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Coupling and Coordination Relationship between Traditional Mosques and Urbanization: A Case Study of the Grand Canal in Shandong Province, China

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Abstract: The impact of urbanization is multifaceted, especially in China, the coordinated development between cities and traditional architecture is paramount. Therefore, to further promote the coordinated development between cities and traditional architecture, this study selects Traditional Mosques (TMs) along the Shandong section of the Grand Canal and their urban contexts as research subjects. By capturing Point of Information (POI) data from mosques along this section, the study observes the coupling relationship between traditional buildings and urban development within this area. The research reveals that TMs along the canal predominantly exhibit two distribution patterns: random and clustered. These patterns correspond to two types of relationships with urban development: alignment with the direction of the city and concentric inclusion. Within the random distribution pattern of TMs, a clustering phenomenon emerges, indicating a strengthening of the coupling and coordination between mosques and urban areas. Additionally, with the highest core densities of mosques at 212.2 and 106.1, it is evident that highly dense areas contribute to the agglomeration of the city's economy and population, whereas less dense and isolated clusters have a lesser effect on the urban economy and population cohesion. Furthermore, the study finds that the central distribution of TMs is primarily driven by Hui migration and Muslim commercial settlement. Combined with the coupling and coordination values (*C* and *D*), it is observed that the distribution of mosques increasingly aligns and coordinates with urban development.

Keywords: the grand canal; traditional mosques (TMs); urbanization; coupling pattern; GIS

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1. Introduction

Since its inception, the Grand Canal has witnessed gradual commercial and trade development along its route, driven by advancements in transportation and rapid urbanization, with the Shandong section being one of the most prosperous multi-ethnic gathering areas along the canal [1]. Accompanied by the influx of people, urban construction and development has also accelerated, leading to a surge in architectural endeavors. This study uses the Beijing-Hangzhou Grand Canal as a starting point, focusing on traditional mosque architecture and cities along the Shandong section of the canal. Most of these mosques were built during the flourishing Ming and Qing dynasties; they widely distributed across commercially thriving cities such as Dezhou, Liaocheng, Linqing, and Jining, as well as the surrounding rural areas. These mosques developed in synchrony with the urban growth during the periods of active north–south traffic on the Grand Canal. Over time, with the development of the canal, economic growth, and urban expansion, mosques have increasingly integrated with urban development [2,3]. Today, the coupling and coordination relationship between traditional architecture and urban development is gaining increasing attention. Thus, this study focuses on the distribution characteristics of TMs along the Shandong section of the canal to clarify the coupling and coordination aqrelationship between TMs and urban development and to analyze whether, in addition to factors such as river traffic, the commercial economy, and the natural environment, traditional architectural layouts also influence urban construction processes.

Current scholars have studied the spatio-temporal distribution characteristics of mosques, yet there are still deficiencies: (1) Study area: Current studies mainly focus on the spatio-temporal evolution of individual mosques or regional mosques, such as the Guangzhou Huai Sheng Mosque [4], the development of the Lanzhou Xiguan Mosque [5], the spatio-temporal evolution of mosques in Qinghai [6,7], and studies on traditional architecture along the Grand Canal [8]. However, there is less focus on the distribution characteristics of TMs within the canal sections in cities. (2) Research content: Most scholars currently focus on the traditional architecture of the Shandong section of the Grand Canal [9], cultural spaces and places [10], the fluidity of architectural cultural heritage landscapes [11], urban spatial forms along the canal [12], and studies on the protection of linear cultural heritage [13]. It is evident that much of the research is centered on architectural culture, urban spatial forms, and heritage protection of the Grand Canal's Shandong section, with less study of the coupling and coordination relationship between TMs and urban development along the route. (3) Research methods: Previous scholars have predominantly used the nearest neighbor index, kernel density, and standard deviation ellipse to assess the distribution characteristics of mosques in cities [6,7,14]; utilized GIS to evaluate the sustainable spatial functions of mosques [15]; applied GIS and spatial statistical methods to explain the historical urban development relationships based on the locations of mosques [16]; and incorporated mosques into urban planning through historical overviews [17]. Yet, there is less involvement in studying the coupling and coordination relationship between traditional architecture distribution and urban development.

It is noteworthy that the diffusion of mosques is not only a natural phenomenon accompanying urban expansion; it is also influenced by later urban development efforts. This study discusses the relationship between religious architecture and urbanization, which can be analyzed from three perspectives: historical geography, sociology, and urban planning. From a historical geographical perspective, by investigating the establishment times and locations of mosques over the years, one can examine the relationship between TMs and urban expansion. From a sociological lens, the study primarily considers the relationship between the public spaces of TMs and urban communities and how these influence local urban culture and community identity. Mosques serve not only as places for religious activities but also as centers for social and cultural activities within the city. From the standpoint of urban planning, which is a focal point of this study, the positioning of mosques can significantly impact urban road and housing plans, indirectly guiding the development of the city in specific directions. Thus, to examine these issues, this study conducts field surveys along the Shandong section of the Grand Canal, using the canal as a reference point, TMs as an entry point, and the city as a base to provide empirical research cases for coordinated modern urban development, urban spatial coupling, and urban development and construction. The findings can offer theoretical insights and practical references for other traditional buildings and urban coupling and coordination relationships in similar regions, thus enriching and enhancing the study of urban development along the Grand Canal in Shandong Province, China.

2. Materials and Methods

2.1. Study Area

The Shandong section of the Grand Canal is located in the middle section of the Beijing-Hangzhou Grand Canal, connecting to Beijing-Tianjin-Hebei in the north and Jiangsu-Zhejiang in the south, passing through 16 counties and districts across five cities in Shandong Province: Dezhou, Liaocheng, Tai'an, Jining, and Zaozhuang (Figure 1 and Table 1). This study primarily focuses on four cities: Dezhou, Liaocheng, Jining, and Zaozhuang. These cities are rich in historical and cultural elements and have a profound canal culture background, having undergone significant historical changes and urban development. To better document and illustrate the historical evolution of TMs within these cities, research into ancient texts revealed that during the Ming Dynasty's Wanli era and the Qing Dynasty's Guanxu period, there were approximately 105 mosque communities. By 1990, there was a total of 367 mosque communities in Shandong Province, with 81 located in the cities of Dezhou, Liaocheng, Jining, and Zaozhuang [18] (Table 2).

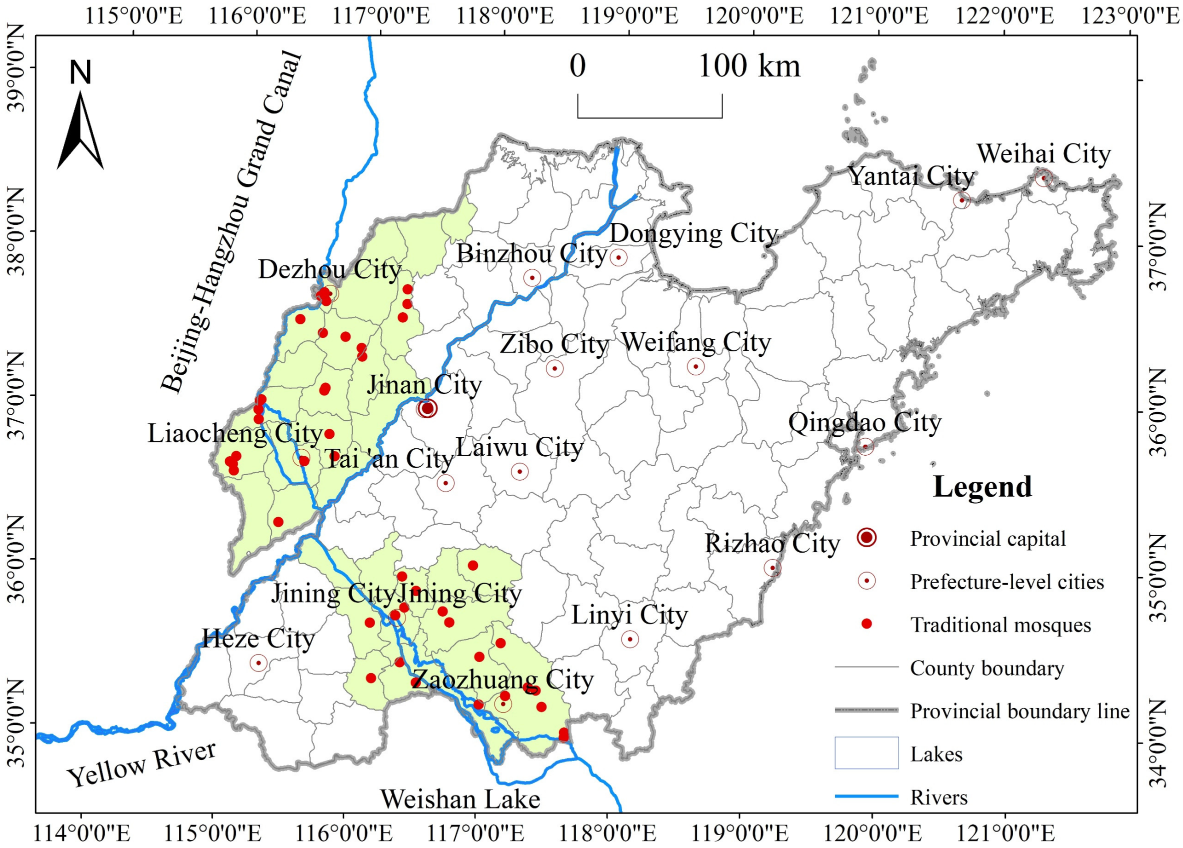


Figure 1. Study area. Note: The map is based on the base map of the standard map of Lu SG (2021) 025 downloaded from the standard map service website of the Ministry of Natural Resources; the base map is not modified.

Table 1. Geographical coordinates of four cities.

Cities	Latitude (φ)	Longitude (λ)
Dezhou	116.36°	37.44°
Liaocheng	115.99°	36.46°
Jining	116.59°	35.42°
Zaozhuang	117.32°	34.81°

Most of the TMs along the Shandong section of the canal were built in both the Ming and Qing dynasties. During the Ming and Qing dynasties, when the Grand Canal was unblocked, the cities along the line were more prosperous, attracting a large number of Muslim businessmen to settle in the area [19]. Most constructions of the mosques adopt the traditional Chinese architectural styles in the Ming and Qing dynasties, influenced by cross-cultural exchange and multicultural dissemination [20]. The mosques along the canal in the Shandong section have gradually evolved into Chinese architectural styles by adopting traditional Chinese construction techniques. The Islamic architecture of a courtyard-style has gradually become a model of urban multicultural integration [21]. The mosque architecture along the canal has an impact on the synchronizing development of urban modernization to a certain extent, with consideration of the urban landscape and texture [22]. It is also a platform for exploration of the coupling and coordination relationship of TMs and urban development in the early stages.

In addition, the construction of TMs along the Shandong section of the canal during both the Ming and Qing dynasties was inseparable from the economic benefits, cultural dissemination, and commercial exchanges brought by the canal at that time. The dredging of the canal and the construction of mosques are basically synchronized with the rapid development of cities along the line [23]. Therefore, the development and construction of cities along the Grand Canal are closely related to the canal culture and traditional architectural layout. This development involves complex relationships among the Grand Canal, mosques, and cities, and the coupling and coordination relationship between mosques and their located cities has become part of the linear or serial cultural heritage along the canal. Such close connections show not only the diversity and inclusiveness in the process of urban development but also the correlation between the changes to the canal and cultural integration [24]. On this flowing cultural line, the relationships between traditional architecture and cities gradually became closer over time.

Table 2. Statistics on the number of TMs along the canal in Shandong [25–48].

Cities along the Line	Ming Wanli Years Mosque Number	Qing Guangxu Years Mosque Number	1990 Mosque Number	2023 Mosque Number
Dezhou	15	12	16	20
Liaocheng	17	29	32	24
Jining	10	14	24	17
Zaozhuang	3	5	9	11
Total	45	60	81	72

2.2. Data Sources

This study uses the historical timelines of the Ming Wanli and Qing Guangxu periods and the year 1990 as benchmarks and mosque point data (with a cutoff of June 2023 for POI data) as the primary data source, to explore the coupling relationship between TMs along the Shandong section of the Grand Canal and urban development. The data required for this study mainly include historical statistics of TMs along the canal at various stages, 2023 mosque POI data, and geographic data of cities along the canal. As of June 2023, using Amap (Gaode Map) to search and collect data, a total of 72 traditional mosque POIs were found in four cities. Dezhou has 20 mosques along the canal; Liaocheng has a wide coverage with 24 mosques, including the Dongchangfu District, Linqing City, Gaotang County, and the Zhangqiu Town of Yanggu County; Jining has 17 mosques along the canal; and Zaozhuang has 11 mosques. By referencing the existing literature and conducting field visits to TMs along the canal, detailed information about the location, construction era, jurisdiction, and architectural styles of the mosques was obtained. Urban remote sensing images were acquired from China Geo-Spatial Data Cloud (https://www.gscloud.cn, accessed on 9 June 2023), and city latitude and longitude coordinates were acquired from the National Geographical Information Public Service Platform (https://www.tianditu.gov.cn, accessed on 9 June 2023). Using the Amap API, 2023 mosque point data along the Shandong section of the canal was collected, and GIS was employed to create basemaps using the standard maps downloaded from the National Geographic Information Public Service Platform. The spatial vector map of Shandong Province was created using the basemap downloaded from the Ministry of Natural Resources' standard map service website, with no modifications to the basemap. Shandong's 30 m resolution DEM elevation data was sourced from China Geo-Spatial Data Cloud. Data on urban population size, socioeconomic development levels, the number of mosques during the Ming Wanli and Qing Guangxu periods and in 1990, as well as other related data on urban development, were sourced from the Shandong Provincial Department of Natural Resources, Shandong Provincial

Bureau of Statistics, provincial and local gazetteers, Baidu, and other websites and online shared service platforms. Specific spatial data sources are shown in Table 3.

Table 3. Spatial data classification and source.

Data Classification	Data Sources
Mosque point data	https://ditu.gaode.com, accessed on 1 June 2023
DEM digital elevation data	https://www.gscloud.cn, accessed on 9 June 2023
City latitude and longitude coordinates	https://www.tianditu.gov.cn, accessed on 9 June 2023
Spatial vector map of Shandong Province	http://bzdt.ch.mnr.gov.cn/index.html, accessed on 11 June 2023
Shandong's 30 m resolution DEM elevation data	https://www.gscloud.cn, accessed on 11 June 2023
Urban population scale	http://dnr.shandong.gov.cn, accessed on 9 June 2023
The level of urban social and economic development	http://tjj.shandong.gov.cn, accessed on 9 June 2023
Number of mosques by decade	http://read.nlc.cn/user/index, accessed on 15 June 2023

2.3. Analysis Framework

2.3.1. Standard Deviation Ellipse

The Standard Deviation Ellipse (SDE) method can be used to clearly observe the distribution characteristics, geographical location, and distribution direction of mosques in the studied cities. In the following formulas, the azimuth angle θ represents the distribution direction of the mosques in the urban space. The long axis of the ellipse is the degree to which the mosque deviates from the city center in the main direction. The short axis is the degree to which the mosque deviates from the city center in the secondary direction. The azimuth angle θ is between the north (N) direction of the mosques and the direction of the main axis (long axis) of clockwise rotation [14,49,50]. The specific calculation formula is as follows:

$$\mathrm{Tan}\theta = \frac{\left(\sum_{i=1}^{n} \tilde{x}_i^2 - \sum_{i=1}^{n} \tilde{y}_i^2\right) + \sqrt{\left(\sum_{i=1}^{n} \tilde{x}_i^2 - \sum_{i=1}^{n} \tilde{y}_i^2\right)^2 + 4\left(\sum_{i=1}^{n} \tilde{x}_i \tilde{y}_i\right)^2}}{2\sum_{i=1}^{n} \tilde{x}_i \tilde{y}_i}$$

$$\sigma_x = \sqrt{2}\sqrt{\frac{\sum_{i=1}^{n}\left(\tilde{\chi}_i \cos\theta - \tilde{y}_i \sin\theta\right)^2}{n}}; \sigma_y = \sqrt{2}\sqrt{\frac{\left(\sum_{i=1}^{n} \tilde{x}_i \cos\theta - \tilde{y}_i \sin\theta\right)^2}{n}} \quad (1)$$

In Formula (1), $\tilde{x}_i$ and $\tilde{y}_i$ respectively represent the coordinate deviation value of the geometric center of each urban area from the coordinate city center, and σ_x and σ_y respectively represent the standard deviation of the ellipse along the x and y axes.

2.3.2. Nearest Neighbor Index

The Nearest Neighbor Index (NNI) method is used to study the overall distribution of TMs along the line, indicate the mutual proximity of mosques in urban development, and calculate the average of the nearest neighbor distance between the distribution of TMs and the urban development of their located cities. By comparing with the distance expected by urban development, the location and distribution characteristics of the mosque building entities in urban space could be determined [7,51,52]. The specific calculation formula is as follows:

$$R = \frac{\overline{r_i}}{\overline{r_e}} = \frac{\overline{r_i}}{2\sqrt{\frac{n}{A}}} \quad (2)$$

In Formula (2), $\overline{r_e}$ represents the random nearest neighbor average distance of a mosque in urban space under ideal conditions; $\overline{r_i}$ represents the actual nearest neighbor average distance between the mosque and its location city; A is the area size of the study area; and n is the number of mosques distributed along the line. When R = 1, mosques are randomly distributed in urban space; when $R < 1$, mosques are clustered in urban space; when $R > 1$, mosques are evenly distributed in urban space.

2.3.3. Kernel Density Estimation

The Kernel Density Estimation (KDE) method mainly calculates the distribution density of TMs along the line and determines the densely distributed areas of mosques in cities. The specific calculation formula is as follows:

$$f(x) = \sum_{i=1}^{n} \left[1 - \frac{(x - x_i)^2 + (y - y_i)^2}{h^2}\right]^2 / \left(\pi n h^2\right) \quad (3)$$

In Formula (3), x is the entity point of a mosque; h is the search radius within the area; n is the number of mosque points within the area search radius. The kernel density calculation method is mainly used to study the urban geometric range; each (x_i, y_i) point starts from the highest point in the city center and continues to spread to the periphery. When the distance from the center reaches the search radius (h) to a certain extent, the density value is zero [6,14,53]. When the kernel density value $f(x)$ is higher, it means that the distribution density of mosques is greater; when the kernel density value $f(x)$ is lower, it means that the distribution density of mosques is lower.

2.3.4. Distribution Center Movement Analysis

The Distribution Center Movement Analysis method is used to study the distribution center and change of TMs along the line in urban space. It can more intuitively reflect the regional distribution differences of mosques along the line. Its center trajectory can reflect the spatiotemporal evolution characteristics of the mosques along the canal as well as the changing characteristics of the distribution center of mosques in urban space [54]. The specific calculation formula is as follows:

$$X = \frac{\sum_{i=1}^{n} X_i W_i}{\sum_{i=1}^{n} W_i}, Y = \frac{\sum_{i=1}^{n} Y_i W_i}{\sum_{i=1}^{n} W_i} \quad (4)$$

In Formula (4), X and Y are the longitude and latitude coordinates of the center of gravity of the mosque distribution in the city, W_i is the total number of mosques in the study area, X_i and Y_i are the latitude and longitude coordinates of the ith mosque in a city along the line; the city center of the migration trajectory can reflect the spatiotemporal evolution characteristics of the distribution of TMs in a certain historical period.

2.3.5. Coupling Coordination Identification

The Coupling Coordination Identification method is used to illustrate the degree of dynamic connections between the mosques and their cities. The two specific factors of the mosques and the cities along the line seem to be independent, but in fact, they are inseparable. This method uses the construction of a coupling coordination model to study the coupling and coordination between the TMs and the cities. The specific calculation formula is as follows:

$$C = \sqrt{\frac{G_x G_y}{(G_x + G_y)^2}} \quad (5)$$

In Formula (5), C represents the coupling degree between the distribution of the TMs and urban development, G_x represents the comprehensive score value of urban development, and G_y represents the comprehensive score value of the distribution situation of TMs. The values of G_x and G_y are calculated with SPSS by the fuzzy comprehensive evaluation method. $C \in [0,1]$: when $C = 0$, the coupling degree is the smallest; when $C = 1$, the coupling degree is the largest. That is, the larger the C value, the better the coupling between the mosque and urban development, towards order and coordination; the smaller the C value, the poorer the coupling between the mosque and urban development and the lower the degree of integration. The C value is divided according to the physical coupling stage, and the coupling state of the mosque and urban development is divided into three stages (Table 4).

Table 4. Coupling coordination degree identification and evaluation grade division.

Value Ranges	Coupling Level	Value Ranges	Coupling Coordination Level
$0 < C \leq 0.3$	Low level	$0 < D \leq 0.4$	Low coordinated coupling
$0.3 < C \leq 0.7$	Medium level	$0.4 < D \leq 0.6$	Moderately coordinated coupling
$0.7 < C \leq 1.0$	High level	$0.6 < D \leq 0.8$	Highly coordinated coupling
—	—	$0.8 < D \leq 1.0$	Extremely coordinated coupling

In order to better reflect the degree of coupling and coordination between the mosques and the cities, solve the limitations of the coupling degree model, and display the coordination between mosques and urban development in terms of the overall effect, a coupling coordination degree model was constructed. The specific calculation formula is as follows:

$$D = \sqrt{CT}, T = \alpha G_x + \beta G_y \tag{6}$$

In Formula (6), D represents the degree of coordination between mosques and urban development, which reflects the level of coordination between mosques and cities; T is the comprehensive coordination index between urban development and mosques; α and β are undetermined coefficients (α and β are, respectively, 0.6 and 0.4) [55]. This method is mainly adopted to study the degree of coupling and coordination between mosques and urban development, which is an important means to determine whether the "mosque" and "city" are coordinated. The specific coupling coordination degree judgment criteria can be seen in Table 4 [56].

2.4. Research Indicator and Direction

2.4.1. Research Indicators

Based on survey research and existing data, this study focuses on the distribution characteristics of TMs along the canal in the Shandong section and cities, with urban areas, population, economy, and urban spaces being significant indicators of urban modernization and sustainable development [57]. When mosques are considered as an indicator, the development of cities will be influenced by traditional architecture. The effect of "mosque-city" is expressed as the mosque's "pull" on urban development; the effect of "mosque-population" is shown by the mosque's influence on the inflow and outflow of the city's population; the effect of "mosque-economy" is the mosque's impact on urban economic development [58]; the effect of "mosque-urban space" is the degree of integration and coordination of mosques in urban development [59].

As shown in Table 5, the relationship between mosques and cities indicates that with urbanization and modernization, the construction of new buildings impacts traditional architecture, leading to a gradual disappearance of TMs. However, with national protection of traditional architecture, the preservation and construction of traditional mosque architecture can strongly guide urban development in specific directions. Considering the relationship between mosques and population, the construction of TMs is largely associated with religious customs and the settlement of Hui Muslims, making the inflow and outflow of the population relatively less impactful on their construction. From the perspective of the relationship between the city and the economy, economic development guides urban development, but has a weaker effect on the spatial distribution of TMs. Considering the mosque–urban space relationship, the spatial layout of mosques reveals the relationship between TMs and urban development. The mosque's layout influences the city's spatial arrangement and vice versa, which in turn affects the mosque's distribution, location, and land area, highlighting a significant integrated and coordinated impact between the two.

Table 5. The effect of TMs and coastal city index factors.

Index Factor	Function Method	Effect
Mosque—City	"Traction"	•
Mosque—Population	Proportion of inflow population and outflow population	▲
Mosque—Economy	Influence of Radiation	▲
Mosque—Urban Space	Coupling coordination degree	•

Note: "•" in the table indicates that the effect is obvious; "▲" in the table indicates that the effect is weak.

2.4.2. Research Direction

Based on a factor analysis of research indicators, this study focuses on the degree of coupling and coordination between traditional architecture and urban development. Urban development is influenced by multiple factors, including the size, population, culture, economy, and the distribution characteristics of mosques along the Shandong section of the canal, all of which collectively impact urban development. This research investigates the influence of TMs, based on their distribution characteristics, construction periods, and focal trajectory changes, on the development direction, regional coordination, and urban pulling power of cities along the Shandong section of the canal. The coupling effects of mosques on urban development are analyzed using the ArcGIS 10.8 tool.

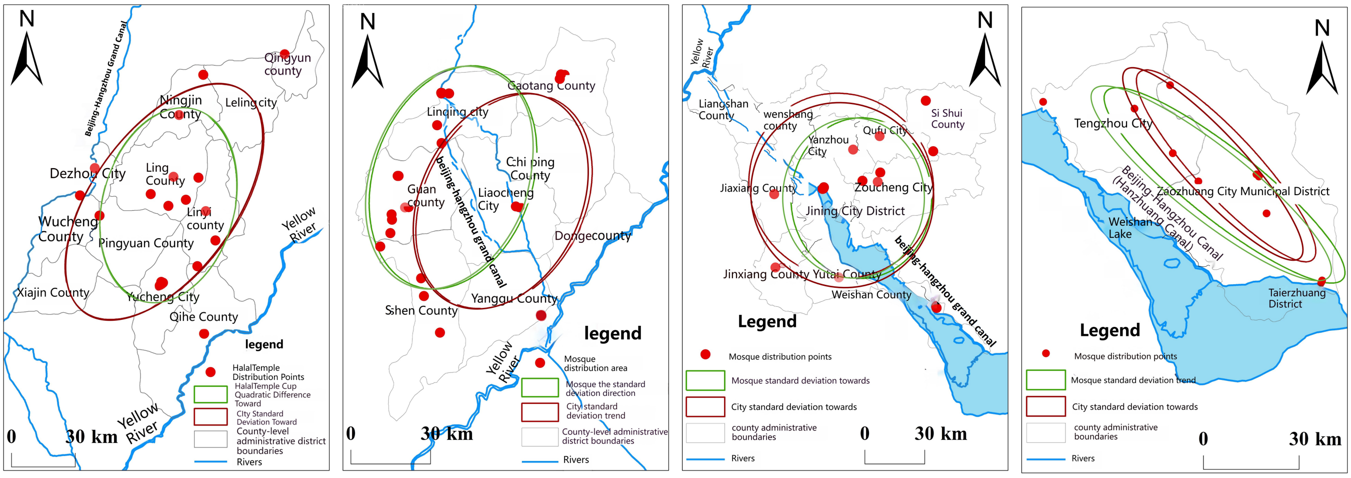
3. Results and Analysis

3.1. Analysis of the Spatial Development Direction

After the Grand Canal became unblocked in the Ming and Qing dynasties, a large number of Hui people (a Muslim people in China) moved into the Shandong section of the Grand Canal, and mosques were built one after another, gradually synchronizing the boom with their cities. At the end of the Qing dynasty, the canal in Shandong was blocked, and the mosques and their located cities also declined [60]. The construction of early mosques relied to a certain extent on cities with prosperous commerce. Over time, the spatial distribution of mosques mainly showed three forms: "random", "agglomeration", and "balance". This study analyzes the distribution of mosques in the four cities of Dezhou, Liaocheng, Jining, and Zaozhuang, which is an important approach and a means to understand the developing direction of mosques and urban space.

Using the "Direction Distribution (SDE)" in the ArcGIS spatial statistics tool, an SDE map of mosques and cities along the Line is created (Figure 2). The distribution direction, azimuth angle θ, ellipse area, and oblateness of the SDE are used to determine the visual expression and perform the data analysis of location number and distribution characteristics for TMs along the line. As seen in Figure 2, the mosques in Dezhou are distributed in a "south–north" direction; the mosques in Liaocheng are distributed in a "northeast–southwest" direction; the mosques in Jining are distributed in a "south–north" direction; and the mosques in Zaozhuang are distributed in a "northwest–southeast" direction. In the direction of the urban SDE, Dezhou and Liaocheng are in the "northeast–southwest" direction; Jining and Zaozhuang are in the "northwest–southeast" direction. In terms of elliptical area and oblateness, the ellipse area and oblateness in Dezhou and Zaozhuang are relatively small; the ellipse area and oblateness in Jining and Liaocheng are relatively large.

Based on the above analysis, it can be seen from the distribution direction of mosques and the urban development direction that there are two patterns between mosques and urban development trends: (1) the Urban development direction includes the distribution direction of mosques (Dezhou, Jining); (2) the distribution direction of mosques is consistent with the direction of urban development (Liaocheng, Zaozhuang). It can be seen from the relationship between the two that when the distribution of TMs is basically coupled with the direction of urban development, adaptive coupling adjustments will be made between the distribution of mosques and urban development. When the SDE area and oblateness are low, the cities and mosques develop in a "strip-like" direction (Dezhou, Zaozhuang); on the contrary, when the ellipse covers a wider area, the cities and mosques develop in a "clump-like" direction (Liaocheng, Jining). This shows that the scale and shape of the city will also have a corresponding impact on the layout of the mosques.



A.Dezhou standard deviation ellipse **B.**Liaocheng standard deviation ellipse **C.**Jining standard deviation ellipse **D.**Zaozhuang standard deviation ellipse

Figure 2. The mosque along the canal in Shandong is elliptical with the standard deviation of the city.

3.2. Analysis of the Traction Effect

The distribution center of mosques refers to the moment balance point of the spatial distribution of mosques in the area, and its comparison with the geometric center of distribution could better reflect the balanced distribution of mosques. Analyzing the "traction" effect of mosques in certain sections on urban development through the distribution center movement in each historical stage can intuitively reflect the distribution differences of mosques in the section in different periods. The trajectory of the distribution center of mosque construction can be roughly divided into four stages: the Wanli period of the Ming dynasty, the Guangxu period of the Qing dynasty, and the data in 1990 and 2023 (Figure 3). Using point set-to-line conversion under the ArcGIS data management tool element, the physical points of the mosques along the line were converted into line sets, thereby calculating the distribution center migration route for the mosques along the line (Figure 4).

(1) The focus of mosque construction along Dezhou is generally more in the northwest and less in the southeast. In the Ming dynasty, Dezhou prospered rapidly, relying on water transportation, and became an important town along the canal. The city expanded accordingly, in which the mosques showed a "diffused" distribution. After the end of the Qing dynasty, the status of the canal gradually declined, and the distribution center of mosques gradually shifted to the central and southeastern parts of the country. The number of mosques near the Yellow River gradually increased. Before 1990, due to the influence of various factors, the Hui population was dispersed from this city in large numbers; thus, the number of mosques built was small and scattered. The mosque construction was mainly concentrated along the Yellow River and in the north of the city. From 1990 to 2023, the government paid attention to the protection and utilization of TMs, and the construction of mosques in the city gradually recovered and grew.

(2) The distribution of mosques along Liaocheng and the urban development trend generally evolve in the direction of $\theta = 45^{\circ}$. In the Ming dynasty, the cities along the canal, such as Linqing and Guanxian, had prosperous commerce and developed markets. The suitable business environment resulted in the cities along the canal becoming densely populated areas, forming new Muslim (mainly for Hui People) gathering areas, which led to the rapid construction of mosques. In the Ming and Qing dynasties, the focus on the overall eastward movement, especially concentrated in Gaotang, was due to the prosperity of water transportation and economic prosperity. The Muslim population increased and gradually spread eastward. In the Qing dynasty, the Gaotang prefecture was adjacent to

Dezhou, and there were obvious geographical advantages, which attracted a large number of Hui people. Therefore, there are many mosques. At the end of the Qing dynasty, the canal was cut off for transportation and the social environment was turbulent, which directly affected the normal life of the Hui people along the canal. During that period, the spread of Islam in the areas along the canal was more focused on the rural areas. Therefore, from 1909 to 1990, the number of mosques was relatively scattered, and the main construction focus was concentrated in the rural areas to the north. In recent years, with the economic recovery, the cities along the canal have gradually opened up, and a large number of ancient buildings have been restored. From 1990 to 2023, the number of mosques increased, and the distribution was relatively even around Liaocheng.

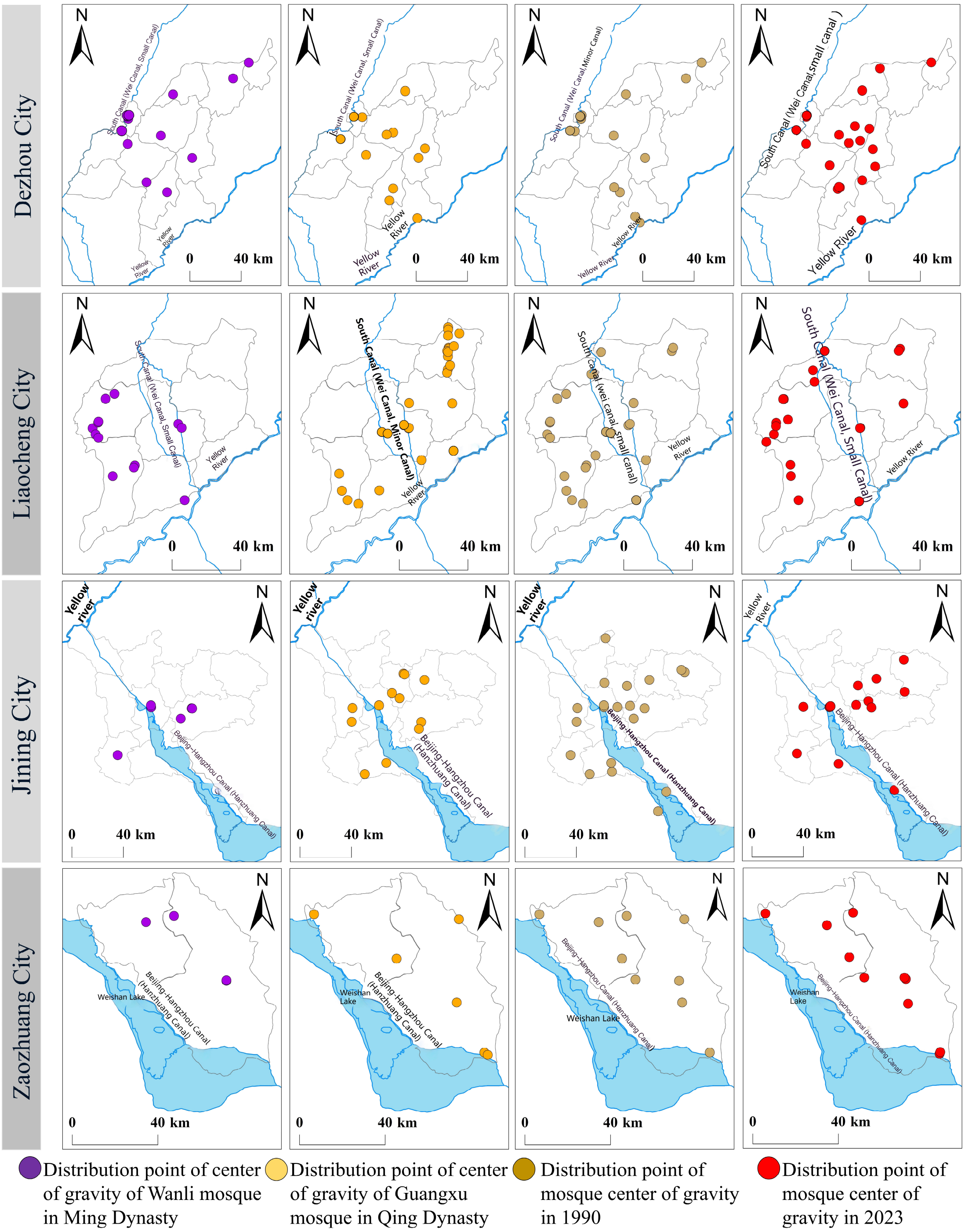
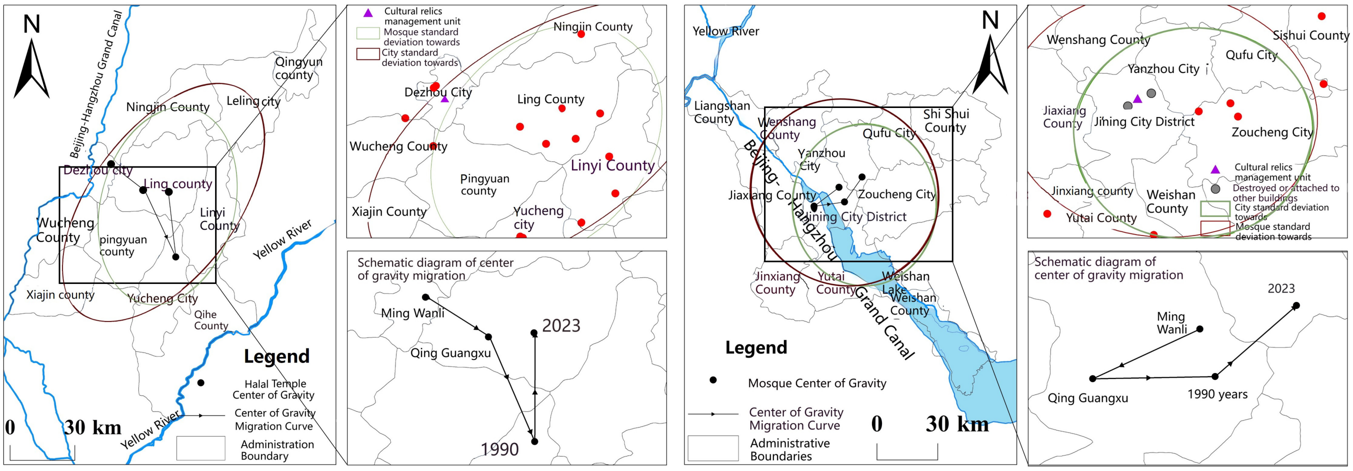
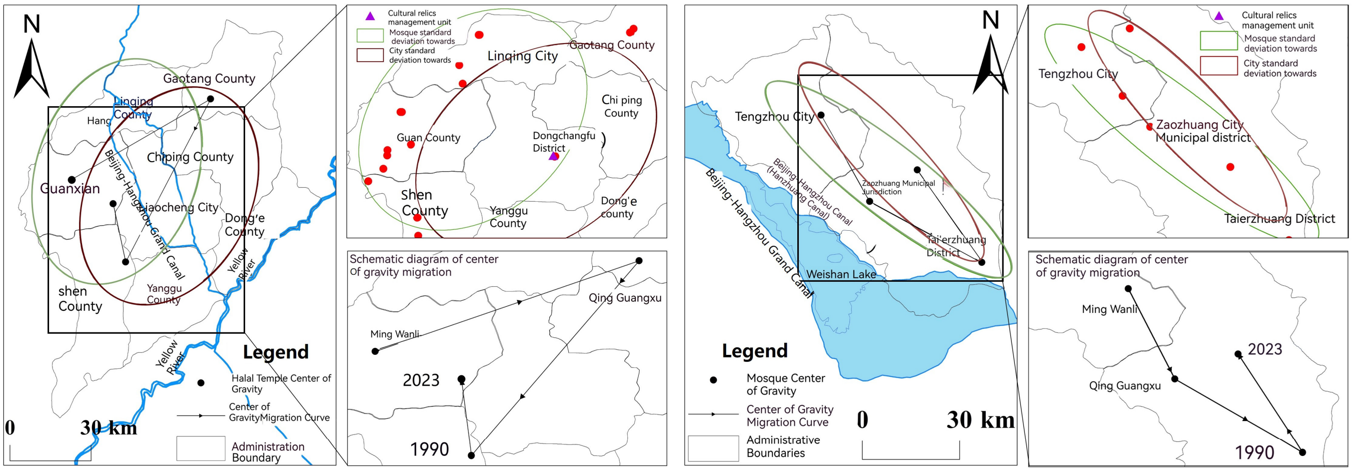


Figure 3. The distribution center of mosques at each stage.



A.Dezhou mosque construction center of gravity change diagram **B.**Jining mosque construction center of gravity change diagram



C.Liaocheng mosque construction center of gravity change diagram **D.**Zaozhuang mosque construction center of gravity change diagram

Figure 4. Schematic diagrams of the change in the distribution center of mosque construction. Note: The red dots in the figure represent "TMs".

(3) Jining is located in the middle section of the Grand Canal, which is a transportation crossover for water and land and a strategic point from north to south. In the Yuan, Ming, and Qing dynasties, the highest institution for governing transportation was located in the Rencheng district of Jining. During the Yongle period of the Ming dynasty, Hui merchants integrated into the multiethnic area of Jining and mostly lived around the Rencheng district. In the early Qing dynasty, a group of "Hui Confucians" appeared in the canal area. Therefore, based on the original construction of the Ming dynasty, the number of mosques increased, and distribution was focused on movement across the canal to the west. At the end of the Qing dynasty, the Yellow River changed its course, and social disputes around that area arose. The Qing dynasty was unable to maintain the smooth flow of the canal, and merchants fled one after another. Therefore, the number of mosques dropped sharply in the context of internal and external troubles in that period. Between 1909 and 1990, the focus of mosque construction began to move eastward, and the distribution scope was wider than before. After 1978, the increase in the number of mosques reached its peak, and the construction scope was wide. After 1990, the focus of mosques gradually shifted to the northeast.

(4) Most of the mosques in Zaozhuang were built in both the Ming and Qing dynasties. They are scattered and small in number. The reason for this is that the ruling class of the Ming and Qing dynasties forced ethnic minorities into military service and adopted the method of "divide and rule" to encourage the Hui people to migrate in large numbers.

During the Guangxu period of the Qing dynasty, the focus gradually moved southward and dispersed to other areas. The old Zaozhuang is one of the relatively concentrated Hui settlements in southern Shandong. During the Ming and Qing dynasties, a spatial evolution pattern of "large dispersion and small settlements" was formed. In modern times, most of the mosques were destroyed by wars. After the reform and opening up, the Hui people returned and concentrated in villages and towns. The distribution center has continued to move southward since 1990, being concentrated in villages and towns and relatively scattered. From 1990 to 2023, the number of mosques increased, gradually moved northward, and became dispersed.

In short, the overall distribution trend of mosques along the Shandong section of the Grand Canal is "rising–decreasing" (Figure 5), with the number reaching its peak in 1990. Mosques were built during both the Ming and Qing dynasties when the canal was open, affected by the canal economy and the migration of the Hui people. At the end of the Qing dynasty, a large number of mosques were destroyed because the canal was cut off and wars broke out frequently. In the years prior to 1990, the Hui people returned, traditional ancient buildings were protected, mosque construction began again, and building density increased. In Figure 5, the direction of the curve is roughly the same as the standard deviation direction of the urban ellipse, which shows that the development of the cities and the construction of the mosques are coupled to a certain extent.

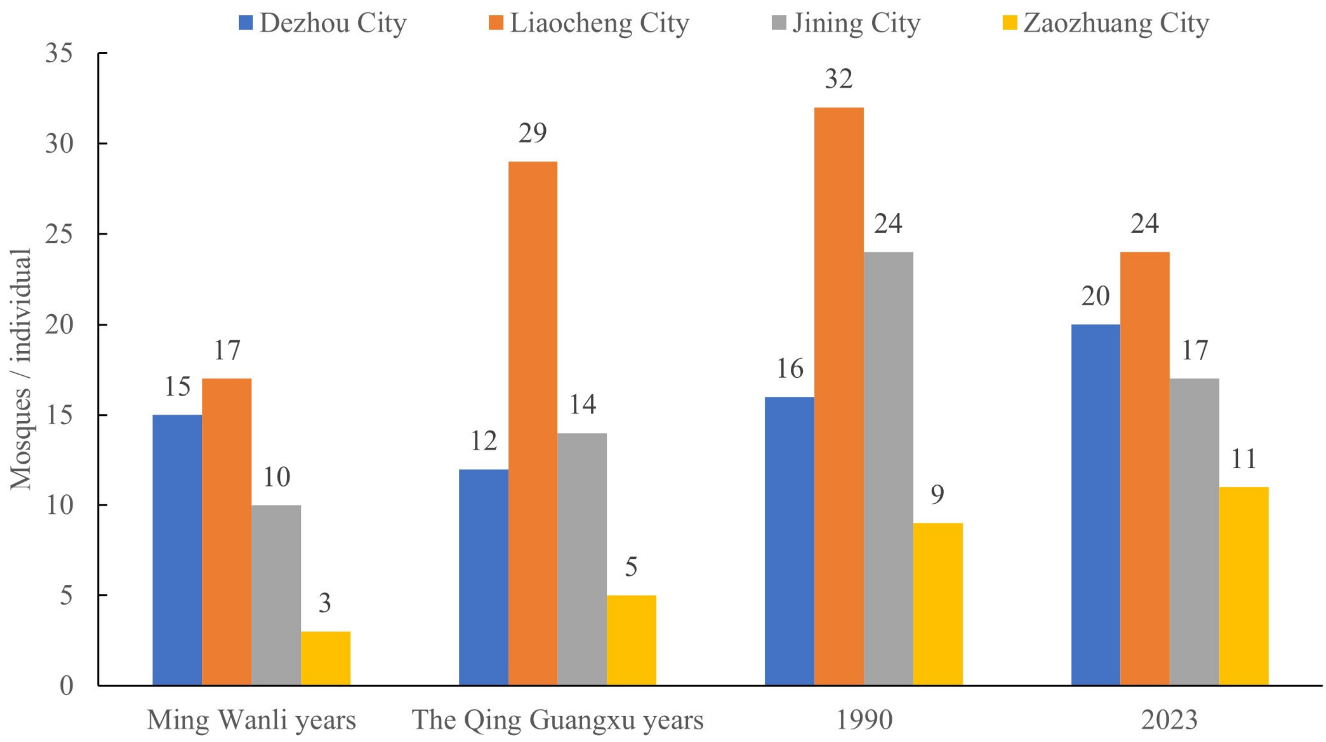
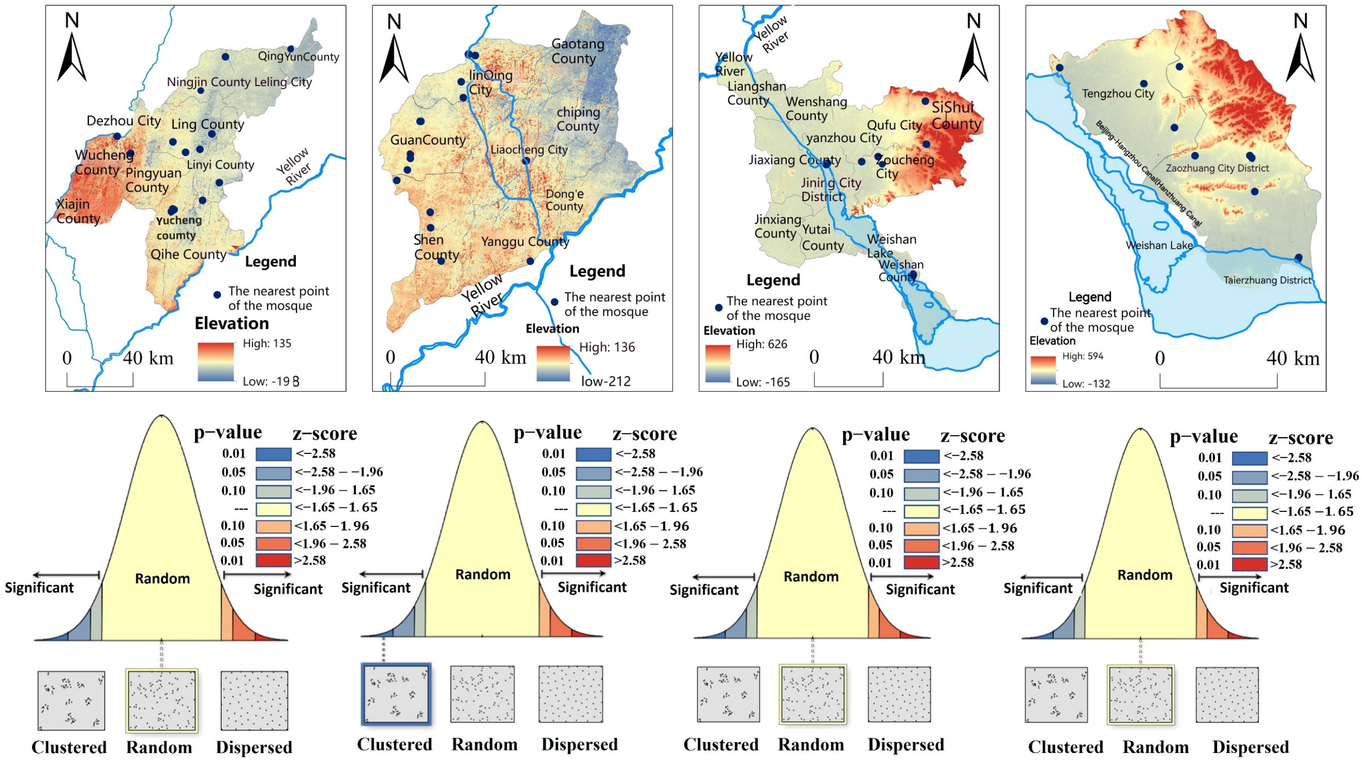


Figure 5. Statistics regarding the number of TMs at each stage.

3.3. Analysis of Influencing Factors

The influencing factors of TMs along the canal in the Shandong section on urban development are mainly analyzed by NNI and kernel density. Based on these two methods, the distribution characteristics of mosques along the canal in their cities are studied. From the analysis of the two factors, the primary and secondary gathering areas of mosques in this section are analyzed, and the coupling status of the development of mosques in the four cities of Dezhou, Liaocheng, Jining, and Zaozhuang is analyzed. Firstly, the overall distribution situation and regional agglomeration status of mosques are determined through NNI. Secondly, a kernel density analysis of mosques along the canal is conducted based on the distribution situation of mosques in each city.

The NNI is a measure of the proximity of mosques to each other in urban space. Taking the mosque as a "point element", the three forms of "random", "agglomeration", and "uniform" as the main judgment criteria are adopted to determine the distribution type in urban space. Using the average nearest neighbor in the spatial statistical data analysis mode in the "ArcGIS 10.8" application, the nearest neighbor analysis was conducted on TMs in the four cities of Dezhou, Liaocheng, Jining, and Zaozhuang, and the distribution types of mosques (point elements) were obtained. The results are shown below (Figure 6).



A. Distribution of the nearest points of Dezhou mosque
B. The distribution of the nearest points of Liaocheng mosque
C. Distribution of the nearest points of Jining Mosque
D. Distribution of the nearest points of Zaozhuang Mosque

Figure 6. Analysis of the average NNI of mosques along the Shandong section of the canal.

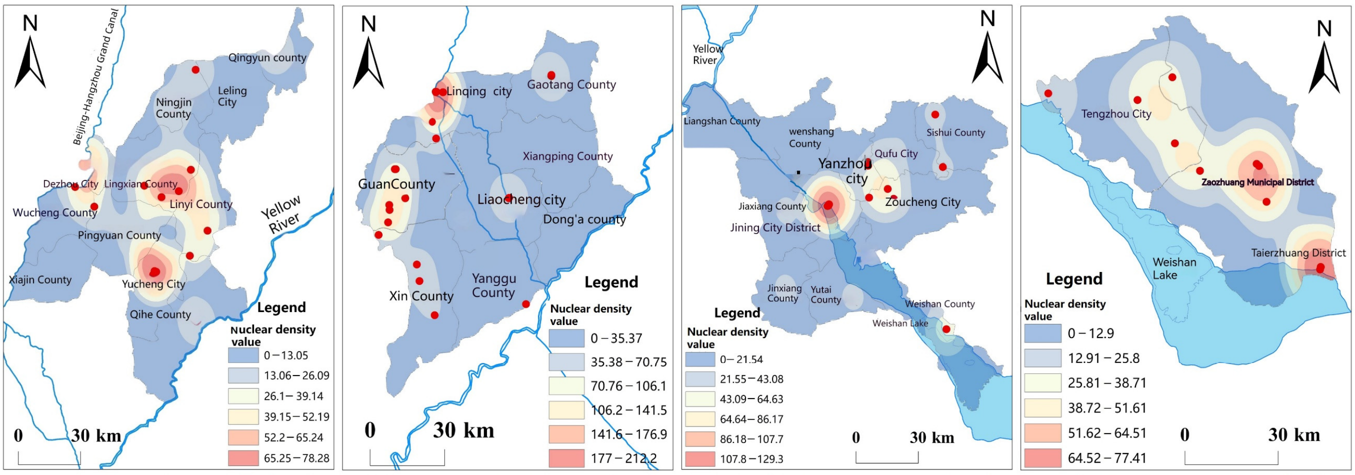
The results show that the distribution type of mosques is closely related to urban development. The distribution of mosques in their cities is either concentrated or even. There are two main distribution patterns of mosques along the canal in the Shandong section. One is random distribution, mainly in Dezhou, Jining, and Zaozhuang, and the other is clustered distribution, mainly in Liaocheng. On one side, it can be seen from the "Random" distribution of mosques that, although mosques are distributed freely in urban spaces and run through various regions, they also appear to be clustered in various cities (such as Guanxian, Linqing, etc.), indicating that the distribution of mosques is related to the differences of inter-cities and that coupling coordination gradually becomes stronger. On the other hand, it can be seen from the "Clustered" distribution of mosques that mosques are concentrated in cities with high agglomeration levels (such as Guanxian and Linqing), which shows that mosques are related to the local business economy, population migration, and other factors in their cities. Although the distribution situation of mosques in their cities shows two different results, in terms of this flowing linear culture, mosques are generally distributed in large numbers and concentrated in cities along the canal.

ArcGIS was utilized to conduct the nearest neighbor calculation of TMs, and the average observed distance and expected average distance of mosques in four cities were obtained (Table 6). It can be seen from the table that mosques present two distribution patterns: the "Random" and the "Clustered". Among the cities, the number of mosques in Dezhou and Liaocheng is larger, accounting for 61% of the total; the number of mosques in Jining and Zaozhuang is smaller, accounting for 39% of the total. Under the balance distribution situation, the nearest neighbor ratio (R) is significantly greater than 1, and the mosques are far apart and scattered in the cities; under the clustered distribution situation, the nearest neighbor ratio (R) is infinitely close to 1, and the mosques are close together, with the distribution relatively concentrated in the cities.

Table 6. The nearest distance distribution of TMs along the canal in the Shandong section.

Cities along the Line	Mosques (Number)	Average Observation Distance (m)	Expected Average Distance (m)	The Nearest Neighbor Ratio (R)	Distribution Situation
Dezhou	20	12,850.47	11,232.92	1.144 ($R > 1$)	Uniform distribution
Liaocheng	24	5651.12	8580.87	0.659 ($R \rightarrow 1$)	Agglomeration distribution
Jining	17	11,064.91	10,807.28	1.024 ($R > 1$)	Uniform distribution
Zaozhuang	11	8586.80	7864.64	1.092 ($R > 1$)	Uniform distribution

Based on the NNI analysis, this study analyzed the point features of mosques generated in ArcGIS. Using the kernel density estimation tool in Spatial Analyst, a kernel density analysis was conducted for four cities: Dezhou, Liaocheng, Jining, and Zaozhuang. This analysis ultimately resulted in a distribution pattern map of mosques (Figure 7).



A. Nuclear density distribution in Dezhou City **B.** The nuclear density distribution of Liaocheng City **C.** Distribution of nuclear density in Jining City **D.** Distribution of nuclear density in Zaozhuang City

Figure 7. Distribution of mosque kernel density along the canal in Shandong. Note: The red dots in the figure represent "TMs".

Figure 7 shows that Dezhou mosques are distributed in three highly dense areas (Decheng district, Yucheng city, and Ling county), and the sub-dense areas are distributed in a "point-and-belt" pattern; the mosques in Liaocheng are distributed in two highly dense areas (Guan county, Linqing city), and the sub-dense areas are mostly distributed in a "point-like" pattern; the mosques in Jining are distributed in two highly dense areas (Jining municipal district, Zoucheng city in Yanzhou), and the sub-dense areas are distributed in a "multi-core, point-and-belt" distribution pattern; the mosques in Zaozhuang are distributed in two highly dense areas (Zaozhuang municipal district and Taierzhuang district), and the sub-dense areas are mostly distributed in a "point-and-belt" pattern (Tengzhou city). Based on the reference value of the nearest neighbor ratio (R), the nearest neighbor ratio $R \rightarrow 1$ in Liaocheng appears as "point-like" in the clustered distribution state; the nearest neighbor ratios $R > 1$ in Dezhou, Jining, and Zaozhuang appear as "multi-core and point-and-belt" in the balance distribution state. The statistical results are shown in Table 7.

Table 7. Statistics of nuclear density distribution of mosques along the canal in the Shandong section.

Cities along the Line	Mosques (Number)	High Density Gathering Area	Sub-Density Gathering Area	Allocation Schema
Dezhou	20	Decheng District, Yucheng City, Lingxian County	Ningjin County, Qingyun County, Linyi County, Qihe County	Multi-core, point banded
Liaocheng	24	Guanxian County, Linqing City	Gaotang County, Liaocheng City, Shen County	Pitting
Jining	17	Jining City, Yanzhou-Zoucheng City	Jiaxiang County, Jinxiang County, Yutai County, Weishan County, Sishui County	Multi-core, point banded
Zaozhuang	11	Zaozhuang City, Taierzhuang District	Tengzhou City	Multi-core, point banded

Judging from the overall kernel density distribution, the mosques along the Shandong section radiate from individual districts and counties to the surrounding areas, with a wider radiating area and more radiating areas, forming a "multi-center, multi-core" distribution pattern. The high core density value is $f(x) \in (38.72, 212.2)$ for the four cities along the canal, which means that mosques are distributed more densely in those cities, with more highly clustered and stronger urban cohesion; the sub-core density value is $f(x) \in (0, 106.1)$, which means that the distribution density of mosques in the city is low and the degree of dispersion is high.

3.4. Analysis of the Coordination Degree

Formulas (5) and (6) respectively calculate the coupling degree C value and the coordination degree D value of the mosque distribution and urban development. By comparing the coupling coordination degree identification and evaluation grades in Table 4, the coupling coordination level between mosques and their cities is obtained. When calculating G_x and G_y values, the fuzzy subsets of mosques and cities should be firstly determined. Combined with the Section 2.4.1 research indicators, scores for the urban population, economy, culture, and space satisfaction are assigned respectively, to determine the score proportions of each element of the index items for the cities. Then, the variables for the distribution focus center of mosques, the degree of cultural integration, the degree of space satisfaction, and the traction scores are assigned respectively, to calculate the score proportion of each element of the indicator item for the mosque distribution; the range of the membership grade is $[0, 1]$. The comprehensive score values G_x and G_y between the mosques and their located cities are calculated respectively through the fuzzy comprehensive evaluation method of SPSS application. The calculation results are shown in Tables 8 and 9.

Table 8. Urban development comprehensive score membership fuzzy evaluation calculation results.

Cities along the Line	Comprehensive Score (G_x)	Population Score	Economic Score	Cultural Integration Score	Space Satisfaction Score
Dezhou	0.424	0.125	0.144	0.155	0.153
Liaocheng	0.413	0.125	0.144	0.163	0.156
Jining	0.412	0.138	0.165	0.142	0.144
Zaozhuang	0.420	0.148	0.143	0.148	0.141

Table 9. Mosque distribution situation comprehensive score membership fuzzy evaluation calculation results.

Mosques in Cities along the Route	Comprehensive Score (G_y)	Distribution Score	Cultural Integration Score	Space Satisfaction Score	Traction Score
Dezhou Mosque	0.461	0.145	0.150	0.155	0.088
Liaocheng Mosque	0.464	0.115	0.170	0.139	0.111
Jining Mosque	0.365	0.077	0.342	0.107	0.110
Zaozhuang Mosque	0.430	0.108	0.150	0.150	0.162

The comprehensive score values of the city (G_x) and the mosque (G_y) are obtained via the calculations in Tables 8 and 9. According to Formulas (5) and (6), the coupling degree C value, coordination degree D value, and comprehensive coordination index T value, are calculated respectively. The coupling level and coordination stage between the city and the mosque are determined based on Table 4. The calculation results are shown in Table 10:

Table 10. Coupling evaluation results and coupling coordination between city and mosque.

Cities along the Line	Comprehensive Score of Urban Development (G_x)	Mosque Distribution Situation Comprehensive Score Value (G_y)	Comprehensive Coordination Index T	Coupling Degree C	Coordination Degree D	Coupling Level	Coordination Stage
Dezhou	0.424	0.461	0.4388	0.4996	0.4682	Medium level	Moderately coordinated coupling
Liaocheng	0.413	0.464	0.4334	0.4994	0.4651	Medium level	Moderately coordinated coupling
Jining	0.412	0.365	0.3932	0.4991	0.4430	Medium level	Moderately coordinated coupling
Zaozhuang	0.420	0.430	0.4240	0.5000	0.4604	Medium level	Moderately coordinated coupling

From the data in Table 10, the values of the comprehensive coordination index T between the four cities (Dezhou, Liaocheng, Jining, and Zaozhuang) and TMs are all around 0.4, the coupling degree C values tend toward 0.5, and the coordination degree D values are in the range between 0.44 and 0.47. The coupling degree levels are medium, and the coordination stages are in the medium coordination coupling stage. To more intuitively point out the total score of urban development, the total score of the mosque distribution situation, and the coupling coordination status of the two systems, a corresponding line chart is drawn according to Table 10. The result is shown in Figure 8.

The results indicate, as shown in Table 10 and Figure 8, that there is a moderate level of coordination between the four cities and their mosques. The composite scores of urban development and mosque distribution trends are generally stable, suggesting that mosques are increasingly aligned with urban development trends. This moderate level of coupling indicates that TMs are harmoniously integrated within urban development, with diminishing conflicts and contradictions between the two.

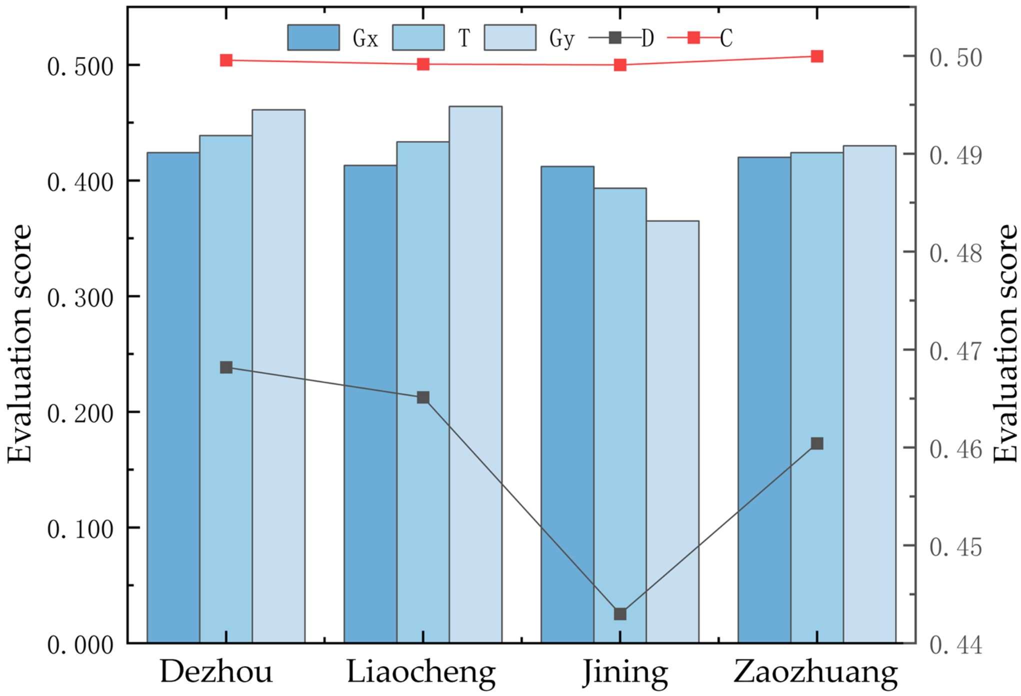


Figure 8. Evaluation results of coupling between city and mosque and coupling coordination curve.

4. Discussion

The main contributions of this study are reflected in three aspects:

(1) In related research on coordinated urban development, academic communities generally recognize that factors such as water transportation, commercial economy, geographical location, and natural environment are the main driving forces for coordinated urban development in the urban development process [61–64]. However, other factors also play an important role in the process of coordinated urban development, which have not been analyzed, apart from these previously stated important factors. This study takes traditional architecture in the cities as another external factor and takes TMs as a specific theme, to analyze the coupling and coordination relationship between TMs and urban development. On the one hand, by comparing the number of mosques and the change trajectory of the distribution center in each historical stage, the evolution process of the cities in terms of historical changes is analyzed, which provides a new perspective for understanding the location relationship between mosques and cities. It is proposed that mosques, as internal factors, are important conditions in the overall coordinated development of cities. This indicates that traditional architecture also plays an important role in the process of coordinated urban development. On the other hand, this could show that mosques and urban development have a moderate level of coordination and coupling, which conforms to the current trend of the gradual integration of mosques and urban development. From the SDE and coupling coordination degree identification, this study illustrates that the mosque construction process is another internal factor, which is gradually harmonious with urban development, providing feasible examples for this research topic.

(2) Regarding the study of mosque areas, current scholars predominantly focus on the individual TMs of certain regions [64,65] and the spatial-temporal evolution of city mosques within a province [6,7]. Additionally, scholars have conducted extensive research on the architectural styles of mosques [66]. Overall, while there is significant research on mosques, studies on TMs within specific sections are still lacking. During the Ming and Qing dynasties, the dredging of the previously silted sections of the Grand Canal within Shandong promoted rapid urban development along its Shandong section. The flourishing commerce attracted a large number of Hui merchants

and Muslim businessmen, leading to the construction of mosques to accommodate their cultural practices, with these mosques generally adopting traditional Chinese architectural styles. Consequently, there are numerous TMs along the Shandong section of the Grand Canal, concentrated primarily in cities that experienced early commercial prosperity (such as Liaocheng, Linqing, Jining, and Dezhou). This is the reason for selecting the Shandong section of the Grand Canal as the focus of this study. The study deeply analyzes the coupling relationship between the distribution characteristics of TMs along the Shandong section of the canal and urban development influencing factors.

(3) A theoretical analysis framework is constructed in this study. Firstly, we analyze the reason why TMs are more widely distributed along the Shandong section of the Grand Canal, as one of the research topics listed, and whether the distribution of these mosques has a certain coupling and coordination relationship with the development of cities along the line. Secondly, we apply a variety of research methods [6,7,14,49–55] to conduct the coupling analysis of the TMs along the line and urban development. Finally, it was demonstrated that there is a coupling and coordination relationship between the TMs and urban development along the line. Near the Grand Canal, mosque distribution and urban development are interconnected and influence each other; the theoretical analysis framework of this study could provide the theoretical and practical references for the coupling and coordination relationship between other traditional buildings and cities in similar areas.

However, with the continuous impacts of modernization, industrialization, and new urbanization, the spatial distribution characteristics of TMs will also change with the development of cities, and the coupled coordination relationship between TMs and cities will also undergo changes. Due to the influence of various uncertain factors, while focusing on urban development, we must also consider the protection of traditional architecture, promoting the overall coordinated development between traditional buildings and cities. Furthermore, this study has many shortcomings; it only analyzes the case of the Shandong section of the Grand Canal in Shandong Province, China, and has does not address other sections of the canal. Influenced by factors such as the passage of time, urban development, and cultural integration, sustainable development of TMs and cities will become a focus of subsequent research.

5. Conclusions

This study uses the Shandong section of the Grand Canal as a case study, examining the coupling relationship between TMs and urban development to establish a framework for the coupling and coordination relationship between mosques and cities. Based on mosque data from the Ming dynasty, Qing dynasty, 1990, and 2023, and using ArcGIS spatial analysis, this study identifies the coupling relationships between TMs and urban development in the cities of Dezhou, Liaocheng, Jining, and Zaozhuang. The results show the following:

(1) Overall, mosques are numerous and concentrated along the cities of the Grand Canal. The study categorizes the relationship between TMs and urban development into "aligned with urban direction" and "concentric inclusion." When the distribution of mosques is fundamentally coupled with the direction of urban development, adaptive adjustments are made between them.

(2) According to the NNI analysis, TMs along the Shandong section of the canal mainly exhibit two distribution patterns: a random distribution focused in Dezhou, Jining, and Zaozhuang, and a clustered distribution centered in Liaocheng.

(3) The overall kernel density distribution shows that mosques along the Shandong section of the canal have a "multi-center, multi-core" distribution pattern, indicating an increase in density and expansion of distribution areas during urban development.

(4) The centroid migration trajectory of mosques primarily reflects Hui migration and Muslim commercial settlements, showing an overall "rise–fall" trend from the Ming

dynasty to 2023, peaking in 1990. This indicates that changes in the number of mosques are influenced by multiple factors, including urban policies, population, economy, and history.

(5) Based on the values of coupling degree C and coordination degree D, mosques and cities exhibit a moderate level of coordinated coupling, indicating that mosques are increasingly integrated with urban development trends.

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