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HGIS based analysis of urban morphological evolution in historic Kaifeng

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Historic cities face increasing pressure from rapid urbanization, highlighting the need to understand long-term urban morphological evolution for sustainable heritage conservation. This study examines the spatial evolution of Kaifeng from the Northern Song Dynasty to the Republic of China by integrating Conzenian urban morphology with Historical Geographic Information Systems (HGIS). Four representative historical stages were reconstructed to analyze changes in urban boundaries, street networks, and functional structures. The results reveal a cyclical process of expansion, contraction, and re-expansion driven by political transformation, Yellow River flooding, and shifts in transportation systems. Kaifeng's urban structure evolved from a highly legible axial imperial layout to a multi-centered and increasingly complex configuration, accompanied by a transition from water-based to transportation-oriented functions. A coupled institution–environment–transportation mechanism is proposed to explain the city's long-term morphological dynamics.

Under the backdrop of rapid contemporary urbanization, the importance—and the challenges—of urban heritage conservation have become increasingly pronounced. In past conservation practices, urban heritage was often treated as a “time-frozen” static entity, overlooking its broader role as an element of *urban organization*¹. This narrow perspective has contributed to problems such as the fragmentation of historical continuity, the erosion of local character, and growing spatial homogenization in many cities². Against this background, the principle of authenticity—now a core consensus in international heritage conservation—has gained increasing attention. Its meaning has undergone a critical shift from the static preservation of material fabric to a dynamic recognition of heritage values. This shift has, in turn, underscored the growing importance of urban morphological research in heritage conservation.

Since the twentieth century, the principle of authenticity has been progressively refined through a series of international heritage charters, gradually shifting from an emphasis on static material conditions to a concern for the continuous expression of heritage values over time³. The 1931 *Athens Charter* first highlighted the originality and verifiability required in monument restoration, with its core focus still placed on the preservation of physical form⁴. The 1964 *Venice Charter* formally introduced the concept of “authenticity,” establishing a basic framework of material authenticity by emphasizing original materials, craftsmanship, and environmental context⁵.

As understandings of heritage expanded, the 1994 *Nara Document on Authenticity* marked a pivotal paradigm shift: authenticity was no longer

confined to form or materiality⁶, but understood as embedded within the historical processes, cultural contexts, and intangible values embodied by heritage. This reconceptualization redirected attention from the preservation of static entities toward a holistic recognition of the mechanisms by which heritage values are generated and the logic of their evolution.

This shift from a focus on the “material entity” to an emphasis on “process and context” established the theoretical foundation for the growing importance of urban morphology research in heritage conservation⁷. Subsequently, in 2011, UNESCO introduced the *Historic Urban Landscape (HUL)* approach⁸, which further underscored the need to identify and sustain the continuity of historical urban forms amid ongoing urban transformation. The HUL framework advocates integrating heritage conservation into the dynamic interactions among urban development, social functions, and spatial structures⁹. This perspective highlights a key insight: understanding urban authenticity requires tracing the temporal trajectories of changes in urban form, environment, and function.

Accordingly, the understanding of authenticity in heritage conservation has evolved from “preserving the material state at a given moment” to “safeguarding the integrity of values expressed throughout historical evolution.” Urban morphology, as a discipline that examines the physical form of cities and the forces and processes driving its transformation, provides essential analytical tools for this shift¹⁰. By identifying morphological characteristics and underlying mechanisms of change, it helps illuminate the intrinsic continuity of cities as historical carriers. In doing so, it offers a

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Table 1 | Overview of major case study in historical GIS

No.	Analytical method	Year	Study area	Advantages	Limitations
1	Historical Map Digitization	2010	US Counties ³⁷	Classifies and digitizes historical maps suitable for HGIS	Relies primarily on map sources; map quality varies significantly
		2019	Non-specific region ⁶³		
		2020	Limousin Region, France ⁶⁴		
2	HGIS Data Modeling	2010	Izmir, Turkey ³⁷	Constructs thematic databases (point, line, polygon) using classification models, converting data models into layered spatial maps	Uses historical data as research material; insufficient for exploring urban history and social characteristics
		2016	Cesena, Italy ⁶⁵		
		2019	Blanice River Basin, Czech Republic ⁶⁶		
		2024	Great Wall of China ⁶⁷		
3	HGIS Spatial Analysis	2017	Cuenca, Ecuador ⁶⁸	Utilizes quantitative methods to support urban studies	Lacks longitudinal comparison of urban form and social conditions across different stages
		2024	Nanjing, China ¹⁷		
		2025	Xi'an, China ²⁷		

(Source: Drawn by the author).

scientific foundation for maintaining authenticity amid contemporary development and for reconciling the tensions between heritage conservation and urban construction¹¹.

Within this framework, “authenticity” is no longer equated with preserving the material condition of a single temporal cross-section. Rather, it concerns whether the coupled relationships among morphological evolution, spatial order, and social function can be sustained and meaningfully interpreted¹². As a result, the core of authenticity has shifted toward dynamism, continuity, and process. This shift positions the study of urban morphological change as a crucial avenue for revealing the authenticity of historic cities. Only by understanding how a city is continually produced, adapted, and reconstructed under multiple driving forces can we grasp the true sources of its historical value.

Within the diverse research traditions of urban morphology, analytical approaches to morphological evolution exhibit distinct emphases¹³. Unlike the typological approach of Caniggia and Muratori, which emphasizes the evolution of morphological types, the Conzenian school concentrates on the systematic analysis of temporal layering and plot structure transformation, introducing the widely used method of “plan-unit analysis”¹⁴. According to Conzen’s definition, which advanced plan analysis research in the latter half of the twentieth century, a “plan” refers to the topographical layout of all man-made elements within a city’s built-up area, comprising three inter-related components: streets, plots, and building fabric¹⁵. By tracing the formation, growth, and transformation of urban morphology, researchers reveal the interrelations among these components, identify patterns of morphological change, and interpret the historical stratification and spatial structure of urban form. With advancements in information technology, the application of Geographic Information Systems (GIS) in historical and urban studies has expanded rapidly, marking a shift in morphological research from qualitative description to quantitative analysis¹⁶.

Historical Geographic Information Systems (HGIS) are GIS-based spatial platforms that integrate historical maps, documents, and spatial data to create multi-layered spatiotemporal databases, enabling dynamic simulation and quantitative analysis of urban morphological evolution¹⁷. HGIS offers a cross-temporal and multi-scalar approach to quantitative comparison, allowing researchers to combine texts, maps, and archeological materials to reconstruct the dynamic processes of urban transformation. As a product of the digital era, HGIS plays an increasingly significant role in the study of ancient urban morphology, both in practical applications and academic research¹⁸. First, HGIS integrates historical spatial elements such as morphological units, street networks, and landmarks, facilitating the tracking of urban growth, decline, and restructuring patterns over centuries^{19,20}. Second, core GIS techniques—including space syntax and kernel density analysis—enable the quantitative examination of spatial relationships, enhancing our understanding of how social and economic dynamics influence urban spatial structures^{21–23}. Third, HGIS databases can

visualize the spatial configurations of historical cities and delineate conservation boundaries, while incorporating natural geographic conditions and land-use data as references for urban planning, thereby providing an objective foundation for heritage conservation and spatial planning²⁴. This technology has been widely applied in research on historic cities across Europe and East Asia^{25–27}.

In recent years, both domestic and international scholars have made significant progress in applying HGIS to historical urban studies. However, certain limitations persist, including inconsistencies in data standards, short temporal sequences, and insufficient quantitative analysis (see Table 1). Collectively, these studies illustrate the technical approaches of HGIS in extracting historical spatial elements, constructing spatiotemporal databases, and performing spatial statistical analyses, thereby providing valuable methodological insights for this research.

The morphology of ancient Chinese cities is a crucial aspect of global urban morphology research. Known as the of eight dynasties, Kaifeng played a significant role in China’s historical and economic development. However, due to the city’s declining political importance and repeated flooding of the Yellow River, Kaifeng experienced a transition from prosperity to decline, with its urban scale shrinking drastically. Over time, six successive city layers—including three imperial capitals, two provincial capitals, and one military stronghold—were superimposed beneath the modern city, creating a typical urban palimpsest phenomenon^{28,29}. The selection of Kaifeng as a case study is based on two factors: first, its rich historical documentation as a major city; and second, its relatively stable geographical location over a millennium, which has preserved a coherent urban pattern and spatial layout. Nevertheless, previous studies have largely focused on archeological sites and surface relics, lacking an integrated spatial analysis grounded in morphological theory and temporal data^{30,31}.

Although researchers in archaeology, architecture, geography, and urban planning have long studied Kaifeng’s ancient city, most existing research focuses on archeological excavations and surface remains, with limited diachronic quantitative analysis or exploration of spatial mechanisms grounded in urban morphological theory. Therefore, it is essential to re-examine the formation logic and evolutionary patterns of Kaifeng’s urban structure through the lens of morphological evolution, supported by a HGIS.

In summary, although prior research has primarily focused on medieval Western cities or specific historical periods, long-term studies examining the complex, multi-layered morphological structures of East Asian cities remain insufficient. Accordingly, this study establishes three main objectives:

- (1) To construct an HGIS database of Kaifeng’s urban morphology encompassing four historical periods—the Northern Song Dynasty, the Ming Dynasty, the Qing Dynasty, and the Republic of China—to enable comparative reconstruction of multi-period urban layouts;

- (2) To integrate Conzenian urban morphology with quantitative techniques such as space syntax, boundary shape index, and kernel density analysis, thereby establishing a multi-scalar “surface–line–point” analytical framework;
- (3) To reveal the mechanisms of urban morphological evolution driven by the combined influences of political institutions, hydrological environment, and transportation technology, providing a scientific foundation for heritage conservation and spatial renewal of ancient cities.

Methods

Research framework

This study aims to establish an analytical framework that integrates Conzenian urban morphology with geospatial technologies to reveal the temporal evolution of Kaifeng’s urban form through multi-scale quantitative methods. Extensive empirical research has shown that Conzen’s plan-analysis approach is widely applicable to Western urban contexts^{32–34}. Building on earlier urban morphological studies, this approach proposes a tripartite division of the urban plan—streets, plots, and building fabric¹⁴. These components are interrelated and together constitute “morphological units” at different hierarchical levels. By adopting an “overall-to-part” perspective, the method provides an objective description of urban transformation and highlights the intrinsic relationship between urban form and time²⁴.

Urban morphology traditionally analyzes the physical components of urban form. Although Conzen later introduced property ownership as an additional variable, a major limitation remains: this approach tends to overlook the influence of social, economic, functional, and land-use dynamics on the built environment. Expecting such a method to evolve into a universally replicable model capable of precisely reproducing morphological units across different urban contexts is unrealistic.

The evolutionary trajectory of Chinese historic cities exhibits a distinctive pattern of “stratification and reconstruction.” *Stratification* refers to the accumulation of temporal layers—for example, towns built upon earlier settlement sites where spatial structures from multiple historical periods can still be identified in the present urban fabric³⁵. *Reconstruction*, on the other hand, involves repeated adjustments or reconfigurations of functional distributions throughout urban history. These processes produce far more complex spatial signatures than those typically accounted for in classical Conzenian theory. Consequently, localized adaptation of Conzen’s morphological framework is essential to accurately interpret the spatial dynamics of ancient Chinese cities.

Building on Conzen’s *plan-analysis* framework, this study incorporates the “stratification–reconstruction” characteristics of Chinese historic cities and develops a multi-scale analytical system structured around three dimensions: *boundaries, streets, and functions*. Introducing computational analysis of morphological boundaries shifts the focus beyond internal structural elements toward the broader dynamics of overall spatial change. In parallel, integrating functional land-use statistics deepens the understanding of the dynamic relationship between urban development and functional organization, enabling an interpretation of urban space through the lens of its morphological functionality.

The frame-work comprises three main steps (Fig. 1): (1) georeferencing and vectorizing selected historical maps to ensure that maps from different periods share a unified coordinate system and spatial comparability¹⁰; (2) establishing an HGIS database of Kaifeng’s historical urban morphology by integrating digitized historical and documentary data to support subsequent spatial analyses¹¹; and (3) conducting multi-level analyses of the city’s morphological evolution at the area (surface), line, and point scales, following Conzen’s plan analysis approach.

Study area and data sources

The core area of this study corresponds to the historical urban extent revealed by the archeological remains of the Northern Song capital, Dongjing City. Kaifeng City is located in central China, in the eastern part of Henan Province, on the southern edge of the North China Plain and the

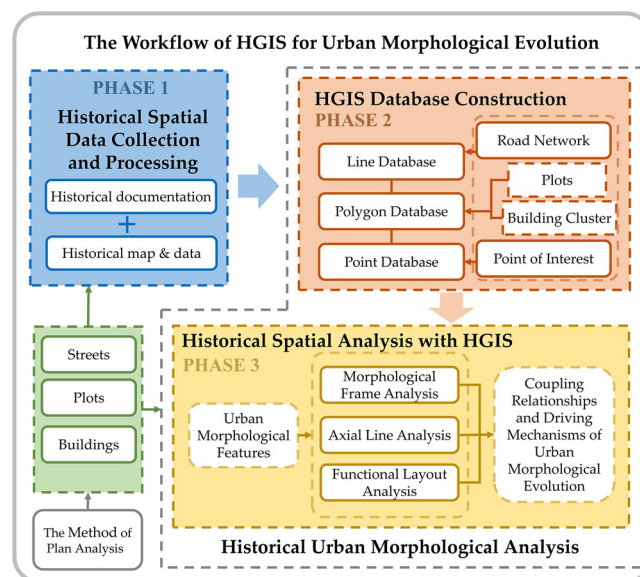


Fig. 1 | Research methodology framework. (Source: Drawn by the author).

Yellow River alluvial fan (Fig. 2). As one of the most important capitals in Chinese history, Kaifeng’s urban layout has experienced repeated flooding and reconstruction, resulting in a phenomenon of urban stratification, or urban palimpsest. Thanks to systematic archeological surveys and excavations, the precise locations and boundaries of the outer city, inner city, imperial city, and imperial avenue (Yujie) of Northern Song Dongjing have been largely confirmed³⁶. Compared to the Northern Song period, the urban extent in subsequent dynasties—the Ming, Qing, and the Republic of China—contracted significantly. Therefore, to maintain temporal consistency and spatial comparability for diachronic analysis, the archeological sites of the Northern Song Dongjing outer city wall were selected as spatial control points. The specific geographical boundaries are 34.76°N to 34.85°N and 114.30°E to 114.38°E, covering an area of 57.94 km².

In line with significant historical events and key morphological changes in Kaifeng’s urban development, this study divides the analysis into four representative stages. These stages correspond to distinct phases of political transformation and spatial reconstruction, specifically the Northern Song, Ming, Qing, and Republic of China periods.

Northern Song period (AD 1127–1279): As the capital of the Northern Song dynasty, Kaifeng reached the pinnacle of its urban development. The city evolved into a grid-like spatial structure composed of three nested rectangular enclosures: the Imperial City, the Inner City, and the Outer City. This period represents the epitome of axial symmetry and ritual-based urban planning in ancient Chinese capitals, forming the foundation of Kaifeng’s millennial urban structure. After 1126, Kaifeng came under Jin rule. Although the palace complex was rebuilt and expanded northward, the overall urban pattern of the Inner and Outer Cities from the Song period remained largely unchanged. Therefore, this stage is incorporated into the study of the Northern Song Dongjing period.

Ming Period (AD 1368–1644): Following wars and Yellow River floods during the late Yuan and early Ming dynasties, Kaifeng was reconstructed in the early Ming period. The city boundaries contracted to the Northern Song Inner City, and the Outer City was abandoned. The spatial structure gradually transformed from a grid-like pattern to a radial one. This phase effectively represents the relatively stable configuration of a traditional prefectural city after the Ming reconstruction, serving as a crucial transitional stage for analyzing the morphological evolution from the Song to the Republic era. In AD 1642, Kaifeng was destroyed when rebel forces breached the Yellow River dikes, flooding the city.

Qing Period (AD 1662–1911): The late Ming to early Qing period marked a phase of urban reconstruction. Due to the lack of reliable spatial

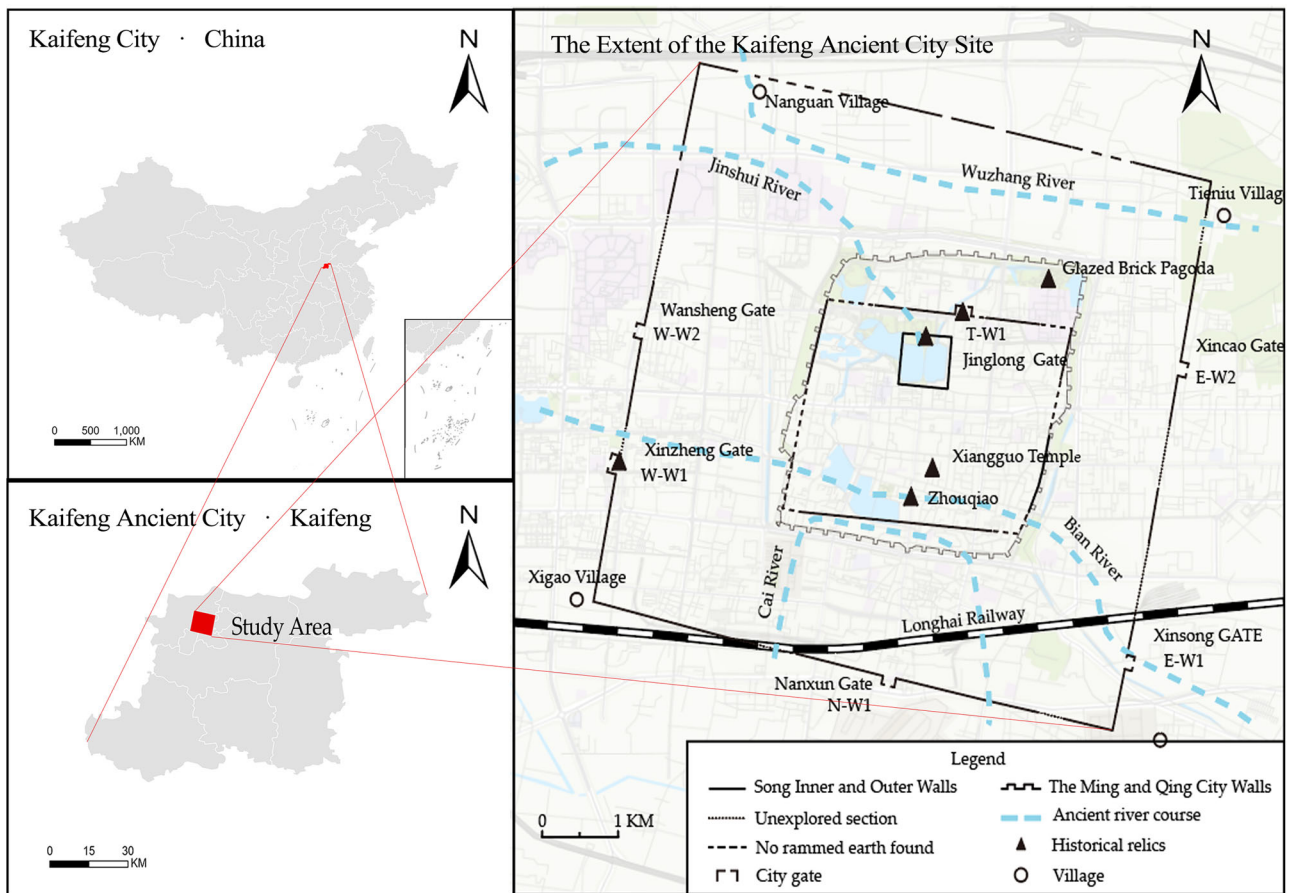


Fig. 2 | The location of the study area. (Source: Drawn by the author)

data, this study begins with the 1662 reconstruction and extends to AD 1911. The Qing dynasty rebuilt Kaifeng on the foundations of the Ming city, with recurrent Yellow River floods reshaping its spatial configuration. Through continuous repair and adaptation, the city’s form eventually stabilized. This period represents the final stage in the development of traditional Chinese urban morphology.

Republic of China Period (AD 1912–1949): The collapse of the feudal dynasties brought about profound social transformation. The introduction of modern transportation, particularly railways, spurred the city’s linear expansion, leading to features characteristic of modern urbanization. This stage marks both the end of ancient urban morphology and the beginning of the modern urban form, representing a crucial transitional phase in Kaifeng’s historical evolution.

The data for this study primarily come from four categories of sources: archaeological records, historical maps, historical documents, and previous research results. By compiling, cross-verifying, and spatially processing multi-source data, a cross-period and multi-scale HGIS database was constructed to ensure spatiotemporal comparability and geometric accuracy across different time periods (Table 2).

(1) Archaeological data provide the most reliable basis for defining the spatial boundaries and main landmarks of the ancient city. The core archaeological datasets used in this study include the Archeological Report of Northern Song Dongjing City, the Archeological Report of the Zhouqiao Site, and the List of Cultural Heritage Protection Units of Kaifeng City. These materials provide precise coordinates of city wall ruins, palace boundaries, river systems, and key landmark buildings, which serve as spatial control points for the georeferencing of historical maps. The spatial accuracy of the archaeological data reaches the meter level, forming an essential foundation for geometric correction in the HGIS database.

(2) Historical maps record the urban layouts of different periods, depicting features such as street networks, water systems, gates, markets, and defense structures. The primary maps used include Wai Cheng Zhi Tu (AD 1120) from Shilin Guangji, Postal Route Map from Nanjing to Gansu (AD 1438), Kaifeng County Map (AD 1497), and Xiangfu County Map (AD 1898). After geometric correction, georeferencing, and vectorization, these maps were used to reconstruct the city’s spatial structure at each period. The spatial accuracy after alignment is about 5–10 m, sufficient for comparative analysis across multiple time periods.

(3) Historical texts provide semantic and functional information that complement the archeological and cartographic data. Major references include Dongjing Meng Hua Lu, Ru Meng Lu, Kaifeng Gazetteer, Xiangfu Gazetteer, and Along the River During the Qingming Festival. By spatially extracting place names and directional descriptions (e.g., “Tushi Street runs north to Maxing Street” or “the livestock market lies east of Zhouqiao”), these records were used to verify and supplement the city’s functional distribution. After cross-validation with maps and archeological data, these textual descriptions were recorded as attribute information in the HGIS database.

(4) Previous studies provide essential references for urban spatial reconstruction and data validation. Key works include Studies on the Reconstruction of Northern Song Dongjing Architecture²⁸ and Reconstruction of Ming Dynasty Kaifeng Urban Layout²⁹, which offer reliable references for uncertain or missing areas based on archeological and textual evidence.

To ensure geometric consistency among datasets, this study adopts the China Geodetic Coordinate System 2000 (CGCS2000) and applies multi-source cross-validation to check data errors. All data were classified

Table 2 | Primary sources and functions of HGIS data

Data type	Representative sources	Main Purpose	Spatial precision	Source institution
Archeological data	Archeological Report of the Northern Song Eastern Capital, Zhouqiao Site Archeological Report, Kaifeng Cultural Relics Protection Unit List	Demarcating city walls, palace boundaries; locating key nodes along city waterways; positioning major urban landmarks	High (Meter-scale)	Archives Office of Kaifeng Cultural Relics Administration
Historical maps	“Shilin Guangji Map of the Outer City” (AD 1120), “Courier Route Map from Nanjing to Gansu” (AD 1438), “Xiangfu County Map” (AD 1898), “Map of Kaifeng County and Its Environs” (AD 1497)	Vectorization of streets and land plots; reconstruction of street and water system patterns; acquisition of specific building locations	Medium (10-meter scale)	Collection of reproduced materials, Library Historical Documents Center
Historical texts	“Along the River During the Qingming Festival”, “The Eastern Capital: A Dream of Splendor”, “A Record of the Dreamlike Kaifeng”, “Kaifeng Prefecture Gazetteers”, “Xiangfu County Gazetteers”, “Kaifeng County Draft History”	Reconstruction of street and water system patterns; supplementary building location data; verification of key urban nodes	Indicative	Collection of reproduced materials, Kaifeng Archives
Previous research	“Architectural Reconstruction Research of Northern Song Eastern Capital”, “A Study on the Planar Reconstruction of Ming Dynasty Kaifeng City”	Vectorization of streets and land plots; reconstruction of street and water system patterns; acquisition of specific building locations	Referential	Published books and journals

(Source: Drawn by the author).

according to accuracy and provenance, and finally integrated into a multi-layer HGIS database supporting morphological analysis and spatial statistics.

To ensure spatial comparability and geometric accuracy of data across different historical periods, this study employs a unified workflow for georeferencing and vectorization to standardize data processing. By georeferencing and vectorizing historical maps, maps, and attribute data from various periods were converted into a single digital urban map with modern geographic coordinates²³, creating a geographic information database to support urban morphological analysis.

Using ArcGIS software, fixed features such as city walls and major landmarks were employed as spatial references to accurately locate, geometrically correct, and raster-align the selected historical maps. All maps were standardized within the same geographic coordinate system and converted into analyzable spatial datasets. From the georeferenced maps, elements related to urban morphology—including city wall outlines, road networks, water systems, and plot boundaries—were vectorized and classified into corresponding attribute fields for structured storage (Fig. 3).

Quantitative analysis methods for urban morphology

The core of Conzen’s urban morphological theory lies in systematically identifying how various urban forms develop and, more importantly, how they interrelate³⁷. In the plan analysis approach, streets, plots, and building fabrics constitute the three fundamental elements. Most major historical cities in China possess continuous historical maps depicting the layout of streets and urban blocks (plots), yet they lack detailed records of the physical evolution of building structures at the plot scale. Unlike Western cities, which tend to exhibit organic growth, Chinese historical cities followed ritual-based planning principles, emphasizing functional zoning to structure urban form⁶.

Considering the early principles of Chinese urban construction and the absence of Western-style cadastral maps in historical Chinese cities, this study adapts Conzen’s concept of “building fabric” by using “building clusters” as the basic unit. The functional aggregation characteristics of buildings are employed to replace the physical building footprint, thereby aligning the analytical framework with the realities of Chinese urban studies (see Fig. 4). Utilizing the boundary shape index, space syntax, and kernel density analysis, this study examines the evolution of Kaifeng’s urban morphology from the Northern Song to the Republic of China period across three analytical levels: area (plot morphology), line (street network), and point (building clusters).

Boundary Morphological Index. To capture the macroscopic characteristics of Kaifeng’s planar morphological evolution, this study selects three indicators—aspect ratio (λ), shape index (S_1), and fractal dimension index (S_2)—which respectively correspond to urban elongation, compactness, and boundary complexity. By conducting diachronic comparisons of these indicators, the study objectively reveals the evolutionary patterns and stability variations of the city’s overall form³⁸.

Since historical cities were often enclosed by city walls to defend against invasions or equipped with levees to resist flooding, such artificial structures tend to produce regular rectangular boundaries that remain relatively stable over long periods. This physical rigidity runs counter to the purpose of analyzing the temporal evolution of urban morphology. Therefore, in calculating the plot boundary morphology index, man-made physical boundaries such as city walls and flood control embankments are excluded.

Aspect ratio (λ): In urban morphology research, compact and simple shapes such as circles or rectangles are typically used as reference forms. The aspect ratio (λ) is defined as the ratio of the long axis to the short axis of the minimum bounding rectangle of the city boundary. It reflects the degree of elongation of the boundary shape— λ increases as the city form becomes more elongated. Its formula is expressed as follows:

$$\lambda = L/W \tag{1}$$

where L represents the length of the minimum bounding rectangle of the study area, and W represents its width.

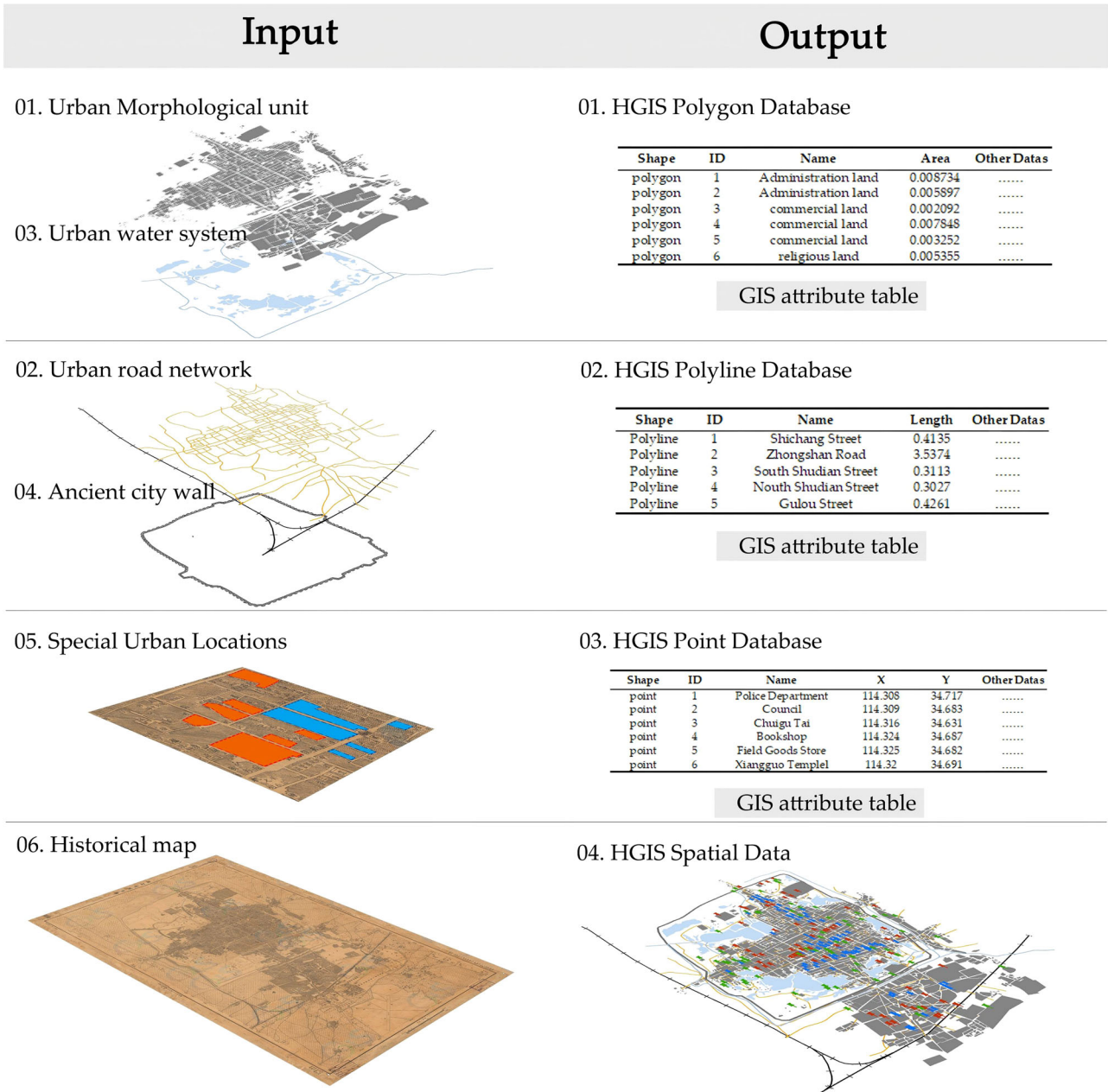


Fig. 3 | Technical workflow of the study. (Source: Drawn by the author).

Shape index (S_1): The shape index is used to quantify the stability and expansion direction of a city’s outer contour, thereby revealing the overall morphological trends of the city across different historical periods. This index is particularly useful for identifying the transitional characteristics of urban forms—from compact (clustered) to linear and finger-like structures. The formula is expressed as follows:

$$S_1 = \frac{P}{1.5\lambda - \sqrt{\lambda} + 1.5} \sqrt{\frac{\lambda}{A\pi}} \quad (2)$$

where P is the perimeter of the city’s outer boundary, A is the urban area, and λ is the aspect ratio of the urban plane. When $S_1 \geq 2$ and $\lambda < 1.5$, the form indicates a clustered-finger layout; when $1.5 \leq \lambda < 2$, it represents a neutral finger-like layout; and when $\lambda \geq 2$, it tends toward a belt-shaped finger layout. Conversely, when $S_1 < 2$ and $\lambda < 1.5$, the city exhibits a clustered form; when $1.5 \leq \lambda < 2$, it shows a clustered-belt transitional form; and when $\lambda \geq 2$, it reflects a belt-shaped form.

Fractal dimension index (S_2): The fractal dimension index measures the fragmentation degree of spatial form by describing the relationship between the perimeter and area of urban blocks. It is calculated as follows:

$$S_2 = 2\lg(0.25P)/\lg A \quad (3)$$

where P represents the perimeter of the city’s outer boundary and A denotes the urban area. The theoretical range of S_2 is 1.0–1.2. When S_2 approaches 1.0, the geometry of the urban block is relatively simple and regular; conversely, when S_2 approaches 2.0, the geometry becomes increasingly irregular and complex, indicating a higher degree of spatial fragmentation in the urban structure.

The standard deviation ellipse (SDE) is a statistical method used to analyze the directional characteristics of spatial data. By calculating the mean center and standard deviations of spatial features, the SDE quantifies the principal orientation and extent of spatial dispersion within a given dataset³⁹.

In this study, the SDE method is employed to examine the directional evolution of Kaifeng’s urban morphology across different historical periods. Using ArcGIS, the parameters of the standard deviation ellipse were calculated, with the analysis set at a one-standard-deviation level, encompassing approximately 68% of the block elements. The main calculation formulas are as follows:

$$C = \begin{pmatrix} \text{var}(x) & \text{cov}(x, y) \\ \text{cov}(y, x) & \text{var}(y) \end{pmatrix} = \frac{1}{n} \begin{pmatrix} \sum_{i=1}^n \tilde{x}_i^2 & \sum_{i=1}^n \tilde{x}_i \tilde{y}_i \\ \sum_{i=1}^n \tilde{x}_i \tilde{y}_i & \sum_{i=1}^n \tilde{y}_i^2 \end{pmatrix} \text{ where} \quad (4)$$

$$\text{var}(x) = \frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2 = \frac{1}{n} \sum_{i=1}^n \tilde{x}_i^2$$

$$\text{cov}(x, y) = \frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y}) = \frac{1}{n} \sum_{i=1}^n \tilde{x}_i \tilde{y}_i$$

$$\text{var}(y) = \frac{1}{n} \sum_{i=1}^n (y_i - \bar{y})^2 = \frac{1}{n} \sum_{i=1}^n \tilde{y}_i^2$$

where x and y represent the coordinates of element i ; $\{\bar{x}, \bar{y}\}$ denotes the mean center of all elements; and n is the total number of elements.

Space syntax analysis. At the meso-scale, this study extracts the street networks of Kaifeng City across different historical periods to capture the evolution of its urban structural system. Space syntax serves as a quantitative tool for analyzing the spatial configuration and functional layout of cities. By

calculating indicators such as integration and choice, it reveals the connectivity and centrality of urban spaces, directly reflecting the structural characteristics and planning priorities of the ancient city during various periods⁴⁰.

Based on the interpretability of historical maps, both main streets and secondary alleys were extracted, and curved segments were simplified into polylines to ensure comparability of the street networks across different periods. The Depthmap X software (v10.0) was used to conduct axial line analysis, with the integration radius set to $n/3$ to capture local-scale characteristics.

The integration index measures the ease with which a given axial line can reach all others within the system (Table 3). It indicates how well a street is connected to others and how integrated it is with its surrounding spatial context⁴¹. The choice value reflects the probability that any given street is traversed along the shortest topological paths connecting other pairs of streets within the network. The intelligibility index describes the correlation between local and global measures of spatial configuration: a higher value indicates that pedestrians can perceive the overall street structure from local visual cues, reflecting the “legibility” of the urban space.

Kernel density analysis is employed to identify the concentration and dispersion characteristics of urban functional spaces across different historical periods, thereby revealing the coupling relationship between functional evolution and urban morphological change⁴². As a spatial analytical tool, kernel density estimation visualizes the density distribution of specific urban features⁴⁵.

This technique is particularly valuable in historical urban studies, as it enables researchers to examine how the degree of functional concentration evolved over time in different historical periods. The analytical results are cross-validated with the documented locations of commercial and administrative districts from local chronicles to ensure spatial accuracy and interpretive consistency. The calculation formula is expressed as follows:

$$f(x, y) = \frac{1}{nh^2} \sum_{i=1}^n k\left(\frac{d_i}{n}\right) \quad (10)$$

In the formula, k represents the kernel function, h is the bandwidth (km), n denotes the number of plots, and d_i is the distance (km) between the estimated point and the i th observation point. According to Silverman’s empirical rule, an adaptive bandwidth is applied based on the urban scale to ensure that the resulting density surface remains smooth yet undistorted.

Results

Urban boundary morphological evolution

Changes in urban scale and orientation. This study analyzes the changes in urban scale and spatial orientation of Kaifeng across different historical periods based on its built-up area, spatial centroid locations, and standard deviation ellipse parameters. From the Northern Song to the Republic of China period (AD 1120–1947), Kaifeng’s urban scale experienced three distinct stages (Table 4): significant contraction, gradual stabilization, and

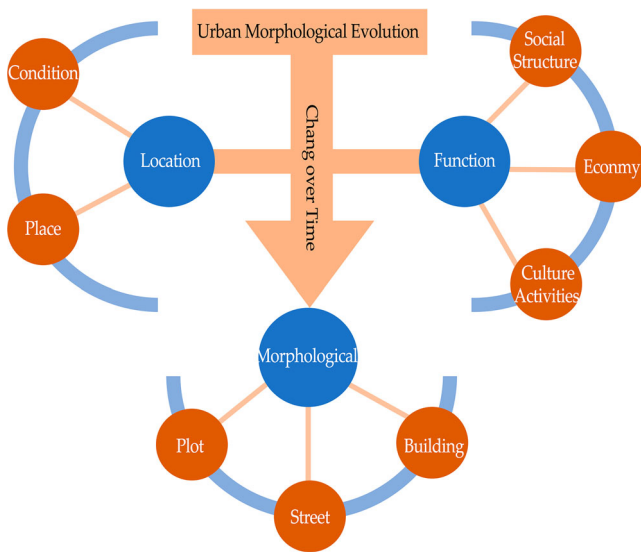


Fig. 4 | The research framework for diachronic urban morphology integrating city location and functional feature analysis. (Source: Drawn by the author).

Table 3 | Definitions and calculation formulas of the three selected space syntax metrics

Analysis indicators	Formula	Interpretation	Function
Integration	$I = \frac{2(D_M - 1)}{n} \quad (5)$ $G = \frac{I}{D_M} \quad (6)$ $D_n = \frac{n [\log_2 (1 - \frac{D_M}{n})] - 1}{(n-1)(n-2)} \quad (7)$	In the formula, I is the global integration, n is the total number of axes or nodes, G is the local integration value, D_M is the average depth value, D_n is the standardized parameter, and n is the total number of axes.	Measures the centrality of a street within the system.
Choice	$C = \frac{\log_2 \left(\frac{1}{n_0 + 10n_0} \sum_{i=1}^n \sum_{j=1}^n \sigma_{ij}^{i+1} \right)}{\log_2 \left[\sum_{j=1}^n d(x_j) + 3 \right]} \quad (8)$	In the formula, C is the choice, $i \neq x \neq j$, $d(x, i)$ is the shortest distance from x to j in the axial space, and $\sigma(i, x, j)$ is the shortest topological path from i to j in the axial space.	Reflects the frequency of a street being used as a through-movement path.
Intelligibility	Intelligibility = $R^2 \quad (9)$	In the formula, R^2 is the determination coefficient.	Represents the intelligibility of the global network from its local spatial structure.

(Source: Drawn by the author).

Table 4 | Changes in urban built-up area and perimeter across the four periods

Period	Northern song period (AD 1120–1367)	Ming period (AD 1368–1642)	Qing period (AD 1662–1911)	Republic of China period (AD 1912–1949)
Total build-up area (km ²)	57.941	10.778	9.991	18.387
Perimeter (km)	53.336	16.116	15.487	25.307

(Source: Drawn by the author).

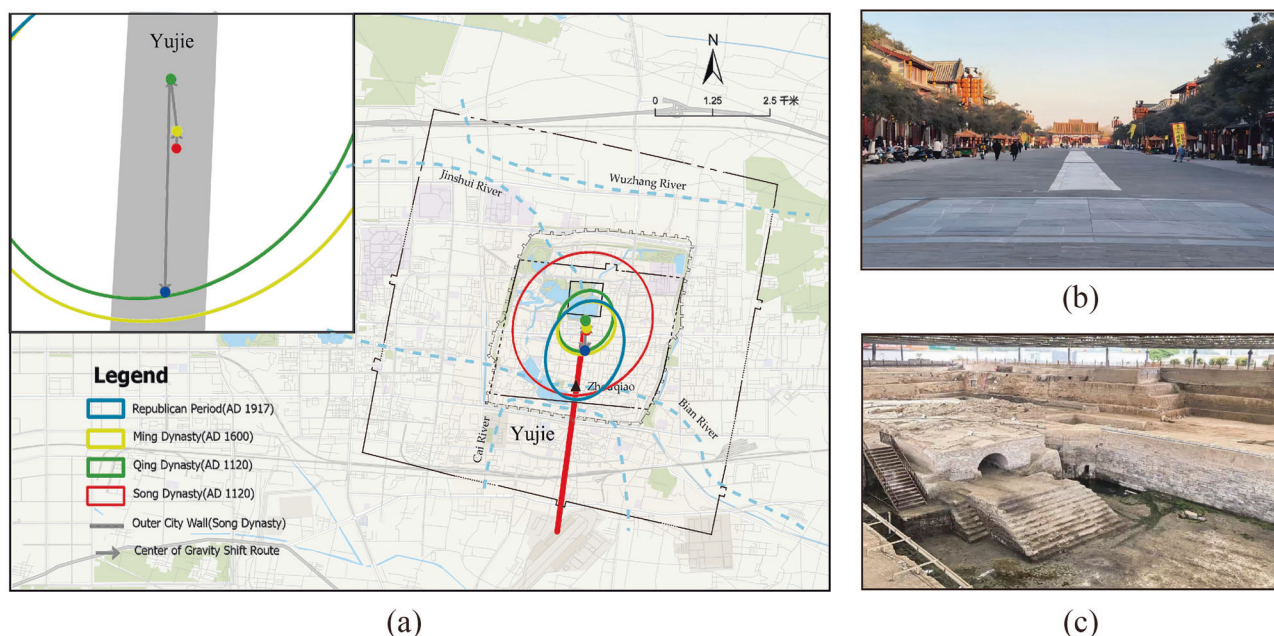


Fig. 5 | Analysis results of urban center of gravity. a Migration path of the mean center (standard deviational ellipse). **b** The existing view of Yujie. **c** Excavation Site of the Zhouqiao Archaeological Site. (Source: Drawn by the author).

Table 5 | Ellipse variance analysis results of urban form

Period	Center X/°	Center Y/°	XtdDist/KM	YStdDist/KM	Rotation/°
Northern Song period (AD 1120–1367)	114.348506	34.795352	2.95833	2.67134	49.63952
Ming period (AD 1368–1642)	114.348975	34.802192	1.21038	0.98541	65.39525
Qing period (AD 1662–1911)	114.348763	34.80433	1.25235	1.04617	35.98806
Republic of China period (AD 1912–1949)	114.348976	34.801251	1.99665	1.50933	23.04577

(Source: Drawn by the author).

rapid expansion. The built-up area decreased from 57.94 km² during the Northern Song to 10.78 km² in the Ming dynasty, a reduction of 81.4%. The rate of decline slowed from the Ming to the Qing period, marking a phase of relative stability. During the Republic of China period, the built-up area expanded to 18.39 km², recovering to 31.74% of its Northern Song extent.

Analysis of centroid migration reveals that the city’s spatial center first shifted northward, then rapidly southward, with the migration path almost coinciding with the central axis along the Northern Song Imperial Avenue (Fig. 5). During the Northern Song period (AD 1120–1367), the spatial center was located just outside the southern gate of the Imperial City (34.795°N, 114.349°E). In the Ming and Qing periods (AD 1368–1911), the centroid moved slightly northward but remained near the southern part of the former Imperial City (34.802°N, 114.349°E and 34.804°N, 114.349°E). By the Republic of China period (AD 1912–1949), the centroid shifted markedly southward, indicating the city’s gradual expansion toward the south during this time.

The standard distance (StdDist) and directional expansion parameters (Table 5) further illustrate these spatial transformations. From the Northern Song to the Ming period (AD 1120–1367), the StdDist rapidly decreased from 2.96 and 2.67 km to 1.21 and 0.99 km, suggesting that urban land parcels became more concentrated inward. The change between the Ming and Qing periods was minimal, reflecting stability. However, during the Republic of China period (AD 1912–1949), the StdDist increased again to 2.00 and 1.51 km, indicating a significant outward expansion of the spatial distribution of urban plots.

Changes in boundary morphological complexity. This study calculates the aspect ratio (λ), shape index (S_1), and fractal dimension index (S_2) of Kaifeng’s urban boundary morphology across different historical periods (Table 6). From the Northern Song to the Republic of China period (AD 1120–1947), Kaifeng’s urban boundary morphology underwent substantial transformations, showing an overall dynamic evolution from a clustered finger-like form → compact clustered form → banded clustered form.

Table 6 | Changes in urban morphological metrics across the four periods

Period	Aspect ratio (λ)	Shape index (S_1)	Fractal dimension index (S_2)	Boundary form characterization
Northern Song period (AD 1120–1367)	1.097	2.083	1.276	Clustered with a finger-like tendency
Ming period (AD 1368–1642)	1.124	1.381	1.172	Clustered form
Qing period (AD 1662–1911)	1.195	1.374	1.176	Clustered form
Republic of China period (AD 1912–1949)	3.202	1.320	1.267	Clustered with a linear tendency

(Source: Drawn by the author).

Table 7 | Changes in space syntax metrics across the four periods

Period	Number of axial lines	Mean integration	Mean choice	Intelligibility (R^2)	Core structural characteristics
Northern Song period (AD 1120–1367)	51	1.630	46.118	0.954	Formation of a “double-cross” urban skeleton
Ming period (AD 1368–1642)	119	1.726	83.950	0.921	Organic growth of roads parallel to waterways
Qing period (AD 1662–1911)	193	1.529	84.715	0.902	Formation of a polycentric urban framework
Republic of China period (AD 1912–1949)	508	1.282	78.835	0.813	Multi-centered woven corridor nodes

(Source: Drawn by the author).

During the Northern Song period (AD 1120–1367), the aspect ratio (λ) increased slightly from 1.097 (nearly square) to 1.124 (more rectangular), while the shape index (S_1) decreased from 2.083 to 1.381, indicating a significant reduction in boundary complexity. This change was primarily due to the urban built-up area retracting within the city walls during the Ming and Qing periods, which caused the boundary to evolve toward a more regular rectangular form. Consequently, the city’s spatial morphology transitioned from a clustered finger-like settlement to a compact clustered settlement.

In the Ming and Qing periods (AD 1368–1911), the boundary morphology indices remained relatively stable, reflecting a period of urban equilibrium and limited outward expansion.

During the Republic of China period (AD 1912–1949), all three indices—aspect ratio (λ), shape index (S_1), and fractal dimension (S_2)—showed notable increases: λ rose to 1.568 (significantly higher than the Northern Song value of 1.404), S_1 increased to 1.620, and S_2 reached 1.267. These increases indicate a substantial rise in boundary complexity and fragmentation. The main cause was the emergence of new urban transport nodes (e.g., the railway station), which drove the city’s expansion beyond the former walled boundary, particularly along the major gate roads. During this stage, Kaifeng’s urban form continued to flatten and elongate, evolving from a compact clustered form toward a banded clustered configuration.

Structural characteristics of the urban road network

Based on the Depthmap computational results, three key spatial syntax indicators—Integration, Choice, and Intelligibility—were extracted for four historical periods to reveal the evolutionary characteristics of Kaifeng’s urban road network structure. From the Northern Song to the Republic of China period, the city’s street system evolved from a single-axis structure into a multi-core and complex network configuration, reflecting a gradual diversification of spatial organization (Table 7).

Meanwhile, intelligibility exhibited a continuous decline, indicating that the spatial relationship between local and global accessibility weakened over time, and the overall readability of the urban network decreased as the city’s morphology became more intricate (Fig.6).

Northern Song period (AD 1120–1367): Centralized “Double-Cross” Road Framework. During the Northern Song period, Kaifeng’s road network exhibited a typical hierarchical structure of an imperial capital. Spatial syntax analysis shows that the highest integration values were concentrated along two major east–west arterial roads (Fig. 7a1–7a2) and the north–south exit roads (Fig. 7a3) as well as the Imperial Avenue (Fig. 7a4), forming a

clearly defined “double-cross” spatial skeleton. This axial system corresponds closely to the “Imperial Avenue–Bian River” transportation corridor documented in historical records, reflecting the spatial order imposed by ritual-based planning principles.

In terms of choice distribution, the Imperial Avenue and the major north–south roads (Fig. 7b1 and 7b2) had the highest global Choice values, owing to their pivotal role in linking the east–west and north–south directions. The intersection near the southern gate of the Imperial City functioned as the city’s most critical transportation hub. During this period, the Intelligibility value reached 0.95, indicating a highly legible spatial configuration. The regular grid-like street layout made it easy for pedestrians to perceive the overall urban network structure from local spatial cues.

Ming period (AD 1368–1642): Organic Growth of Roads Parallel to River Channels. During the Ming period, Kaifeng’s road network underwent a structural reorganization, exhibiting an organic growth pattern along the river channels. The Integration map (Fig. 8a) shows a notable increase in the number of high-integration axes. The east–west axis passing through the Drum Tower (a ceremonial building used for time-keeping and public events in ancient Chinese cities) (Fig. 8a1) surpassed the Imperial Avenue axis (Fig. 8a2) to become the new global core. Other highly integrated axes included the road along the north bank of the Bian River (Fig. 8a3), the north–south road connecting the North Gate (Fig. 8a4), and the road east of Kaifeng-fu (the Kaifeng Prefectural Government) (Fig. 8a5), together forming a multi-level network of urban centers.

The Choice analysis indicates that the city’s transportation hub shifted southward, with peak values concentrated along the new main axes (Fig. 8b1 and Fig. 8b2). During this period, frequent Yellow River floods created low-lying depressions in the northwestern part of the city, forming spatial voids. The course change of the Yellow River caused Kaifeng to lose most of its internal canals, with only the Bian River remaining navigable. Driven by the Bian River, multiple parallel roads developed in the southern part of the city, and the urban spatial structure gradually transformed from a grid-based orthogonal layout to a river-oriented linear pattern.

The Intelligibility of the road network decreased to 0.92, confirming the transition from a regular, planned spatial pattern to one characterized by organic growth and indicating an increase in the structural complexity of the urban spatial system.

Qing period (AD 1662–1911): Formation of a Multi-Center Urban Framework. During the Qing period, Kaifeng’s road network further evolved based on the Ming-era structure, with a multi-centered urban framework gradually taking shape. Integration analysis shows that the road

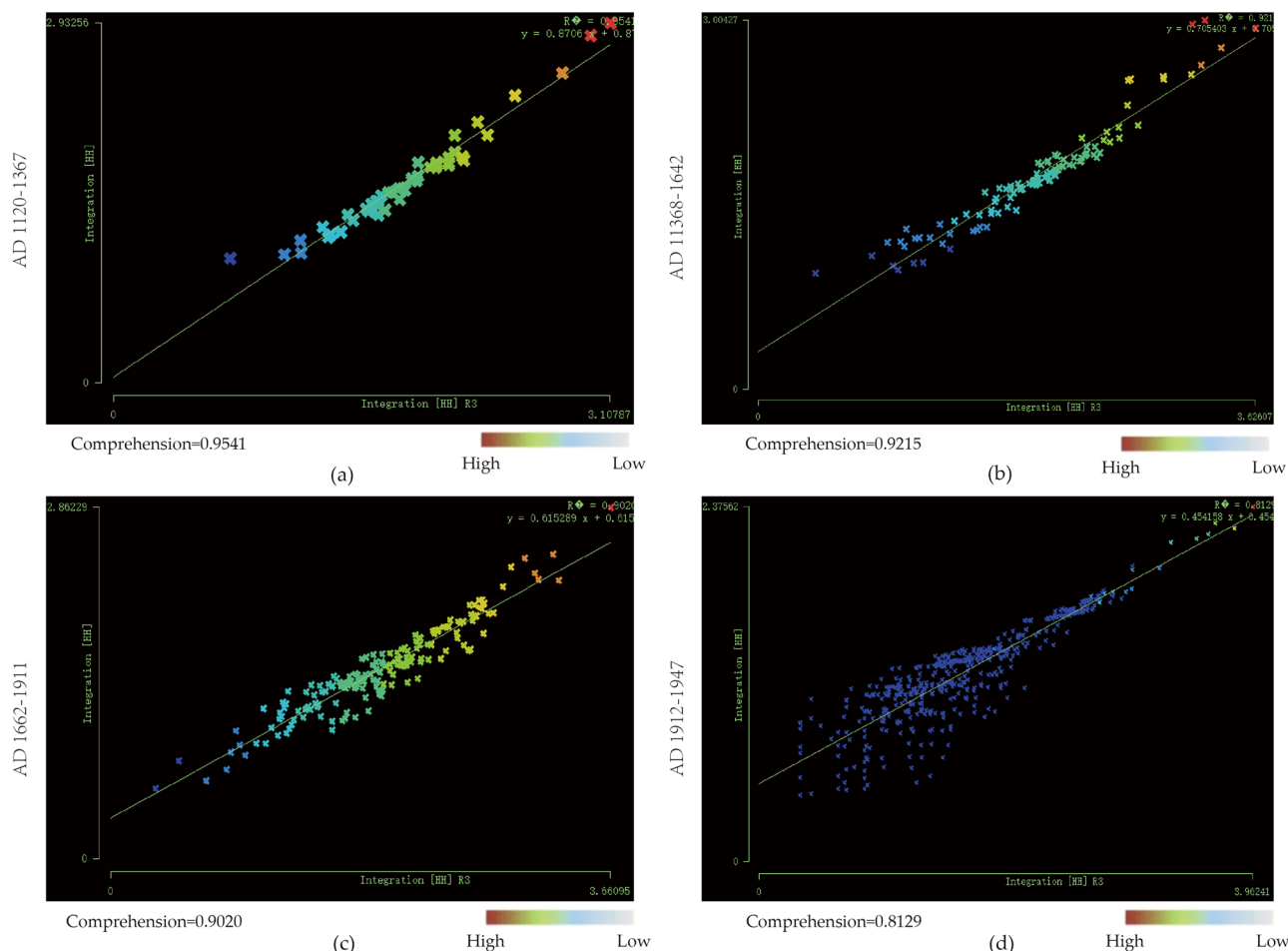


Fig. 6 | Intelligibility analysis results of the four periods. **a** AD 1120-1367. **b** AD 1368-1642. **c** AD1662-1911. **d** AD1912-1942. (Source: Drawn by the author).

connecting the North Gate (Fig. 9a1) exhibited the highest global integration value, while the Imperial Avenue (Fig. 9a2), the southeastern outbound road (Fig. 9a3), and the east–west axis through the Drum Tower (Fig. 9a4) together formed a multi-core integration structure.

During this time, repeated Yellow River floods struck the city again, creating large lakes in the northwestern and southwestern parts of Kaifeng. The east–west road connecting the city gates south of the Ming royal palace became distorted and non-linear due to flood damage. High-integration zones were mainly concentrated around the North Gate road, the Southeast Gate road, the east–west connecting road (Fig. 9a5), and the Imperial Avenue, together defining the urban core area.

The Choice distribution became more balanced, as the siltation of the ancient Bian River reduced the Choice values of its adjacent roads, while the secondary streets within the city exhibited increased betweenness. This shift indicates a transition from a backbone-dominated network to a more hierarchically balanced road system. The Intelligibility further declined to 0.90 (Fig. 6), reflecting a continued increase in spatial complexity under the emerging multi-centered urban framework.

Republic of China period (AD 1912–1949): Multi-Center Weaving of Urban Corridors. During the Republic of China period, Kaifeng’s road network exhibited a multi-centered corridor structure characterized by the interweaving of traditional and modern elements. The Integration map (Fig. 10a) reveals a hybrid spatial pattern where old and new cores coexisted. Traditional centers such as the Imperial Avenue (Fig. 10a1), the east–west connecting road between city gates (Fig. 10a2), and the axes surrounding the Drum Tower (Fig. 10a3, 10a4) maintained high integration values, while newly constructed roads near the southern railway station (Fig. 10a6) emerged as new high-integration potential zones. Meanwhile, the northern

entry road extended further beyond the city walls, linking with newly developed areas to the south.

The Choice distribution underwent a significant restructuring. Traditional main roads retained relatively stable Choice values (Fig. 10b1), whereas the roads connected to the railway station (Fig. 10b2) exhibited a sharp increase, marking the rise of a new type of transportation hub. The Intelligibility of the network declined to 0.81 (Fig. 6), indicating a low level of spatial legibility. This accurately reflects the increasing complexity caused by the overlay of traditional urban fabrics and emerging functional zones, embodying the spatial characteristics of Kaifeng’s transition from a traditional city to a modern one.

Spatiotemporal evolution of urban functional distribution

Northern Song period (AD 1120–1367): Regular Functional Zoning Pattern. The urban functional distribution during this period exhibited a regular pattern dominated by the political center. As the imperial capital, Kaifeng’s spatial organization strictly followed the traditional ritual-based planning principles of ancient Chinese cities. The administrative and military functions (Fig. 11a) formed a single high-density core within the imperial palace precinct, complemented by multiple dispersed nodes near the outer city gates. This structure reflects the influence of centralized governance and military prioritization under the Northern Song dynasty, reinforcing Kaifeng’s dual role as both an administrative hub and a strategic fortress.

The commercial functions (Fig. 11c) were distributed in distinct high-density belt-like zones along the Bian River and Cai River, with hotspots concentrated around Shuzhou Bridge and Xiangguo Temple. This pattern confirms that Northern Song Kaifeng had broken away from the “ward

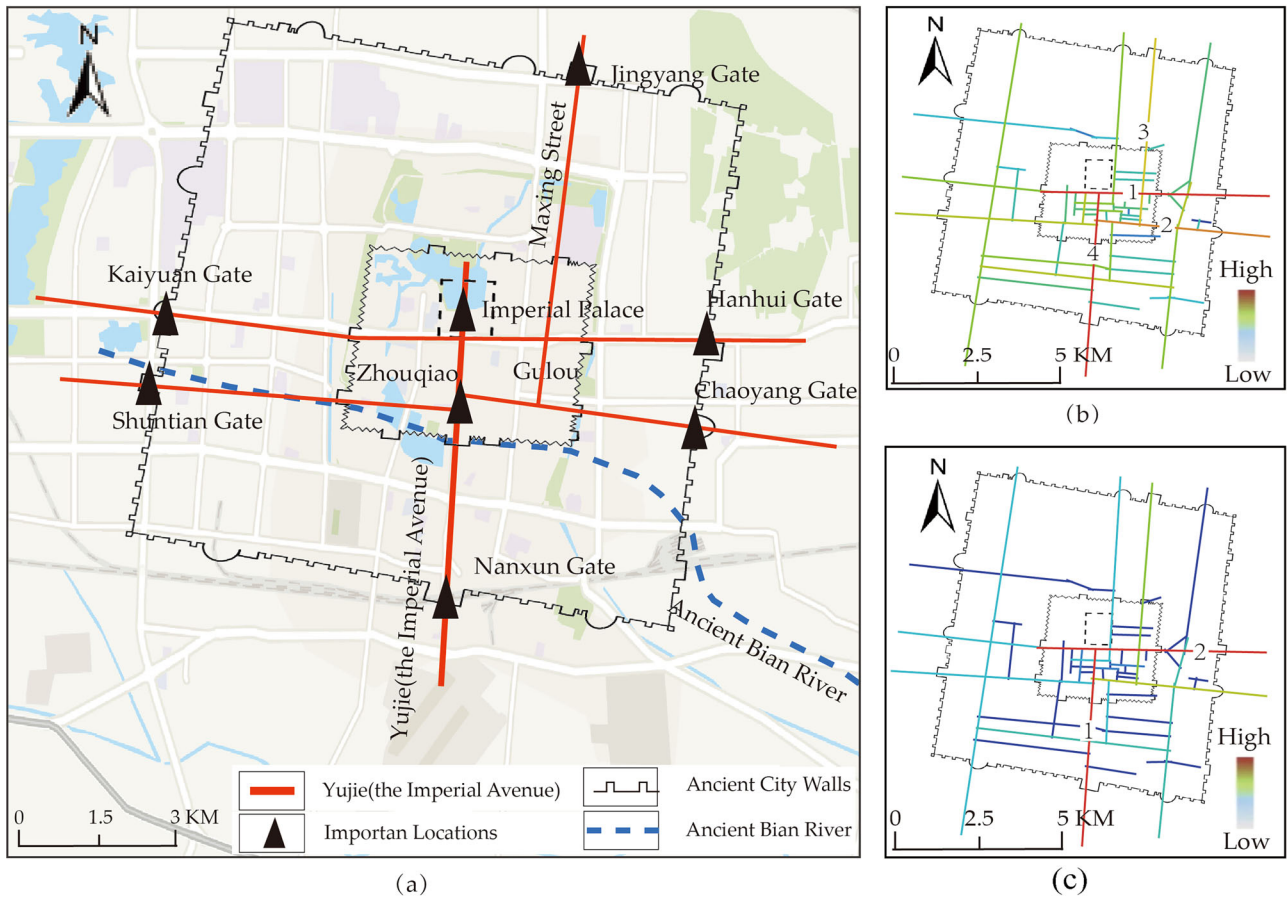


Fig. 7 | Integration and Choice Analysis Results of the Northern Song Period. a Primary Urban Axes of the Northern Song Period. b Integration analysis results. c Choice analysis results. (Source: Drawn by the author).

system”—a closed spatial management order separating residential and commercial districts—and had transitioned to an open urban layout. The expansion of the urban canal network stimulated the prosperity of the “river markets” (heshi) along both banks of the Bian River. According to historical records, this area was lined with restaurants, inns, entertainment venues (wazi, traditional performance spaces), and livestock markets, with the Shuzhou Bridge section of the Imperial Avenue developing into a major trading hub for both residents and traveling merchants, further driving commercial growth in the city.

The residential function (Fig. 11d), still constrained by the legacy of the ward system, exhibited a multi-nodal pattern within the city, with localized clustering within enclosed residential wards (li). Meanwhile, religious institutions and gardens (Fig. 11b) were widely distributed both inside and outside the city walls, often interwoven with residential areas, reflecting a spatial pattern of coexistence and permeability between sacred and secular urban spaces.

Ming period (AD 1368–1642): inward-oriented reorganization. During the Ming period, Kaifeng’s urban functional structure underwent a significant inward-oriented reorganization. As the city’s political status declined from an imperial capital to a provincial seat, and the frequent Yellow River floods led to the decline of the canal system, the city’s functional layout experienced a fundamental transformation. Kernel density analysis reveals a profound restructuring of Kaifeng’s urban functions under the dual influence of political downgrading and hydrological disturbance.

The administrative and military functions (Fig. 12a) shifted from a single high-density core during the Northern Song period to a dual-core structure centered around the Prince’s Mansion (Zhou Wangfu) and the Kaifeng Prefectural Government (Kaifeng-fu). The commercial functions (Fig. 12c) contracted sharply from the once continuous belt-shaped corridor

traversing the entire city to a compact central cluster. The Drum Tower area emerged as a new commercial hub, stimulated jointly by southern canal trade and northern urban arterial commerce.

The religious and garden functions (Fig. 12b) remained spatially extensive but exhibited a noticeable contraction inward toward the new city walls, with religious spaces that once occupied the outer city during the Northern Song period largely disappearing. The residential function (Fig. 12d) transformed from a multi-core to a single-core structure, forming continuous medium- to high-density residential belts surrounding the administrative and commercial cores (Kaifeng-fu and the Drum Tower). This pattern reflects an increasingly compact and cohesive urban structure, corresponding to the population contraction and spatial centralization of Ming Kaifeng.

Overall, the kernel density maps highlight the morphological transition of Kaifeng from an expansive imperial capital to a compact provincial city, revealing how environmental constraints and administrative restructuring jointly shaped the inward consolidation of the urban fabric during the Ming dynasty.

Qing period (AD 1662–1911): Multi-core distribution and functional contraction. The urban functional distribution further evolved into a multi-core structure on the basis of the Ming period, while showing a clear functional contraction. The kernel density map reveals further changes in Kaifeng’s urban functions. The Yellow River floods formed large lakes in the western urban area, reducing the space available for functional distribution. The administrative core shifted eastward, while a high-density administrative zone centered on the Manchu military camp emerged in the north (Fig. 13a).

With the drying up of the ancient Bian River, the city’s commercial function weakened further. The commercial core near the northern city gate

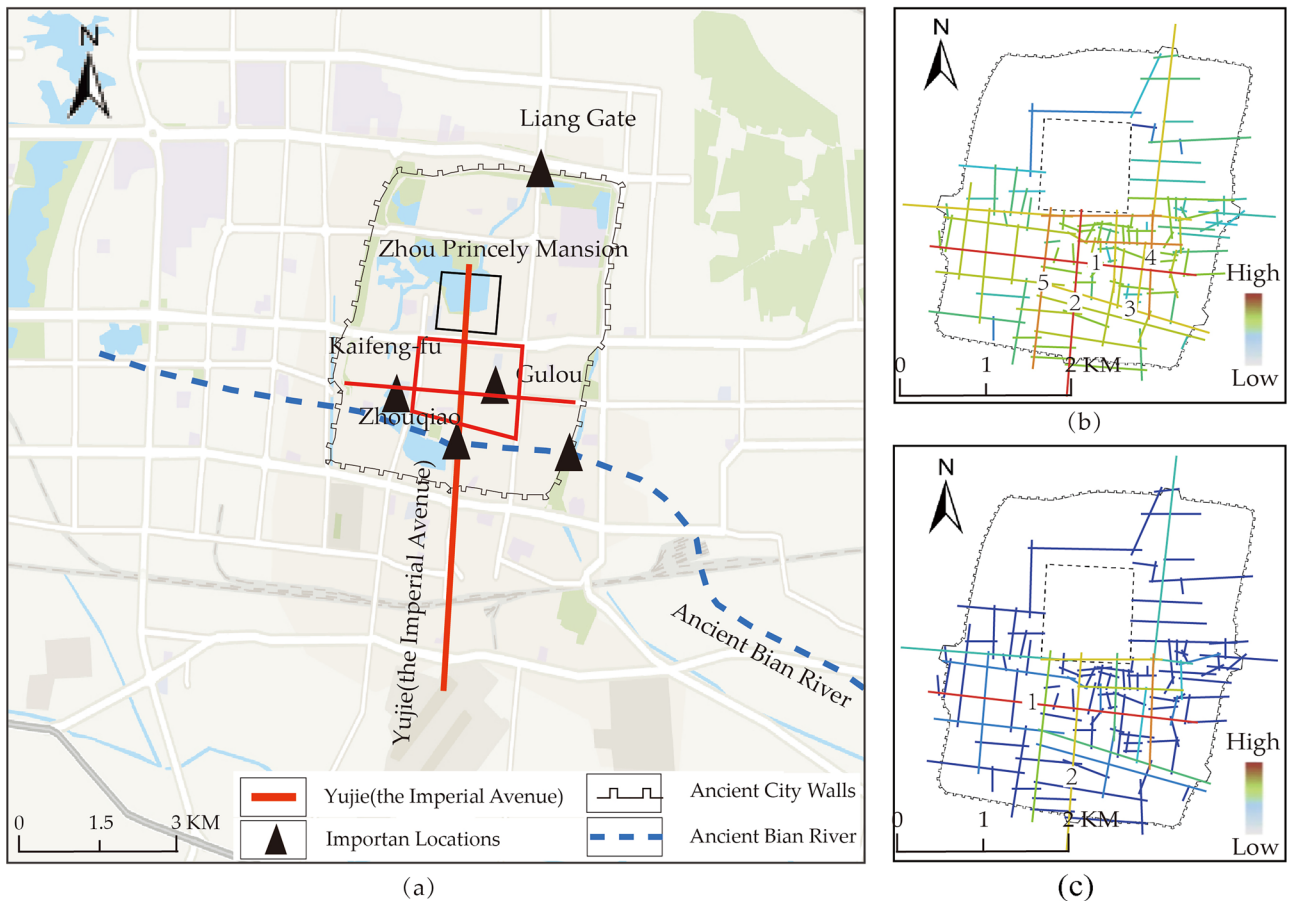


Fig. 8 | Integration and choice analysis results of the Ming period. a Primary Urban Axes of the Ming Period. **b** Integration analysis results. **c** Choice analysis results. (Source: Drawn by the author).

replaced the former river-based commercial hub (Fig. 13c), becoming the area with the highest commercial density. This spatial transformation directly reflects the historical process in which land transportation replaced waterways as the lifeline of urban commerce after the Yellow River’s sedimentation blocked the channels, marking a transition from a “canal-based system” to a “land-transportation-dominated” urban structure.

During this period, religious gardens (Fig. 13b) and residential functions (Fig. 13d) were closely connected, showing a synchronous contraction toward the city center. The high-density values were concentrated in the Drum Tower area.

Republic of China period (AD 1912–1949): Transportation-oriented functional expansion. The spatial distribution of urban functions exhibited a distinct modern transportation-oriented pattern, marking the transition from a traditional enclosed city to a modern open urban form. The kernel density maps show that the administrative functions (Fig. 14a), which had been concentrated and contiguous during the Northern Song, Ming, and Qing periods, became spatially dispersed, forming a multi-core structure with the parliament in the north, government offices in the center, and military barracks in the south.

Traditional commercial centers such as the North Gate market and Drum Tower area further expanded in scale (Fig. 14c), while new, scattered high-density commercial zones emerged around the southern railway station. Religious gardens (Fig. 14b) and residential functions (Fig. 14d) reappeared beyond the old city walls, signifying the end of Kaifeng’s nearly millennium-long phase of urban contraction and the beginning of outward expansion. The emergence of modern public facilities—such as schools, hospitals, and sports grounds—also indicated the initial modernization of the city’s functional structure.

Functional type comparison. The results of the kernel density analysis reveal that Kaifeng’s urban functional spatial distribution exhibits distinct

type differentiation and a systematic spatial migration pattern. By comparing the spatial distributions of the four core functions—administrative and military, commercial, religious and garden, and residential—the city’s evolutionary trajectory can be clearly identified: transitioning from the “single-core, multi-point” layout of the Northern Song period to the “multi-core, inwardly cohesive” structure of the Ming and Qing periods, and finally to the “multi-core, outwardly expanding” pattern of the Republic of China period (Table 8).

The administrative and military functions exhibited a high degree of centrality. During the Northern Song period, a single core centered on the imperial palace was formed; in the Ming period, this structure split into a dual-core pattern consisting of the Prince Zhou’s Mansion and the Kaifeng Prefectural Office. In the Qing period, the original administrative core was submerged by floods, causing the administrative and military functions to disperse toward surrounding areas. By the Republic of China period, the administrative and military functions had evolved once again into a three-core configuration. Overall, their spatial distribution consistently fluctuated along the north–south urban axis.

The commercial function underwent the most significant spatial restructuring, showing a clear transportation-oriented pattern. During the Northern Song period, high-density commercial areas were concentrated along the Bian River–Imperial Street cross-axis, forming a continuous linear commercial corridor. In the Ming period, the commercial core shifted northward to the Drum Tower area, marking the emergence of land-transport orientation. By the Republic of China period, the commercial function had developed a dual-core pattern encompassing the traditional Drum Tower center and the newly emerging railway station district—completing a three-stage transition from river-based commerce, to road-based commerce, and finally to railway-oriented commerce.

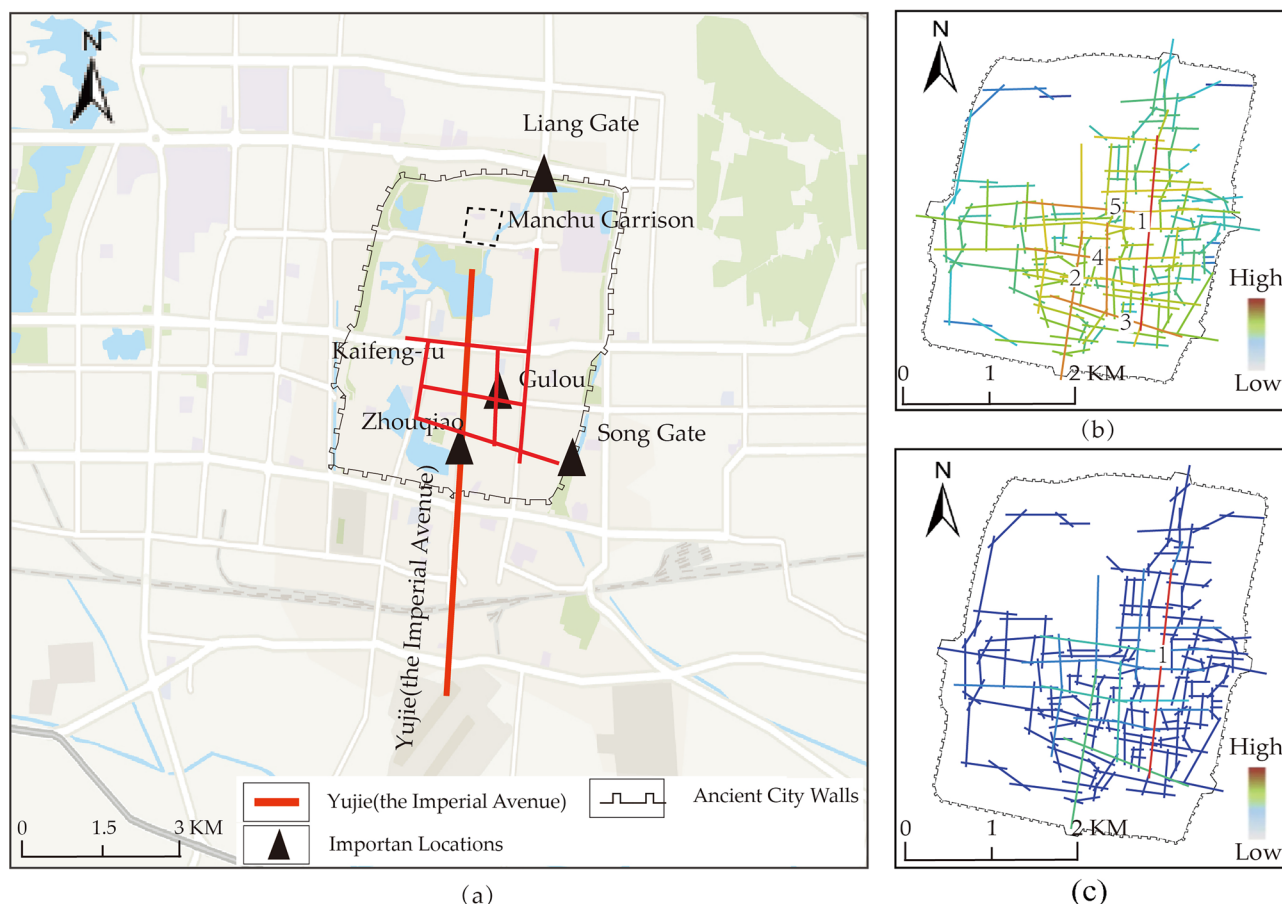


Fig. 9 | Integration and Choice Analysis Results of the Qing Period. **a** Primary Urban Axes of the Qing Period. **b** Integration analysis results. **c** Choice analysis results. (Source: Drawn by the author).

The religious gardens and residential functions displayed both environmental adaptability and social aggregation characteristics. The spatial distribution of religious gardens consistently intertwined with residential areas. After the Song period, high-density religious garden zones became increasingly concentrated around urban lakes and water bodies, reflecting the adaptive adjustment of religious functions to environmental changes. The residential function’s center of gravity closely followed the city’s overall size dynamics—shifting from the balanced, citywide distribution of the Northern Song period, to the inner-city concentration of the Ming and Qing periods, and finally to the outward expansion of the Republic of China period—directly mirroring Kaifeng’s historical transformation from a contracting to an expanding urban form.

Discussion

Grounded in Conzenian morphological theory and supplemented with HGIS methods, this study conducts both heritage documentation and analyses of urban morphological evolution. It offers a research paradigm that supports heritage conservation and urban planning by enabling a clearer understanding of the dynamic transformations of heritage sites—how they emerged, changed, and continue to evolve. Such an understanding helps identify areas of significant historical value and informs assessments of the developmental trajectories and conservation needs of historic cities⁴³.

Multi-Scale Evolution Mechanism of Urban Morphology. The mechanisms underlying the millennium-long evolution of Kaifeng’s urban form represent the material expression of its urban heritage as a living heritage, manifesting across spatial, functional, and social dimensions. Just as infrastructure shapes human behavior within urban spaces, urban functions and morphology are mutually determinative and inseparable⁴⁴. This study incorporates the urban functional structure as a key factor in identifying morphological characteristics. Through an empirical analysis of

Kaifeng’s millennium-long evolution, it reveals a systematic coupling relationship among boundary configuration, road network, and functional distribution. This multi-scalar interaction mechanism not only validates the core concept of spatial configuration in morphological theory⁴⁵ but also highlights distinct coupling characteristics within the context of Chinese historical cities (Fig. 15).

Many elements of Kaifeng’s urban plan originated directly from traditional Chinese principles of city building and gradually developed distinctive morphological characteristics over time⁴⁶. During the Northern Song period, urban plots were typically regular rectangles, continuing the *lifang* system of the Tang dynasty, in which *fang* served as the basic administrative units within the city walls⁴⁷. After the Northern Song, repeated Yellow River floods created inner-city lakes, disrupting the original *lifang* boundaries; as a result, plot fragmentation increased significantly, yielding an irregular spatial distribution and altering boundary morphology (Fig. 15a). Kaifeng also adopted a grid-based street layout in the Northern Song. The main axial street (the Imperial Avenue) aligned directly south of the central administrative institutions—the palace city and princely residences—while other axes ran perpendicular or parallel to it. With the prosperity of waterborne transport, streets grew organically along canals—corresponding to what Conzenian morphology terms “secondary streets” formed along fixed linear edges—and in later stages of urban evolution, some of these secondary routes gradually became major city axes (Fig. 15b). Throughout Kaifeng’s morphological evolution, the administrative core consistently occupied the spatial center of the city, forming a stable “morphological framework” (Fig. 15c). Commercial functions were tightly coupled with the street network, with high-density commercial zones consistently coinciding with axes of highest global integration. Religious functions intertwined with residential areas yet often formed independent “morphological units” (Fig. 15d). Within Conzen’s plan-analysis

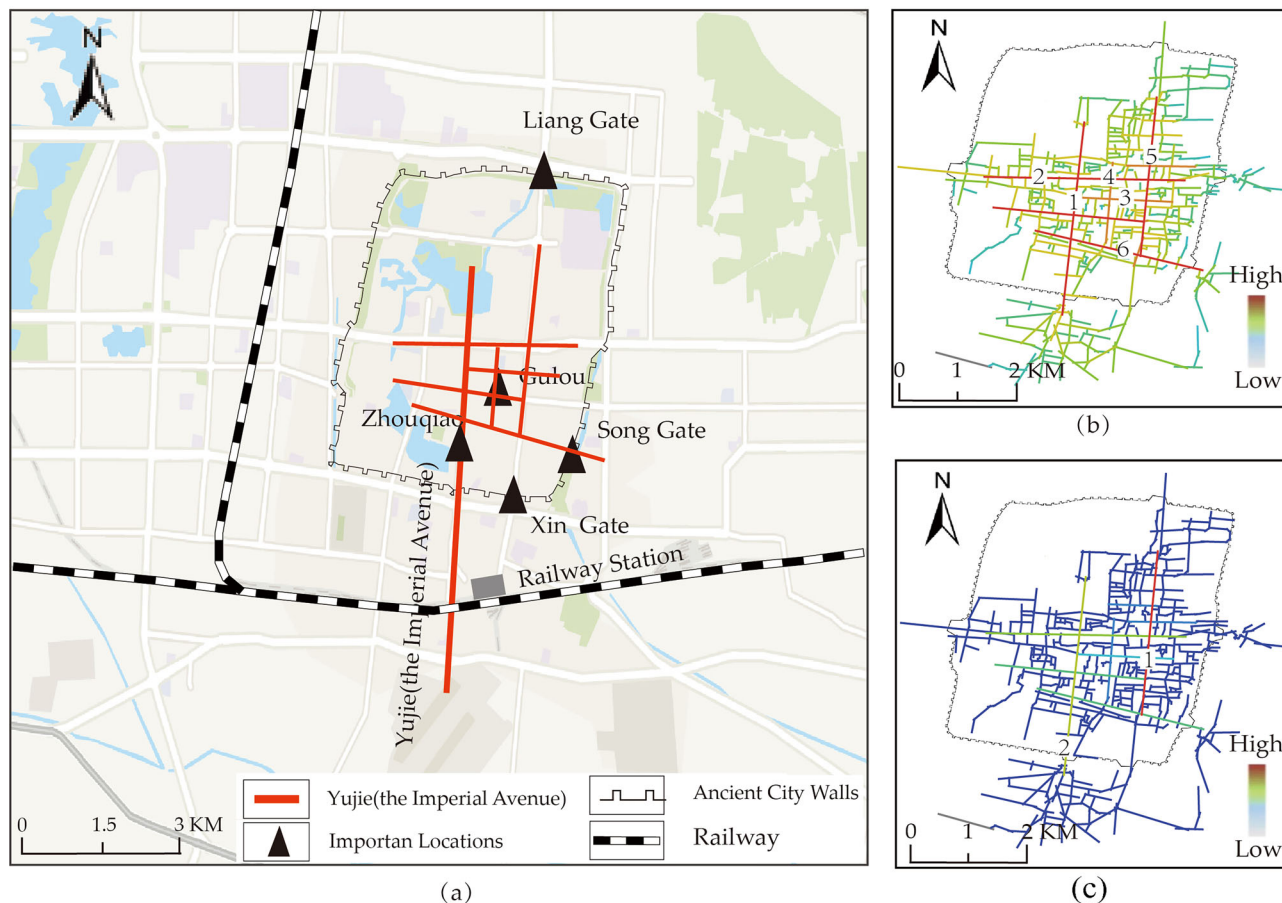


Fig. 10 | Integration and Choice Analysis Results of the Republic of China Period. **a** Primary Urban Axes of the Republic of China Period. **b** Integration analysis results. **c** Choice analysis results. (Source: Drawn by the author).

framework, religious functions served as a connective element between “building fabric” and “urban plan”: as focal points within residential districts, they acted as key nodes in the city’s spatial pattern, while their spatial organization influenced plot subdivision. This dual role generated a localized morphological logic distinct from that of Western European cities⁴⁸. Preserving these coupled relationships and spatial patterns is thus fundamental to maintaining the authenticity of the city’s historical functions and lived social memory.

Interaction Between Internal and External Driving Forces. The authenticity of heritage is equally reflected in the logical authenticity of its formation and evolutionary processes⁴⁹. The transformation of Kaifeng’s urban form is the genuine outcome of complex interactions and dynamic coupling among three major driving forces—political institutions, hydrological conditions, and economic–technological development²⁶. Through distinct mechanisms operating in different historical periods, these forces collectively shaped the structural characteristics and developmental trajectory of the city’s spatial form (Fig. 16).

As a top-down design force, the political and institutional system determined the fundamental framework of urban development during the transition from imperial capital to provincial city²⁷. In the Northern Song period, the centralized imperial system produced a highly regular urban layout organized around the imperial palace and enclosed by three concentric city walls. After the Ming dynasty, the shift to a regional administrative center caused functional contraction and led to a more inwardly cohesive urban structure centered on the Prince Zhou’s Mansion. The fluctuation of political power was directly reflected in the city’s spatial scale: from 57.94 km² during the Northern Song to 10.78 km² in the early Ming, a reduction of 81.4%, clearly

demonstrating the decisive influence of political hierarchy on urban development.

The hydrological environment, as a fundamental natural constraint, continuously influenced the city’s morphology through Yellow River floods and the evolution of canal systems⁴⁴. The Yellow River’s course change in 1232 caused the city to contract more along the east–west axis than the north–south, resulting in a distinct spatially heterogeneous shrinkage pattern. After the Ming period, siltation of the canal network directly triggered a shift in the commercial core from river-based marketplaces (“river markets”) to road-based marketplaces (“road markets”), leading to a restructuring of the city’s development axis (Fig. 17). The transformation of the hydrological system not only altered Kaifeng’s spatial form but also indirectly reshaped its functional layout by modifying transport conditions, revealing the enduring formative role of natural forces in the city’s morphological evolution⁴⁵.

Economic and technological forces acted as transformative drivers that continuously reshaped Kaifeng’s urban space through advancements in transportation technology²⁶. From the canal transport system of the Northern Song dynasty to the railway network of the Republic of China, the evolution of dominant transportation modes consistently served as the primary impetus for urban morphological change⁴⁶. Notably, the opening of the Longhai Railway not only spurred the development of a new functional district in the southern part of the city but also redefined Kaifeng’s spatial relationship with its surrounding region, shifting the city’s development pattern from inward cohesion to outward expansion. Progress in economic and technological systems, by enhancing spatial accessibility, continuously propelled the optimization and reorganization of urban functional layouts⁵⁰.

The Effectiveness of HGIS in the Conservation and Renewal of Historic Urban Heritage. This study establishes and validates an analytical

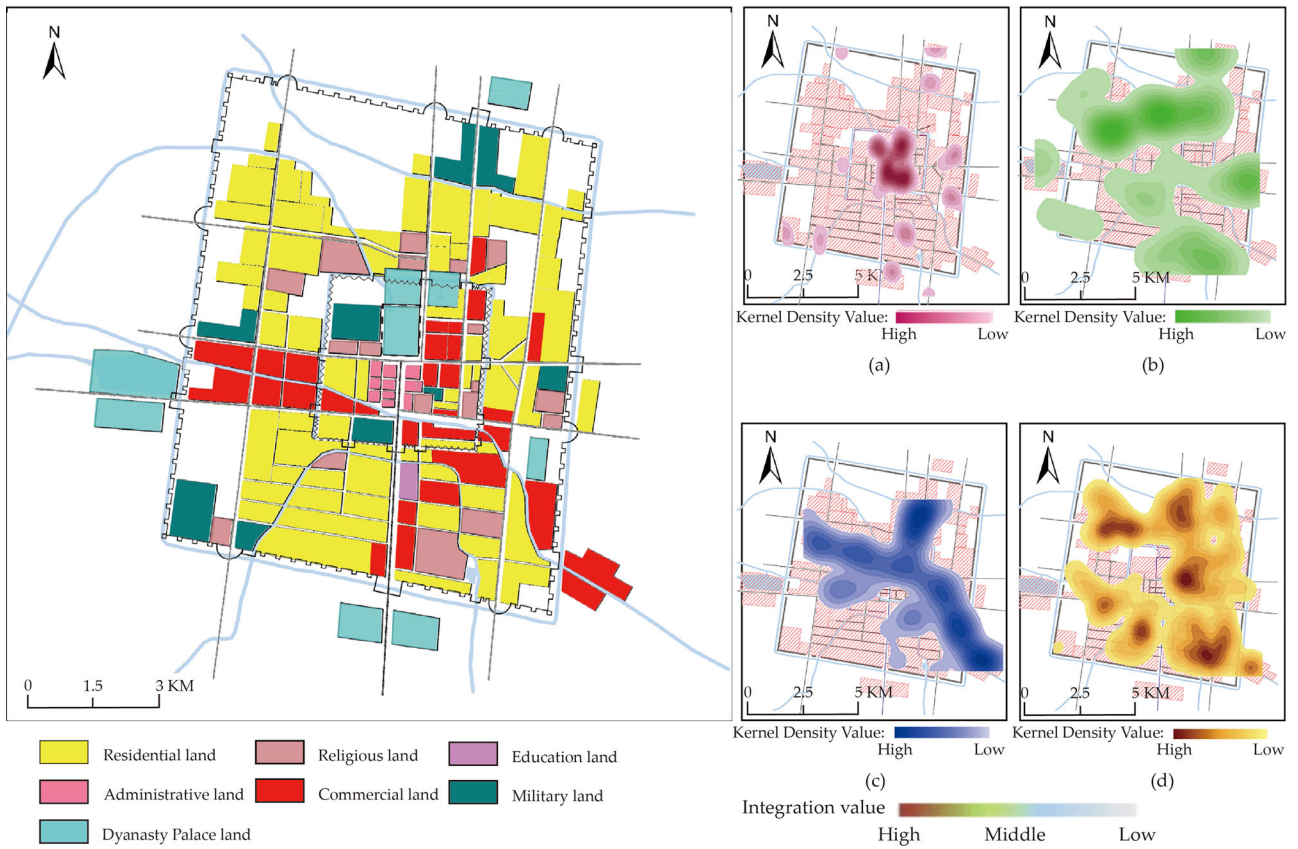


Fig. 11 | Land use types and kernel density analysis of major functions in the Northern Song period. a Land for Administrative & Military. **b** Land for Religious & Garden. **c** Land for Commercial. **d** Land for Residential. (Source: Drawn by the author).

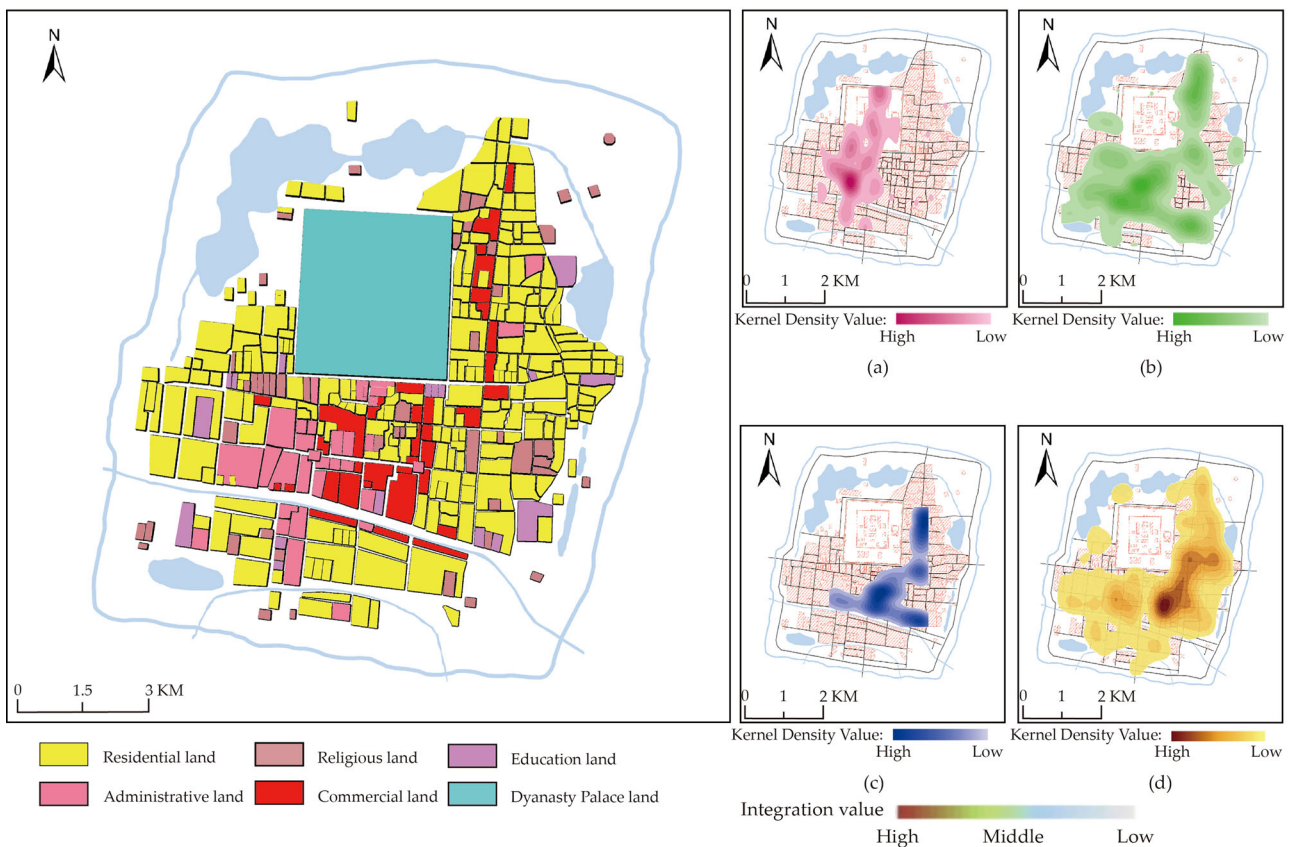


Fig. 12 | Land use types and kernel density analysis of major functions in the Ming period. a Land for Administrative & Military. **b** Land for Religious & Garden. **c** Land for Commercial. **d** Land for Residential. (Source: Drawn by the author).

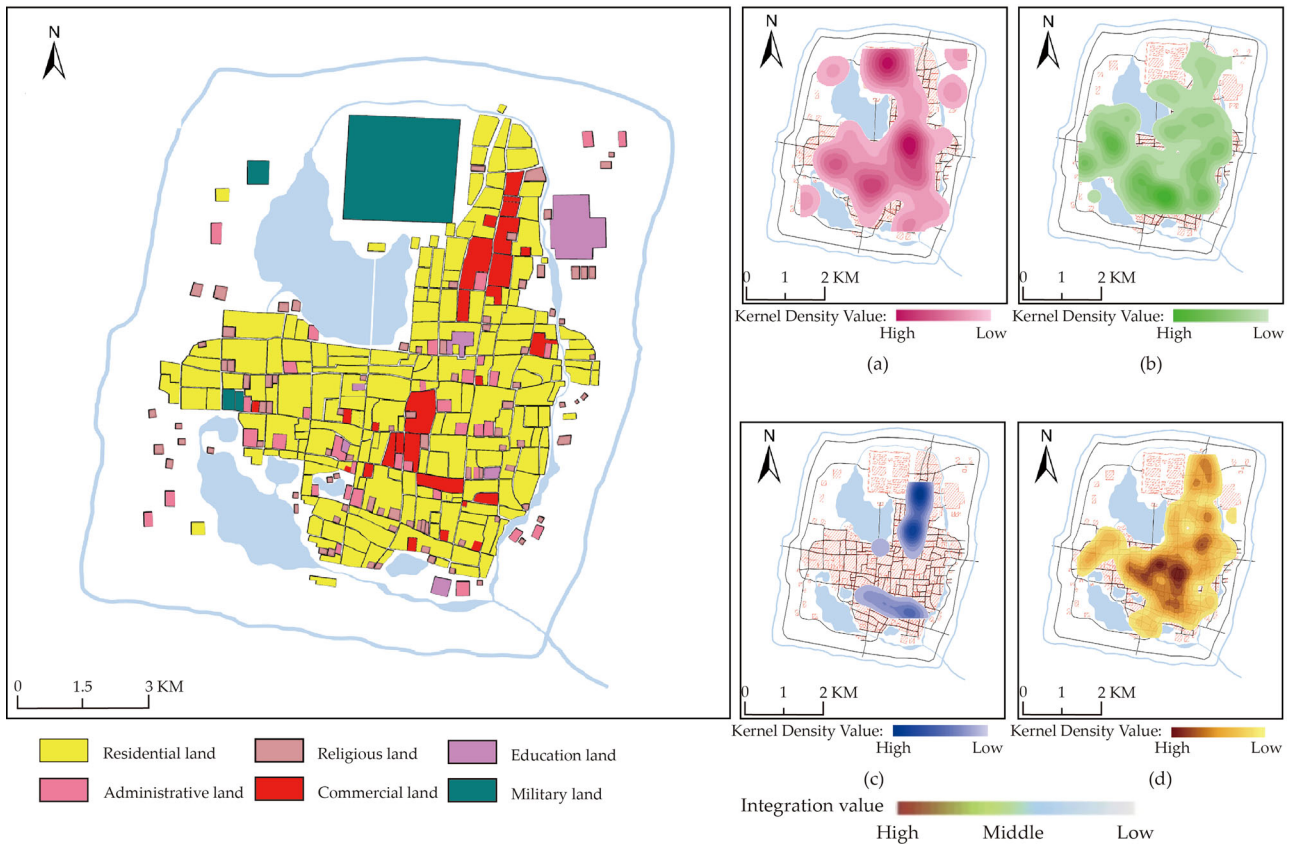


Fig. 13 | Land use types and kernel density analysis of major functions in the Qing period. a Land for Administrative & Military. **b** Land for Religious & Garden. **c** Land for Commercial. **d** Land for Residential. (Source: Drawn by the author).

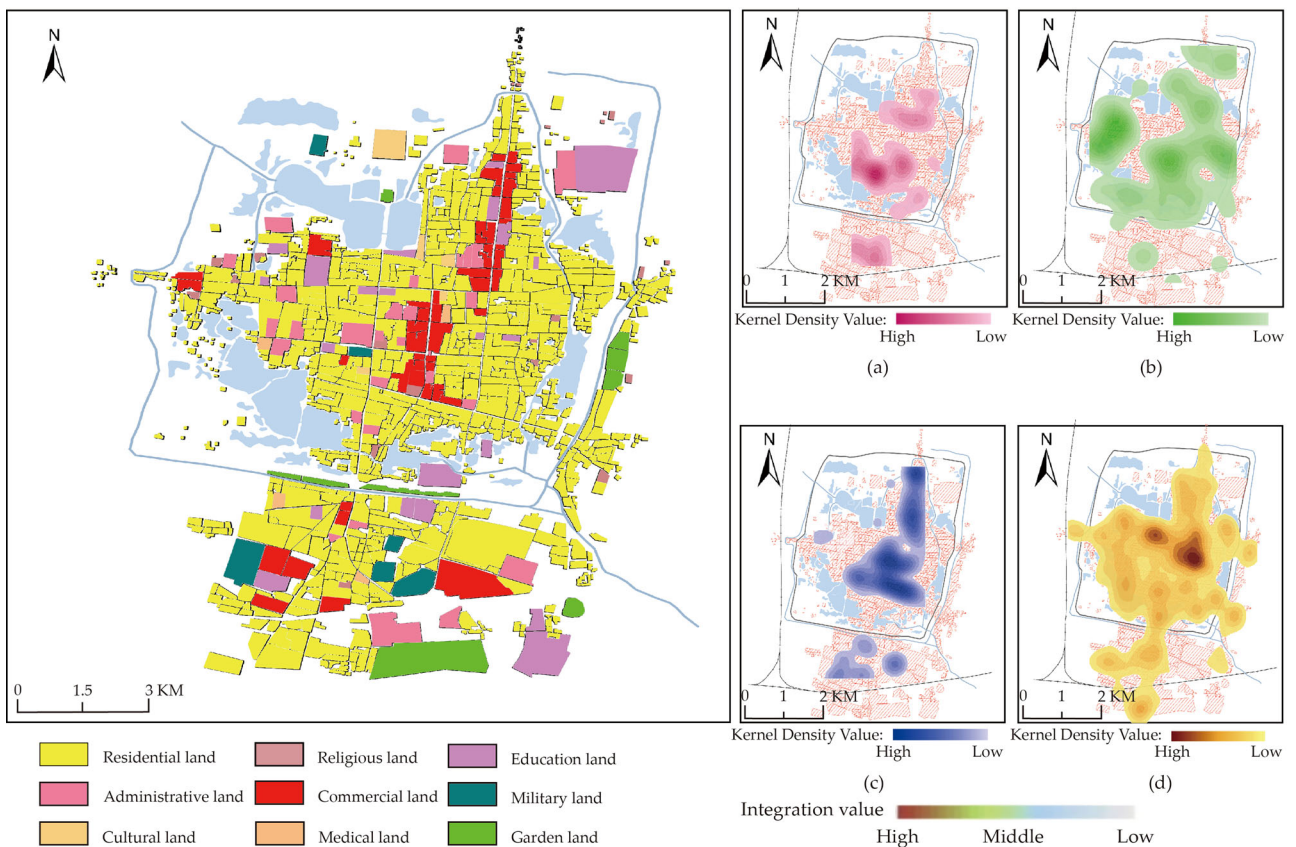


Fig. 14 | Land use types and kernel density analysis of major functions in the Republic of China period. a Land for Administrative & Military. **b** Land for Religious & Garden. **c** Land for Commercial. **d** Land for Residential. (Source: Drawn by the author).

Table 8 | Evolution characteristics of functional cores across the four periods

Period	Number of administrative/military cores	Area of high-density commercial zones (km ²)	Distribution characteristics of religious and garden land	Core structural characteristics
Northern Song period (AD 1120–1367)	1	2.637	City-wide distribution	Single core with multiple points
Ming period (AD 1368–1642)	2	0.652	Concentrated within the inner city	Dual cores, inwardly focused
Qing period (AD 1662–1911)	4	0.804	Clustered towards the center	Multiple cores, inwardly focused
Republic of China period (AD 1912–1949)	3	0.936	Expansion outside the city wall	Multiple cores, outwardly expanding

(Source: Drawn by the author).

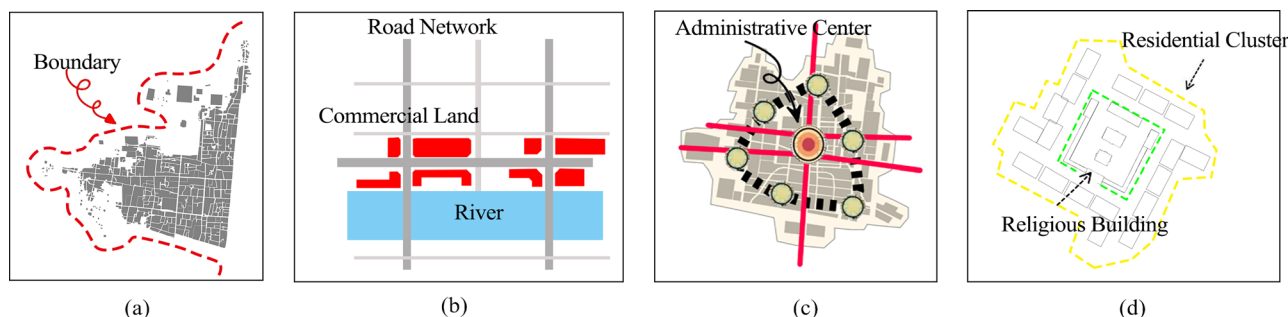


Fig. 15 | Schematic diagram of the coupling model among boundaries, roads, and functions. a The relationship of Plot & Boundary. b The relationship of Commercial Land & Road Network. c The relationship of Administrative Center & Urban Structure. d The relationship of Religious Building & Residential Cluster. (Source: Drawn by the author).

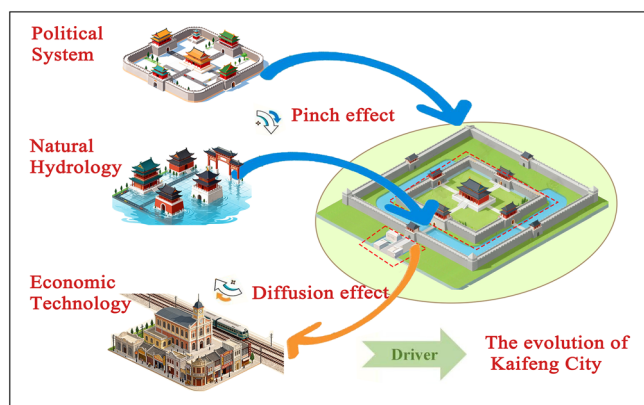


Fig. 16 | The mechanisms of political system, hydrological environment, and economic-technological factors in urban morphological evolution. (Source: Drawn by the author).

framework that integrates Conzenian morphological theory with HGIS methods, demonstrating its broad applicability for advancing research on the urban morphology of small- and medium-sized historic cities in East Asia. HGIS is particularly well-suited to the characteristics of such cities⁵¹. Although they were not capitals of successive dynasties, these cities often served as regional political and economic centers, exhibiting continuous historical development while being significantly shaped by major natural and cultural events⁵². Their research features include: relatively fragmented yet traceable historical documentation; clearly layered, cyclical, and adaptive morphological patterns across different historical periods; and evolutionary mechanisms that more directly reflect the universal interplay of political, environmental, and technological driving forces^{53–55}.

This framework thus holds strong potential for application to numerous comparable historic cities across East Asia. Cities such as Luoyang, Pingyao, and Hancheng in China, Kyoto in Japan, Gyeongju in

Korea, and Huế in Vietnam all display pronounced long-term morphological evolution and are well suited to analysis using this approach (Fig. 18).

The core basis and necessary conditions for applying HGIS to the analysis of urban morphological evolution lie in two requirements: the target city must exhibit a continuous process of morphological transformation, and sufficient multi-period foundational data must be available^{56,57}. The essential sources include: (1) historical maps and surveying records from different periods; (2) systematic archeological excavation reports and site-location data; and (3) spatial descriptions found in local gazetteers, classical texts, and other historical documents. Technically, beyond the construction and georeferencing of a basic GIS spatial database, the crucial step is the use of multi-scale quantitative spatial analysis methods⁵⁸. These methods enable the visual reconstruction and precise comparison of spatial patterns across multiple periods, thus overcoming the limitations of traditional research, which often relies on qualitative description and cannot easily support systematic, long-term comparative analysis.

Planning and Conservation Recommendations for the Heritage Areas of Kaifeng’s Historic City. Identifying the historical patterns of urban morphological evolution provides a multi-level reference framework for the conservation and renewal of urban heritage⁵⁹. The most prominent features of Kaifeng’s historic city today are its pronounced “urban stratification” and the cyclical process through which its urban form contracted, stabilized, and later expanded under the influence of political, hydrological, and economic forces⁶⁰. Consequently, the conservation of Kaifeng’s historic fabric should transcend the protection of any single historical period and instead adopt an integrated approach that recognizes and preserves the continuity of morphological change⁶¹.

At the macro level, an overarching conservation structure informed by the concept of “urban stratification” should be established. New urban development must be strictly regulated to prevent encroachment upon the Ming–Qing city-wall remains that define the city’s historical outline, thereby maintaining the integrity of its overall plan form. At the meso level, safeguarding the structural integrity of the historical transportation network is essential. The spatial scale of major high-integration axes—such as Imperial Avenue and the Drum Tower Cross Street—should be preserved, and the

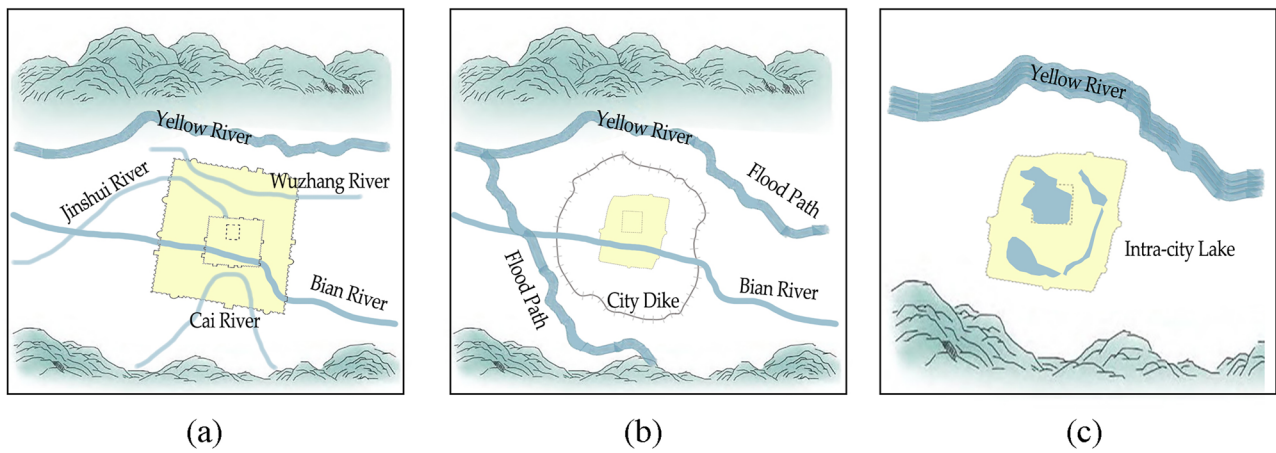


Fig. 17 | Schematic diagram of the water-city interaction relationship. a AD 1120-1367. b AD 1368-1642. c AD 1662-1949. (Source: Drawn by the author).

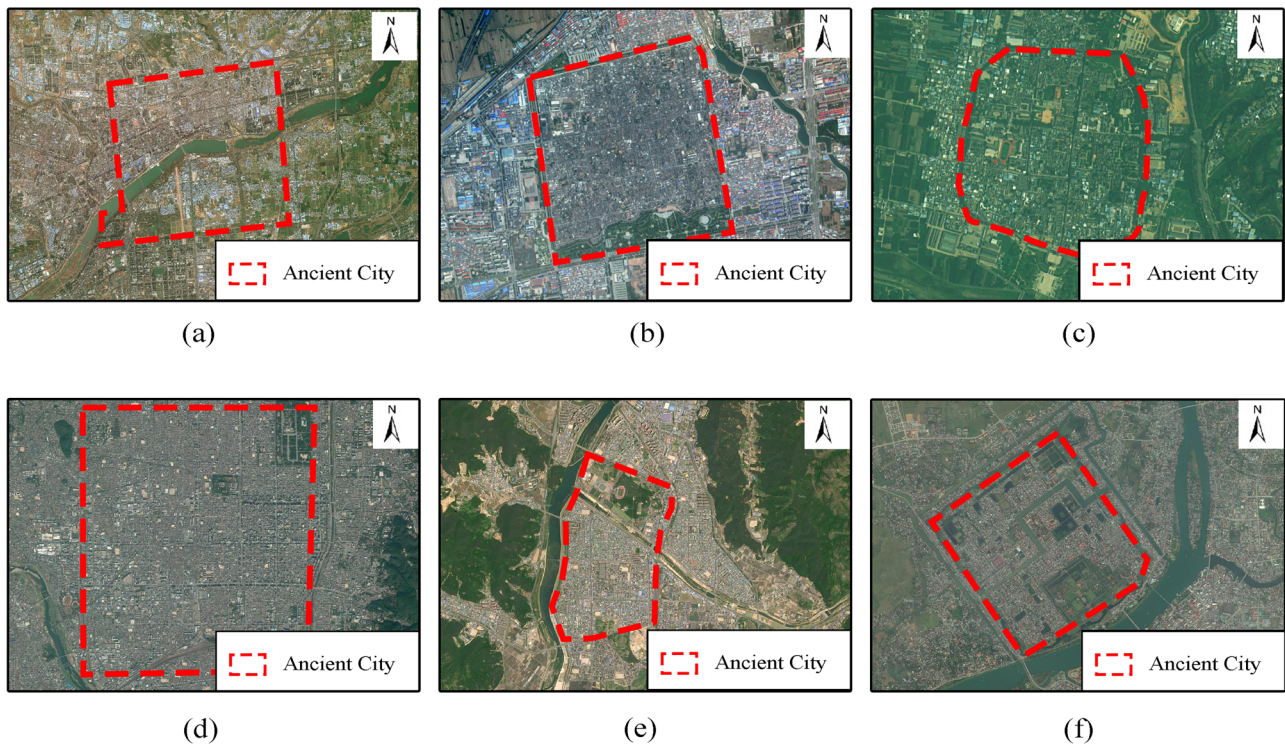


Fig. 18 | Similar-type historic cities applicable to HGIS analysis. a Luoyang. b Pingyao. c Hancheng. d Kyoto. e Gyeongju. f Hué. (Source: Drawn by the author).

remains of the Bian River canal system should be protected holistically as “historic route corridors” to sustain the city’s spatial legibility. At the micro level, targeted spatial interventions should be implemented based on functional distribution patterns, such as preserving the traditional “temple-market-residential” spatial configuration to maintain the authenticity of local social networks. Establishing this multi-tiered conservation framework marks a paradigm shift in the protection of Kaifeng’s historic city—from “static preservation” to dynamic “stratified management.” The outcomes of morphological analysis can be transformed into spatial decision-making tools for heritage conservation and urban renewal, creating a closed knowledge loop that links the understanding of urban morphological evolution with effective planning and regulatory practice.

This study proposes a framework for examining the evolution of historic urban form by integrating Conzenian urban morphology with HGIS, thereby offering a spatial perspective for analyzing the complex and dynamic

transformation of historic urban environments. Building upon Conzen’s plan-analysis approach, the framework incorporates an examination of changes in urban functional structure, further enriching the theoretical depth of Conzenian urban morphology. It also discusses the application of HGIS in studies of urban morphological evolution. By processing and visualizing morphological elements from different historical periods, HGIS enhances the scientific rigor and analytical capacity of urban morphological research.

This study focuses on the urban form of Kaifeng from the Northern Song to the Republican period, revealing the city’s spatiotemporal evolution over a millennium. The main findings are as follows: (1) Kaifeng’s urban morphology exhibits a cyclical pattern of “expansion-contraction-renewed outward growth.” As the imperial capital during the Northern Song, its grid-like layout reflected the spatial logic of traditional Chinese ritual planning. During the Ming and Qing dynasties, severe Yellow River floods and declining political status led to significant urban contraction, a shift toward

irregular rectangular forms, and increased plot fragmentation. Nevertheless, the ritual main axis (Imperial Avenue) and the commercial axis along the Bian River continued to structure urban development, forming a stable spatial framework. After the Ming dynasty, the drying of the Bian River shifted the commercial center toward the Drum Tower, the key ritual structure within the city, though the former riverine commercial axis continued to influence street patterns. In the Republican period, the rise of rail transport enabled the city to break through the constraints of the old walls and expand once again. (2) The millennium-long morphological evolution of Kaifeng can be interpreted through a coupled “institution–environment–transportation” mechanism driven by political power, natural conditions, and technological changes in mobility. Shifts in political status governed changes in city scale, hydrological dynamics reshaped boundary forms and the city’s spatial framework, and transformations in the transportation system reconfigured internal functional structures. (3) This study demonstrates the effectiveness of HGIS in the conservation and renewal of historic urban heritage. By integrating archaeological data, historical maps, and textual sources into a multi-period spatiotemporal database, it enables precise reconstruction and dynamic simulation of the ancient city’s form. The quantitative analytical methods employed here allow detailed examination of the mechanisms driving morphological evolution, identification of core spatial relationships and diachronic characteristics of urban heritage, and provide methodological and theoretical guidance for future heritage conservation and renewal in similar contexts.

However, this study also has shortcomings: (1) variations in scale and accuracy among historical maps have caused the accumulation of registration errors across temporal datasets, hindering perfect spatial alignment between plots and street boundaries. Future research could utilize high-resolution remote sensing archaeology and digital stratigraphic reconstruction techniques to enhance the geometric precision and temporal continuity of historical data⁶¹. (2) This study primarily focuses on the evolution of physical urban morphology, with insufficient consideration of the spatial effects of socio-economic variables such as population, taxation, and industry. Future research could integrate historical archives and statistical data to develop socio-spatial coupling models, thereby enhancing the understanding of the driving forces behind morphological transformation⁵². (3) The intelligibility index used in the space syntax analysis is based on assumptions derived from modern spatial cognition, which may differ from the perceptual patterns of pre-modern societies. Future research could employ agent-based modeling (ABM) to simulate historical spatial behavior, thereby verifying and refining the cognitive characteristics of spatial perception in ancient cities⁶². Future research is likely to explore this further.

Data availability

Y.Z. organized and participated deeply in the investigation of this study and has all the original data. If you are interested, please contact Y.Z.(zhuyiming@stumail.nwu.edu.cn) for further information.

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Conceptualization, Y.Z. and Y.H.; methodology, Y.Z. and Y.H.; software, Y.Z.; validation, Y.Z. and Y.H.; formal analysis, Y.Z.; investigation, Y.Z.; resources, Y.Z.; data curation, Y.Z.; writing—original draft preparation, Y.Z.; writing—review and editing, Y.Z.; visualization, Y.Z.; supervision, Y.H.; project administration, Y.Z. and Y.H.; funding acquisition, Y.Z. and Y.H. 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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