spatial distribution changed significantly. The nearest neighbor index was $R=0.5337$, and the degree of aggregation was greater than that in the late Qing Dynasty. For the first time, the distribution core moved from the south to the north of the city, with Yihe Road becoming the absolute distribution core. House gardens are the most common type, accounting for 58.3% of the total. Yihe Road, Gaoloumen Road, and Hankou Road are the gathering areas of officials' high-class residential areas, dominating the spatial

gathering areas of all the characteristic places. The 82 government buildings are distributed along Zhongshan North Road in a “linear” shape, such as the Supreme Court and the Ministry of Transportation.

In the early years of new China, the number of characteristic places decreased to 720. The core distribution area was still in the northern part of the city. House gardens, government buildings, and educational buildings occupied the top three places. Influenced by the policy of controlling and banning religious sites, the number of temples and ancestral halls plummeted from 103 and 66 in the Republic of China to 23 and 11, respectively. After the reform and opening up, the number of characteristic places increased to 988, with a nearest neighbor index of $R=0.5201$, and the distribution area began to disperse. Yihe Road remains the core of the distribution, but with the protection of the historical and cultural city, many characteristic places have been rebuilt and restored, and Mendong, Confucius temple, and Pingshi Street in the southern part of the city have become subcores again. To meet the public’s daily leisure and aesthetic needs, scenic buildings and public gardens have become the dominant types, increasing in number to 60 and 55, respectively.

(2) Typical case study: house garden

Except for the late Qing Dynasty, the number of house gardens was the highest in all periods, and the core area of distribution moved from the south to the north of the city. During the Ming Dynasty, it was located in

Mendong and Menxi and began to move to the center during the Qing Dynasty. The Republic of China is the turning point in the distribution direction of house gardens. Yihe Road became the main distribution area, with Central Road and Gaoloumen as secondary gathering areas. During the Ming and Qing Dynasties, the central point of the house gardens moved from Pingshi Street to Neiqiao in the southern part of the city, showing a south–north distribution trend. In the Republic of China, the direction of spatial distribution has fundamentally changed, with the center point moving to Hankou Road and Jinyin Street in the north of the city, changing in a “northwest–southeast” direction. After New China, the difference between the lengths of the short and long semiaxes of the standard deviation ellipse decreased, and the distribution trend of the house gardens tended to increase (Fig. 15).

After the Taiping Heavenly Kingdom War, most of the house gardens before the end of the Qing Dynasty were destroyed. The existing house gardens are located on Yihe Road, and most of them are residences of officials in the Republic of China. The courtyard is spacious and contains a front yard, a back yard, and a side yard. After the founding of New China, the house gardens on Yihe Road were relegated to the public. The addition and remodeling of buildings are common, and the process of spatial layering has changed.

The layered characteristics of house gardens can be divided into two categories. In the first type, the spatial pattern does not change. These are fewer in number and are mostly privately owned (Fig. 16). Most of the

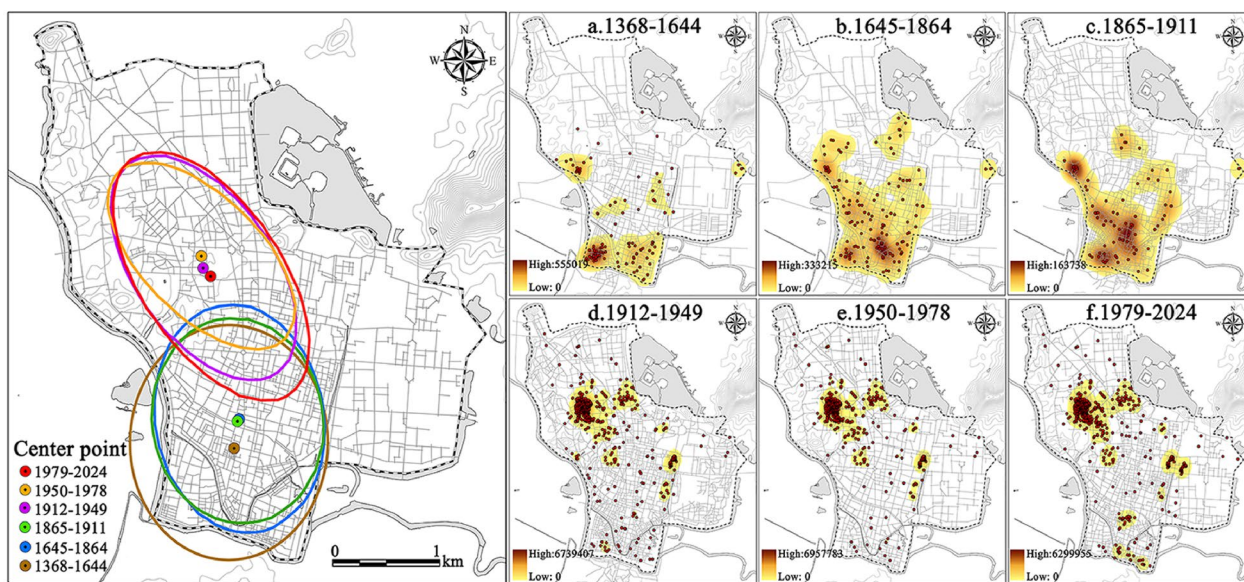


Fig. 15 Movements in the distribution area of house gardens

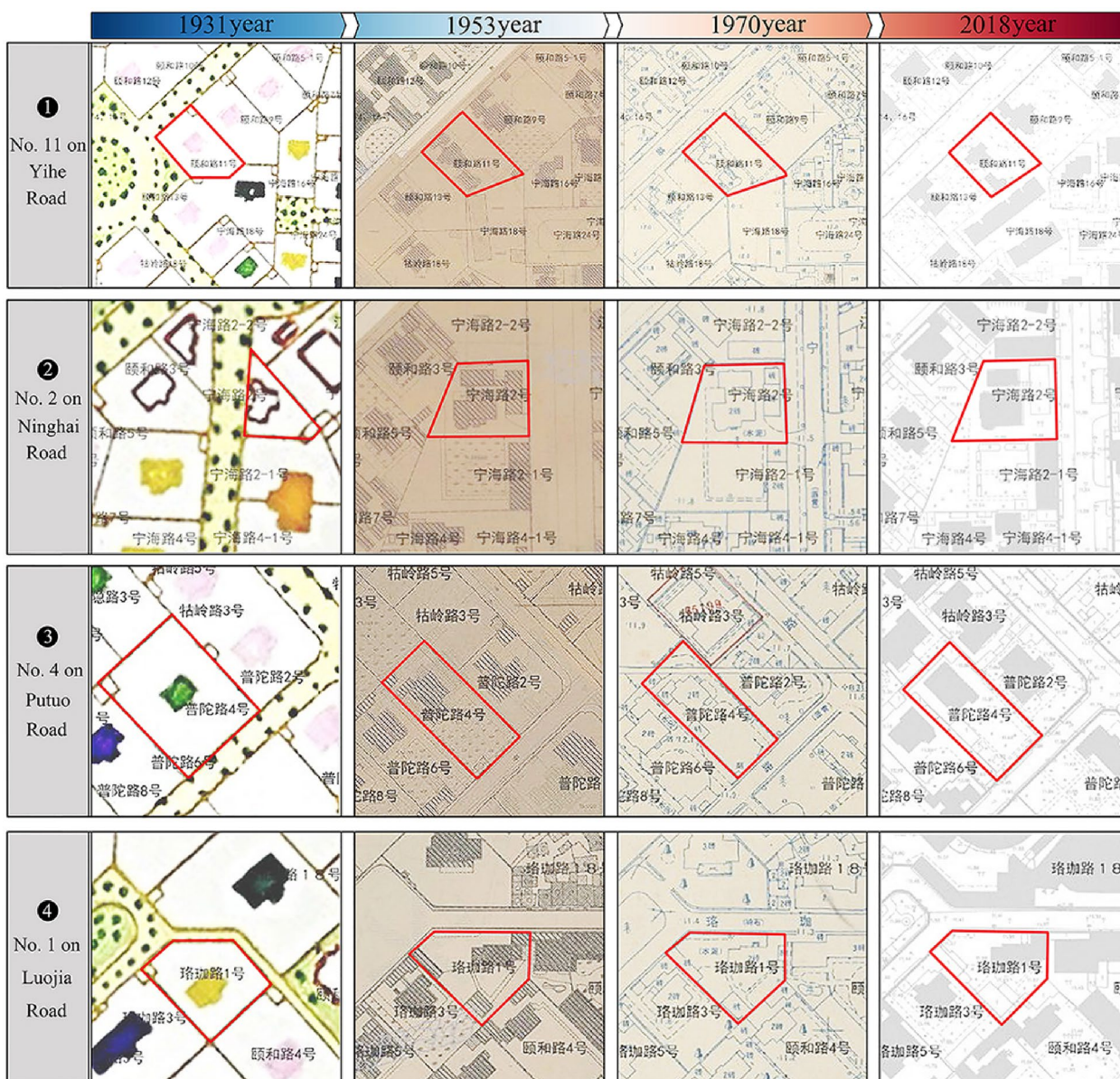


Fig. 16 Evolution of house gardens with less spatial pattern change (Adapted from reference 41)

courtyards are still single families today, including No. 11 on Yihe Road, No. 2 on Ninghai Road, No. 1 on Luoja Road, and No. 4 on Putuo Road. The other is the obvious change in spatial form, and its property rights are mainly for the army and state-owned units. Owing to the financial abundance of these departments, coupled with the fact that their construction activities are not subject to control, the main building additions are common, including No. 12 on Ninghai Road, No. 40 on Luoja Road, and No. 13 on Chibi Road. The house gardens were redivided into courtyards, including No. 7 and No. 35 on Yihe Road, No. 11 on Langya Road, and No. 5 on Guling

Road. New constructions include residential and office buildings. For example, the southern courtyard of No. 24 on Guling Road was demolished and turned into a collection of residences. No. 3 on Chibi Road merged with the southern side of the courtyard to build a residential area for the old cadres of the provincial authorities (Fig. 17).

Factors influencing the evolution of HUL

Historical development factors

Since the Southern Tang Dynasty, the population and road network have been concentrated in the southern part of the city. When Nanjing expanded during the

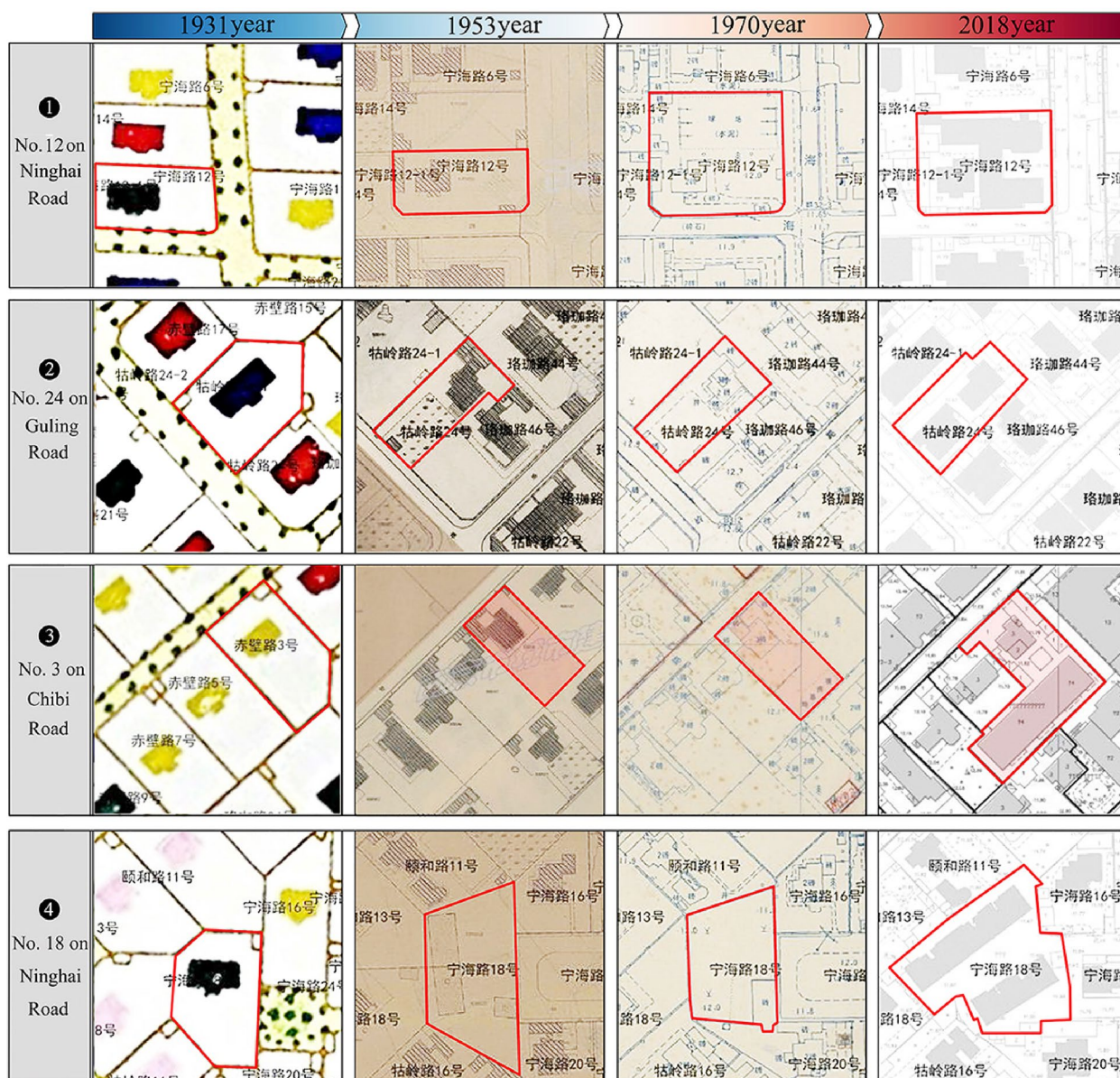


Fig. 17 Evolution of house gardens with significant changes in spatial patterns (Adapted from reference 41)

Ming Dynasty, a large amount of barren land to the east and north of the city was included within the city walls, and even in the Republic of China, the north of the city was still mostly farmland and numerous patches of small ponds [21]. The geographical record of Jiangsu Province, written in 1918, states that “North of Gulou, it is still desolate as if it were a village”. The imbalance of historical development led to a lower level of urbanization and more unused land in the northern part of the city, which determined the spatial movement of the HUL from the south to the north of the city [55].

Political factors

First, the influence of war on the evolution of the HUL. Nanjing was severely damaged by the Taiping Heavenly Kingdom War in 1865 [56]; for example, the urban form of the “garrison city” in the east of the city completely changed, and the number of house gardens, temples, and ancestral halls in the south of the city drastically decreased. In 1937, the Japanese invaded China and captured Nanjing, and the expansion of the HUL to the north of the city was interrupted. Second, the influence of the political system on the evolution of the HUL. In

the Ming and Qing Dynasties, the east of the city was the imperial and the garrison city, with Yudao Street on the north–south axis, preventing people from entering at will and highlighting imperial power. Commercial and residential areas were set in the southern part of the city, separating the ruling class from the common people. A large number of characteristic places, such as temples and ancestral halls, upheld the idea of feudal rule. In the Republic of China, under the influence of the modernization of national capitalism, education, medical, and transportation areas appeared in urban form. The road network became an important place for people to be educated in the “new way of life”. Modern road networks appeared in the northern part of the city, and the NACH and NAIN indices surpassed those in the southern part of the city. Public gardens, such as those in Xiushan Park and Gulou Park, began to appear. As Nanjing became the capital, there was a large number of officials, accounting for 7.08% of the total population [57]. There were numerous house gardens, and they became the dominant type of characteristic place. After 1949, the land for urban construction was allocated without compensation. To develop the socialist economy, many residential areas within the city were transformed into industrial areas [58]. Many industrial areas and workers’ villages, such as Nanjing Radio Factory and Ruijin New Village, have appeared. These factories and workers’ villages, which were regarded as “embodying the ideology of socialism”, usually occupied large plots of land, and the roads were reorganized to form a sparse network with large avenues [59]. For example, during the Republic of China, there were 14 roads in the area of Babao Street, including a botanical garden, a police station, and a livelihood office for the Manchu people. After the founding of New China, only “T” shaped roads remained in the area, and the land was reorganized into the “Nanjing Machine Tool Factory” and “Workers’ New Village”. The accessibility of the main roads increased, with Xinjiekou, Gulou, Zhujiang Road, and Zhongshan East Road being the areas with the highest accessibility indices. Under the influence of the “Destroy the Four Olds (campaign of the Cultural Revolution)” in New China, the number of ancestral halls and temples, which represented feudalism, decreased sharply. After 1978, with the introduction of the “Plan for the Conservation and Improvement of the Historic Urban Area in the South of the City”, Mendong and Nanbuting were transformed into cultural neighborhoods, and the density of the road network increased. The NAIN of Madao Street and Changle Road increased significantly, and the accessibility of the adjacent alleys also improved.

Urban planning

The urban planning and expansion of Nanjing at the beginning of the Ming Dynasty determined that HUL was concentrated in the southern part of the city. In the Republic of China, Nanjing began to carry out scientific urban planning. The southern part of the city was too populated to be easily transformed. To satisfy the residential needs of government officials, the northern part of the city, which was vastly and sparsely populated, was planned as a new-style residential area. A total of 1,700 house gardens were built on Yihe Road, Gulinsi, and Yinyangying, with a greening rate of 65% [57]. Hankou Road was planned as an educational area. The east of the city was planned as the “Central Political District” in 1930, but until 1935, the government did not allow the public to buy and sell freely for five years and did not expropriate them, which led to stagnation of the development of the area [60]. Since the completion of Zhongshan Road in 1929 under the Capital Plan, the road network in the northern part of the city has been arranged parallel or perpendicular to Zhongshan Road and Central Road as the baseline. The western road network pattern occurred in Yinyangying and Gulou, and the NACH index was the highest. After the founding of New China, the relatively empty northwest of the city maintained a concentration of various administrative and educational areas. Starting from the “Preliminary Urban Zoning Plan” in 1954, the urban form continued to expand into the mountains to the north of the city, and the built-up area within the city walls began to become saturated.

Xiaguan commercial port and public transportation

In 1899, the government designated Xiaguan along the Yangtze River as a commercial port [21]. To strengthen the connection between Xiaguan and the southern part of the city, Nanjing’s first modern highway, Jiangning Road, and China’s first modern metropolitan railroad, Nanjing Municipal Railway, were constructed in the late Qing Dynasty. In 1929, Zhongshan North Road was built on the southern side of Jiangning Road. Improved transportation conditions resulted in population concentration, with built-up areas, road networks, and characteristic places expanding rapidly along both sides of Jiangning Road, Zhongshan Road, and the metropolitan railway.

In the Republic of China, public transportation began to appear, facilitating the further spread of the HUL to the north of the city. The metropolitan railway had 30 trips per day, running for approximately 40 min per trip, which greatly decreased the spatial and temporal distances [61]. The earliest buses opened in 1927, “starting from the Menlian Bridge in the south of the city, passing

through Huapailou, Chengxian Street, and along Jiangningma Road to Xiaguan in the north of the city” [62]. In 1931, the 2nd and 5th buses ran from Confucius temple and Xiushan Park in the south of the city to Hepingmen and the residential area of Yihe Road in the north of the city [62]. With the development of public transportation, the HUL intentionally developed toward the north and east of the city, promoting the movement of spatial distribution.

Land price

According to “Shun Pao (申报)” of December 25, 1934, land in Hepingmen was sold for 1690 yuan per square, 4000 yuan per mu in Zhonghua Road, and Chibi Road was worth 5000 yuan per mu. The information on land sales in the Republic of China revealed that Zhongshan North Road, Yixian Bridge, and the fringe areas in the north of the city were sparsely populated and had low land prices [57], so the areas involved in land acquisition were often large, with many house gardens, government buildings, and education buildings. In the southern part of the city, where land prices were relatively high, the area of land acquisition was relatively limited, with fewer new morphological units, and the characteristic places were house gardens, temples, and ancestral halls. After the reform and opening up, many industrial areas in the northern part of the city were purchased by real estate companies and transformed into residential areas, resulting in major changes in the urban form units. Owing to the high land prices in the urban core, large public gardens were located in the suburbs, while the core area was dotted with scenic buildings and small gardens.

The high land price in the southern part of the city also hindered the evolution of the road network. Conflicts often arose between the government and residents due to high compensation. For example, during the construction of Lion Lane, the public collectively boycotted the construction, and a citizen named Liu Yinlu even requested assistance from the General Command of the National Revolutionary Army to reroute the Lion Lane [63]. As a result, the government had to slow the revamping of roads in the southern part of the city. Instead, the northern part of the city, which was sparsely populated and had lower land prices, became the focus of road network construction.

Discussion

Assessing the potential of database construction methods for small cities

The cases in which HGIS is used to study HUL are concentrated mainly in provincial capitals or developed

coastal cities such as Beijing, Suzhou, Guangzhou, Chongqing, Xi’an, Ningbo, and Qingdao [32, 51]. Owing to the lack of historical information, it is rarely used in small cities. The method proposed in our paper has good potential for use in small cities.

The study of the layered characteristics of the Ming and Qing historical landscapes is the most challenging in both large and small cities. The data and information of the Republic of China have important reference value for the Ming and Qing Dynasties. In addition to textual archives, mapping maps are the most direct sources for documenting historical landscapes. There are 989 small cities containing Republic of China mapping maps in the Collection of Chinese Local Records and the Chinese Ancient Books Resource Library of the National Digital Library (<http://www.nlc.cn>), such as Gaoyi in Hebei Province and Gaoyou in Jiangsu Province. For small cities without Republican maps, we can choose U.S. Keyhole (KH) spy satellite images taken in the 1950s (<https://earthexplorer.usgs.gov/>) as a reference for the Ming and Qing Dynasties. The images were taken only half a century after the Qing Dynasty and have been applied to the study of the HUL of Huaiyang and Yili in the Qing Dynasty [64].

The spatial and attribute information of the characteristic places can be obtained from the “Construction” and “Monuments” chapters in the local chronicles according to the “azimuthal, topological, and distance” relationship method proposed in this paper. For example, “Xianfeng Rerevision of Xinghua County Records” in 1852 reported that “Shengyu Pavilion is located in the west of the government”. The extraction of road network information is completed on the basis of Republic of China maps or KH satellite images supplemented by historical archives. For example, although the map in the “Xianfeng Re-examination of Xinghua County Records” had no scale, the basic direction of the road network was drawn, and the spatial information was recorded in the text, “Wu’an Street, west of Guanyu Temple to the front of the government”. Taking the road network in the Republic of China’s local records as a reference, the road network data from the Qing Dynasty were extracted according to the method of mapping the road network whose name and location had not changed and then determining the ancient and modern name and location of the “changed” road network (Fig. 18). The data on urban morphology come from the written records of ancient documents and previous results (Fig. 19). For example, “Kangxi Shangqiu County Records” from the Qing Dynasty recorded the location of the government area: “the government was in the center of the city to

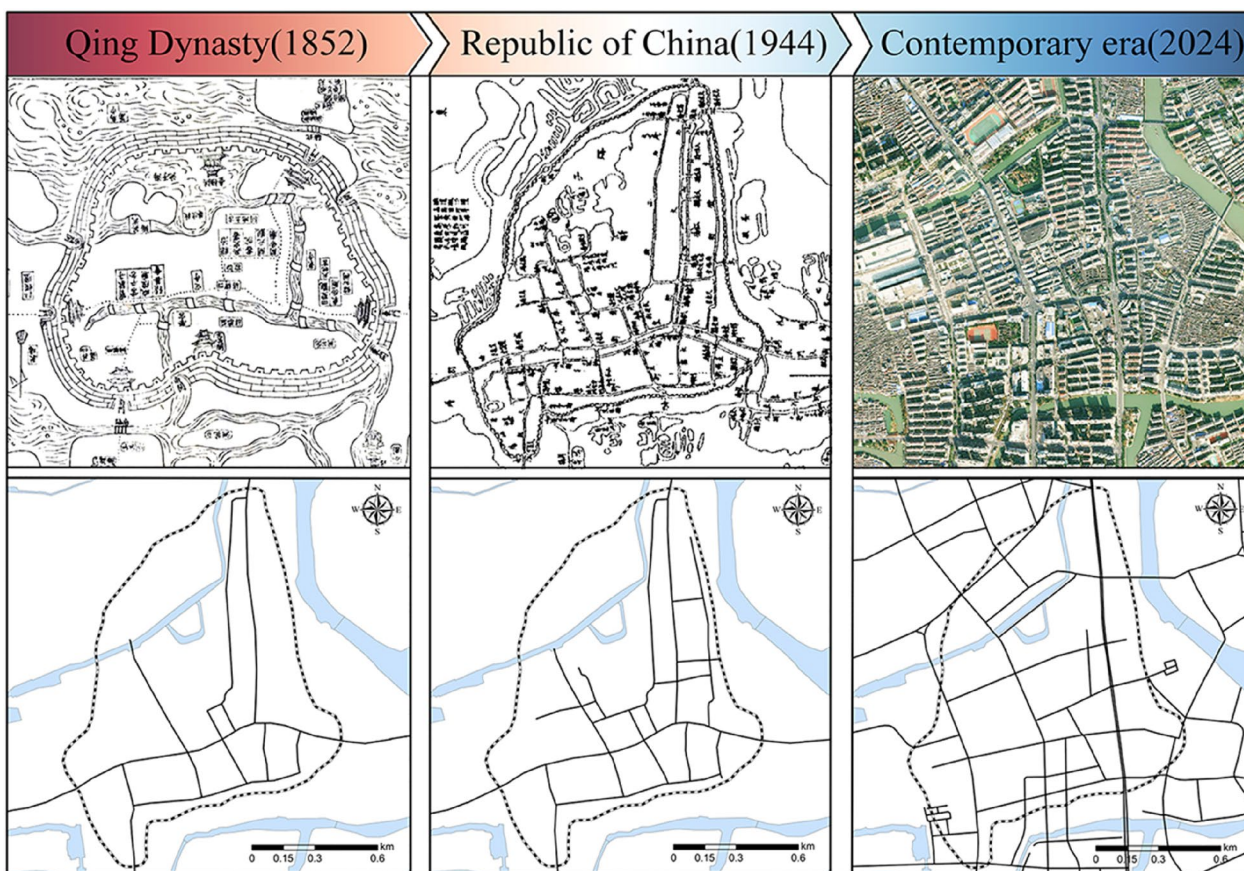


Fig. 18 Evolution of road network in Xinghua County, Jiangsu Province

the east, near the Dayushou east street”. The commercial areas were recorded as “Dayushou Street was the center of the city, and the two sides of the road leading to Bin-yang, Gongchen, Gongyang, and Dieze Gates were the commercial areas”. The Shangqiu County Record, written in 1982, described the urban morphology at the beginning of the new China.

The database construction methodology proposed in our paper provides a good reference for the study of HUL in small cities. However, owing to the relative lack of historical archives in small cities, although they can also be traced back several centuries, they are unable to form multiple historical phases, as in large cities, and the time division is relatively rough [38]. The use of materials such as archaeological reports and garden paintings has increased in recent studies [65, 66]. These methods can compensate for the lack of documentation sources for small cities, have important potential for determining spatial information, and need to be emphasized to enrich our understanding of HUL.

Research shortcomings and future work

Our study has the following shortcomings: (1) The ambiguity and uncertainty of historical data are challenges that cannot be ignored in the construction of HGIS [67, 68]. ① Since there are few historical documents from the Ming Dynasty, our study uses data from the middle to late Ming Dynasty to represent the entire historical period, which may bias the results of the evolution of characteristic places at the microscale of the HUL. ② The accuracy of the morphological unit division in the Ming and Qing Dynasties was relatively low, and future studies involving firsthand cadastral historical data are needed to obtain more accurate and detailed geographic information. (2) Our study focuses on the material elements of the HUL and pays less attention to nonmaterial information. In future research, the HGIS of immaterial elements such as historical events, legends, and poems will be constructed to realize the link with the system of material elements.

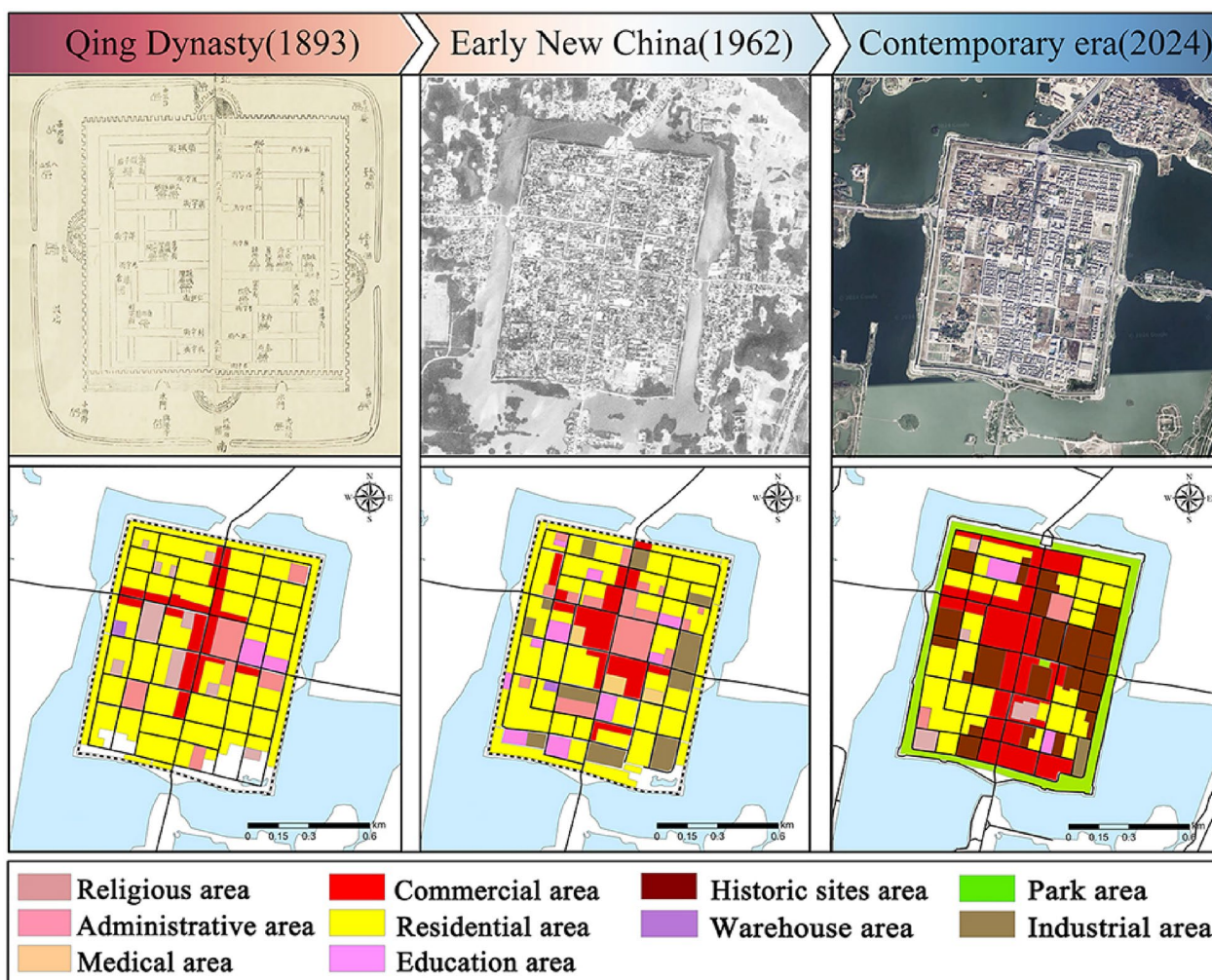


Fig. 19 Evolution of urban morphology in Shangqiu, Henan Province

Conclusion

Our paper proposes a framework for building an HGIS of HUL by digitizing historical documents and ancient maps. Taking Nanjing since the Ming Dynasty as an example, the steps and technology of digitizing historical documents are introduced, and the feasibility of the methodological system for use in small cities is demonstrated. Owing to the layered characteristic of the HUL, HGIS is well suited for historic landscape studies with large periods and rich elements through the visualization of historical periods.

Nanjing’s historic urban landscape has obvious spatial layered characteristics. The urban form, road network, and characteristic places all spread from the south to the north of the city. During the Ming and Qing Dynasties, the residential and commercial areas were in the south

of the city. The NACH and NAIN cores of the road network were at Xiajiekou and Pingshi Street, and the characteristic places were mostly temples and ancestral halls. In the Republic of China, many residential, educational, and administrative areas were located on both sides of Zhongshan North Road. Officials’ house gardens were numerous and concentrated on Yihe Road and Yinyangying, dominating the movement of the distribution core of characteristic places. In the early years of New China, many industrial areas appeared. The road network was transformed and merged, and the core of NAIN shifted toward the drum tower in the north of the city. The number of characteristic places, such as temples and ancestral halls, decreased sharply. After the reform and opening up, the built-up area within the city walls became saturated, and industrial areas were replaced by residential

areas. In the south of the city, under the transformation of historical and cultural city protection, a road network pedestrian system was formed, and many scenic buildings and heritage buildings were restored, which made it a subdistribution core of characteristic places again. Political factors, urban planning, commercial ports, and land prices influence the layering process of the HUL.

HGIS provides new research ideas and paradigms for HUL research. Our study extracts spatial location and attribute information from the literature and remote sensing images, integrates multisource data, visualizes the spatial and temporal evolution of each element, and provides a rich database for the management of HUL. However, we should not rely too much on digital technology. On the basis of digital technology, in-depth qualitative research should be carried out to explore the laws and mechanisms of the development of HUL. Owing to natural and human factors, records of some elements are missing, which leads to difficulties in informatization. Therefore, it is practical to use a combination of precise localization and fuzzy orientation. The database constructed in our study can provide decision-makers with an accurate basis for conservation planning and meet the public's needs for cultural heritage awareness.

Author contributions

XB was responsible for most of the work and writing of the manuscript. XY and TS were responsible for the data analysis of the manuscript. HX was responsible for the review and revision of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used in this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare no competing interests.

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