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Spatial Investigation and Analysis of Bridge Heritage in Jining Based on ArcGIS Pro

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Abstract: This paper investigates the bridge heritage of Jining through literature review, field surveys, and spatial analysis using ArcGIS Pro. The study examines their chronological distribution, spatial patterns, hydrological settings, and protection levels. Findings show that the bridges, dating from the Tang dynasty to the modern era and concentrated in the Ming and Qing periods, are mainly clustered along the Grand Canal and the Si River, reflecting Jining's role as a transportation hub and center of Confucian culture. Most bridges are classified as provincial cultural relics and are located in rural areas, where limited resources and awareness constrain preservation. Current utilization remains largely confined to static display, with insufficient integration into tourism, cultural innovation, and rural revitalization. To address these issues, this study proposes strengthening the "Four Essentials" (scope, signage, archives, management), enhancing digital documentation, and promoting cultural-tourism integration to advance both heritage protection and regional development.

Keywords: Bridge heritage; ArcGIS Pro; Spatial analysis; Preservation and utilization

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1. Introduction

Jining, located in southwestern Shandong Province, is renowned as the "City of Canals" due to the Grand Canal running through it, along with the Yellow, Dawen, and Si Rivers [1]. Influenced by this geographic setting, numerous bridges were historically constructed, many of which are still preserved today. These ancient bridges possess significant historical, scientific, and artistic value, and their further exploration and digital utilization could greatly promote cultural tourism and enhance regional identity. This study focuses on the existing bridge heritage in Jining, compiling data on their names, locations, construction periods, and structural features, and analyzing their historical evolution, spatial distribution, and protection levels. The aim is to provide a foundation for the revitalization and sustainable development of Jining's bridge heritage.

2. Research objects and scope

Bridge heritage refers to the remains of human bridge-building activities, reflecting construction capabilities at different historical stages. Such heritage embodies historical, technological, social, cultural, and artistic values. According to their significance, bridge heritage can be classified into world, national, and local levels, thereby forming a systematic and complete heritage framework [2].

The focus of this study is the existing bridge heritage in Jining. According to the literature review and field surveys, 18 historic bridges at the municipal level or above have been preserved, characterized by diverse types, wide distribution, and a long chronological span. Influenced by Confucian and canal cultures, these bridges possess rich historical and cultural connotations, offering great potential for revitalization and functional transformation. Therefore, this paper investigates and analyzes these 18 bridges through fieldwork and data analysis, aiming to explore new approaches for their protection and utilization.

3. Research methods

3.1. Literature collection

Through the collection and analysis of local gazetteers, government documents, and other relevant literature, the basic information and visual records of Jining's extant ancient bridges were compiled. This provides foundational data for assessing the current condition of the bridges and for conducting subsequent field investigations.

3.2. On-site field survey

Building on the review of relevant literature, conducting on-site surveys constitutes a crucial component of research on Jining's bridge heritage. Field investigations enable a comprehensive understanding of the spatial and temporal distribution, structural forms, and decorative features of extant bridges, as well as an assessment of their preservation status and the environmental factors influencing them. Moreover, such surveys provide firsthand data that inform strategies for the adaptive reuse of bridge heritage, laying a solid foundation for subsequent in-depth research.

3.3. Spatial data analysis using ArcGIS Pro

In this study, the extant bridge heritage in Jining was abstracted as spatial nodes, which were precisely geolocated and vectorized using software such as ArcGIS Pro. Mathematical analyses, including standard deviational ellipse, nearest neighbor index, and kernel density estimation, were then applied to summarize and characterize the temporal patterns and spatial distribution of Jining's existing bridge heritage.

The Standard Deviational Ellipse (SDE) refers to the calculation of distribution centroids for different historical time slices, which provides an intuitive representation of the spatial distribution changes and directional trends of Jining's extant bridge heritage over time, thereby enabling the analysis of its spatiotemporal evolution [3]. The calculation formula is as follows:

$$M(X,\mathrm{Y}) - \left|\sum_{i=1}^{n} x_i/n, \sum_{i=1}^{n} y_i/n\right| \tag{1}$$

$$\tan\theta = \left[\left(\sum_{i=1}^{n} x_i^2 - \sum_{i=1}^{n} y_i^2\right) + \sqrt{\left(\sum_{i=1}^{n} x_i^2 - \sum_{i=1}^{n} y_i^2\right)^2 + 4\left(\sum_{i=1}^{n} x_i\, y_i\right)}\right] / 2\sum_{i=1}^{n} x_i\, y_i \tag{2}$$

In the formulas, M ($\overline{X}$, $\overline{Y}$) represents the coordinates of the mean center, θ, denotes the orientation angle of the ellipse, and x_i,y_i are the spatial coordinates of each point feature.

The Nearest Neighbor Index (NNI) is a method used to measure the spatial distribution patterns of point features [4]. The spatial arrangement of points can be categorized as clustered, random, or uniform. The NNI is determined using the nearest neighbor ratio R, calculated as follows [5]:

$$r_E = 1/2\sqrt{n/A} \tag{3}$$

$$R = r_I/r_E \tag{4}$$

In the formula, r_1 represents the observed mean nearest neighbor distance, r_E is the expected mean nearest neighbor distance, n is the number of ancient stone bridges, and A denotes the study area. The spatial pattern is interpreted as follows: when R<1 (r_1<r_E), the distribution is clustered; when R>1 (r_1>r_E), the distribution is uniform; and when R=1 (r_1=r_E), the distribution is random.

Kernel Density Estimation (KDE) is used to analyze the spatial differentiation of Jining's extant bridge heritage [6]. KDE is defined as follows: given a set of points x_i,xn sampled from a population with an underlying density function *f* the value of *f*(x) at a location x can be estimated using the formula:

$$\mathrm{f}(\mathrm{x}) = (1/\mathrm{n}h)\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{k}[(\mathrm{x}-\mathrm{x_i})/h] \tag{5}$$

In the formula, K[(x-x_1)/*h*] is the kernel function, h is the bandwidth (*h*>0), is the number of sample points, and (x-x_1) represents the distance between the estimation point and the sample point x_1.

4. Results and analysis

4.1. Historical distribution changes

Survey results indicate that the 18 extant bridge heritage sites in Jining can be categorized into five construction periods: Tang, Yuan, Ming, Qing, and modern times. The Ming dynasty accounts for the largest share, with nine bridges (50% of the total), followed by the Qing dynasty with four bridges (23%) and the modern period with three bridges (17%). The earliest and most historically significant examples are Bian Bridge and Huitong Bridge, constructed in the late Tang and Yuan dynasties, respectively, each representing 5% of the total.

Analysis using the Standard Deviational Ellipse (SDE) function in ArcGIS Pro reveals shifts in the spatial centers of bridges across these periods (**Figure 1**). Bridges built during the Ming dynasty were concentrated primarily around Rencheng and Yanzhou districts, displaying a compact distribution pattern. By the Qing dynasty, the center shifted northeastward, encompassing Qufu, Zoucheng, and Sishui, with the distribution becoming more dispersed than in the Ming period. For other periods, the limited number of surviving bridges results in scattered distributions that preclude robust spatial assessment.

This transition from centralized clusters in the Ming dynasty to more dispersed patterns in the Qing period reflects broader regional dynamics, suggesting that the evolution of bridge construction was closely linked to shifting political, economic, and cultural centers within Jining.

Bridges constructed during the Ming dynasty number nine in total, primarily distributed across Rencheng District, Yanzhou District, and Zoucheng City. Among them, Rencheng contains the largest share with four

bridges (44%), followed by Yanzhou with three bridges (33%), and Zoucheng with two bridges (22%). The four bridges built during the Qing dynasty are evenly distributed between Qufu and Sishui, with two in each city (50% respectively). For the modern period, three bridges remain, of which two are located in Rencheng (67%) and one in Qufu (33%). In contrast, the earliest bridges—Bian Bridge from the late Tang dynasty and Huitong Bridge from the Yuan dynasty—are singular survivals, located in Sishui and Rencheng respectively (**Figure 2**).

In summary, across different historical periods, the number of bridge heritage sites in Jining and its subordinate districts has exhibited varying trends. Although the spatial distribution differs by era, the bridges are predominantly concentrated in five areas: Rencheng, Qufu, Sishui, Yanzhou, and Zoucheng. This distribution pattern aligns with the historical status of Rencheng as the "Canal Capital" and the administrative center of Jining during the Ming and Qing dynasties, as well as Yanzhou's role as a transfer hub along the Sishui section of the Grand Canal. Analyzing these historical shifts further corroborates that these regions were densely populated and economically active in ancient times, conditions that necessitated the construction of numerous bridges. The survival of these structures thus serves not only as tangible cultural heritage but also as material evidence of historical development.

Figure 1. Standard deviation ellipse measurement and calculation diagram

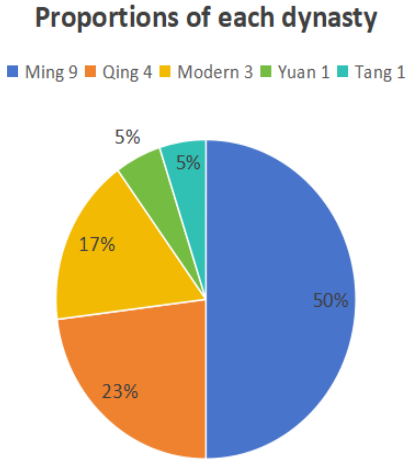


Figure 2. Proportions of each dynasty

4.2. Spatial distribution

4.2.1. Distribution of bridge heritage along river systems

By importing the geographic coordinates of Jining's extant bridge heritage together with the city's major river systems into ArcGIS Pro, a river–bridge distribution map was generated. The results show that among the 18 existing bridges, eight are located within the Si River Basin, accounting for 44% of the total. Representative examples include the nationally protected Bian Bridge in Sishui, as well as provincial-level protected bridges such as Nandai Bridge and Jiuxian Bridge in Yanzhou, underscoring the high cultural value of bridge heritage in the Si River Basin. Within the Grand Canal Basin, six bridges (33% of the total) remain, including provincial-level protected sites such as Xia Bridge and Taihe Bridge in Rencheng. The remaining four bridges (22%) are distributed across other minor river systems within Jining (Figures 3 and 4).

Statistical analysis shows that the majority of Jining's extant bridge heritage is concentrated along the Si River and the Grand Canal basins, which together account for 77% of the total. This predominance indicates the relative density of ancient bridge construction in these two areas. It further suggests that, compared with other river basins, the Si River and the Grand Canal supported denser populations and more frequent travel demands in historical periods, thereby necessitating the construction of a greater number of bridges. This distribution pattern underscores the intrinsic coupling between water systems and human settlement, transportation, and socio-economic development in the region.

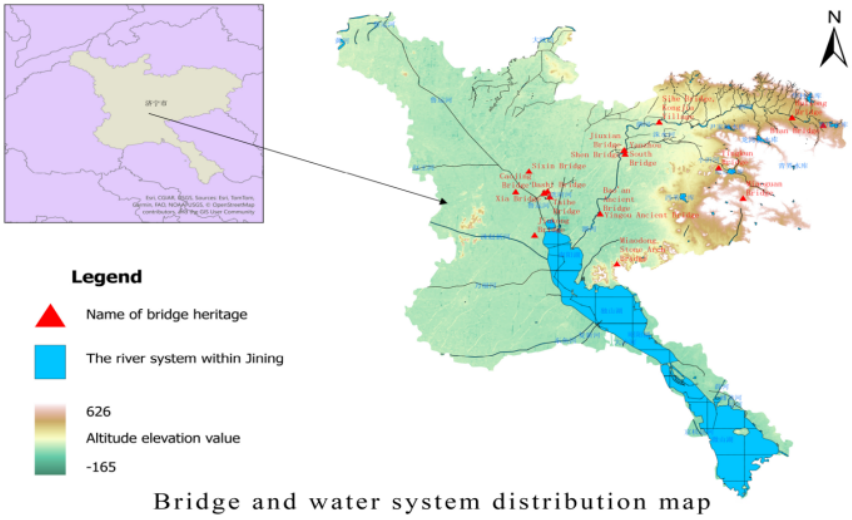


Figure 3. Bridge and water system distribution map

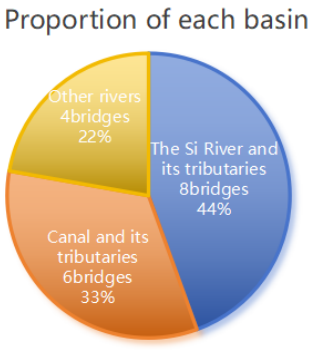


Figure 4. Proportion of each basin

4.2.2. Spatial distribution of bridge heritage

The existing bridge heritage in Jining is primarily concentrated in five administrative regions: Rencheng District, Qufu City, Yanzhou City, Sishui City, and Zoucheng City. Among them, Rencheng District preserves the largest number, with seven bridges, accounting for 39% of the total. Qufu, Yanzhou, and Sishui each retain three bridges, representing 16% respectively, while Zoucheng has the fewest, with only two bridges (13%) (Figures 5 and 6).

Using the Nearest Neighbor Analysis (NNA) function in ArcGIS Pro, the Nearest Neighbor Index (NNI) of Jining's extant bridge heritage was calculated. After importing the precise geographic coordinates of each bridge into the system, the observed mean distance was found to be 6,862.094 m, while the expected mean distance under a random distribution was 7,917.622 m. The resulting nearest neighbor ratio was approximately 0.86, with a Z-score of −1.082 and a *P*-value of 0.279. These results indicate that the overall spatial distribution of Jining's bridge heritage exhibits a clustered pattern (**Figure 7**). In addition, Kernel Density Estimation (KDE) analysis in ArcGIS Pro revealed that the bridge heritage is primarily concentrated around the canal system in Rencheng District and the Si River system near the junction of Qufu and Yanzhou, forming two high-density clusters, while other regions exhibit a scattered point distribution (**Figure 8**). These findings further corroborate that historically, Rencheng, Qufu, and Yanzhou were densely populated areas with frequent waterborne transportation, which facilitated the construction of numerous bridges.

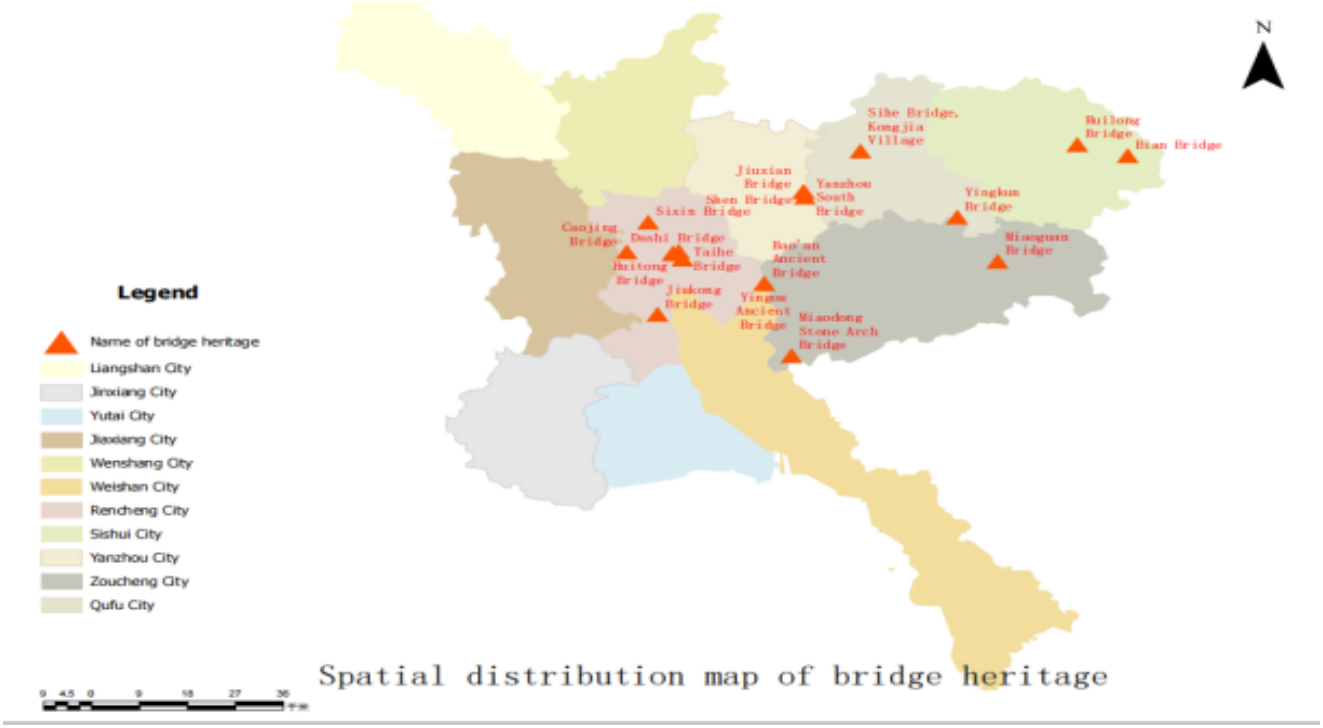


Figure 5. Spatial distribution map of bridge heritage

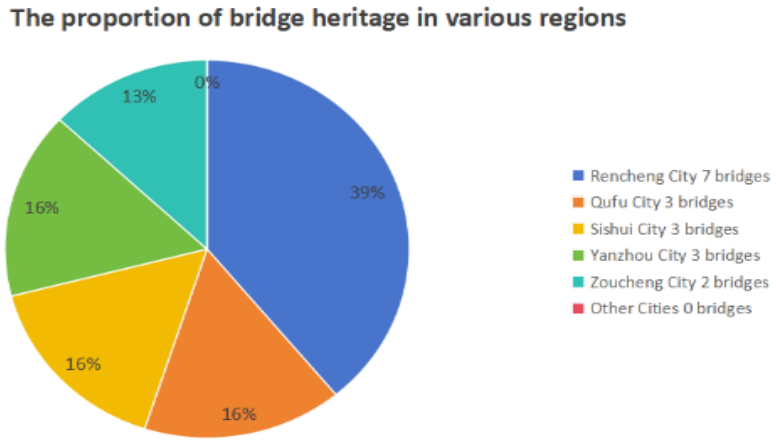


Figure 6. The proportion of bridges in various regions

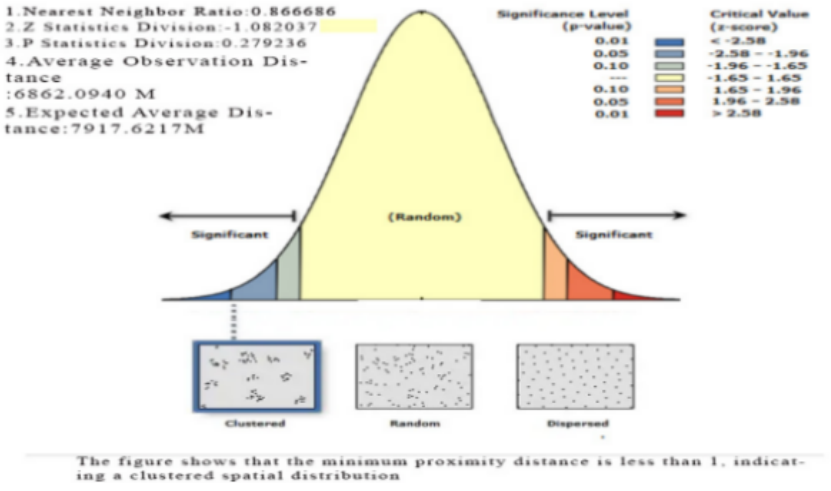


Figure 7. Nearest neighbor exponential distribution plot

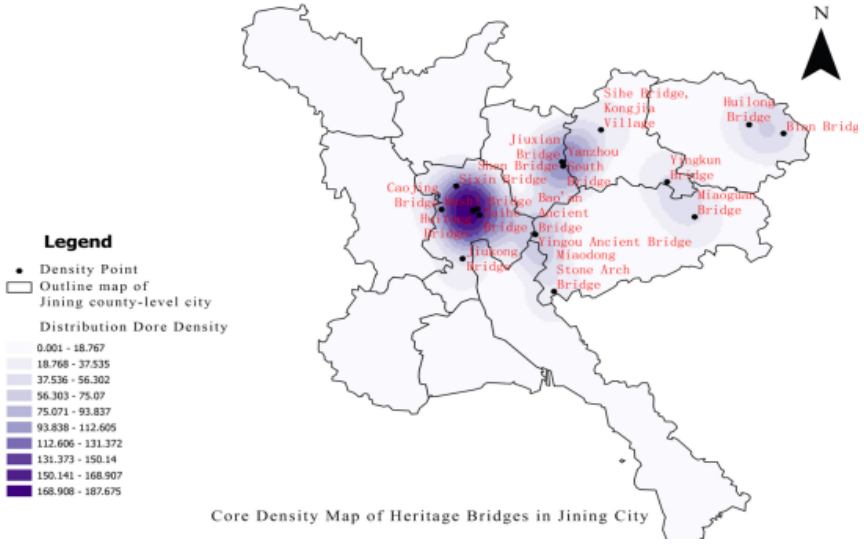


Figure 8. Core density map of heritage bridges in Jining City

4.3. Protection levels and spatial distribution of bridge heritage

Among the 18 extant bridge heritage sites in Jining, the protection levels can be categorized into three tiers: nationally protected key cultural relics, provincial-level protected cultural relics, and municipal-level protected relics. Specifically, there is one nationally protected bridge—the Bian Bridge in Sishui—accounting for 6% of the total. Provincial-level protected bridges number 13, representing 72%, while four bridges are under municipal protection, accounting for 22% (**Figure 9**). These statistics indicate that Jining's bridge heritage is predominantly composed of high-value sites at the national and provincial levels, together accounting for 78% of the total. This underscores the significant cultural and historical value of these structures and highlights the need for focused preservation and further research.

The only nationally protected bridge in Jining—the Bian Bridge in Sishui—is located in a rural area. Among the provincial-level protected bridges, seven are situated in rural areas, five in urban districts, and two in townships. Of the municipal-level protected bridges, two are located in rural areas and one is in a township. In summary, 10 bridges (56% of the total) are located in rural areas, six (33%) in urban districts, and two (11%) in townships. This distribution indicates a predominance of rural-located bridge heritage, which also exhibits a relatively broad spatial coverage. These rural bridges not only represent key components of the historical transportation network but also function as vital links supporting the daily lives and economic activities of local residents (**Figure 10**).

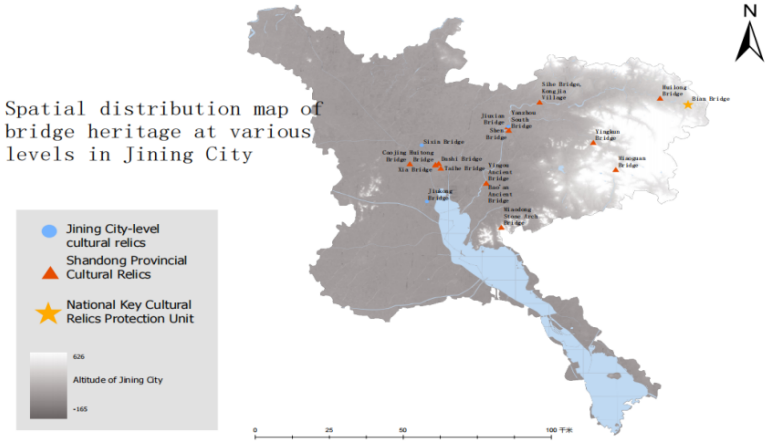


Figure 8. Spatial distribution map of bridge heritage at various levels in Jining City

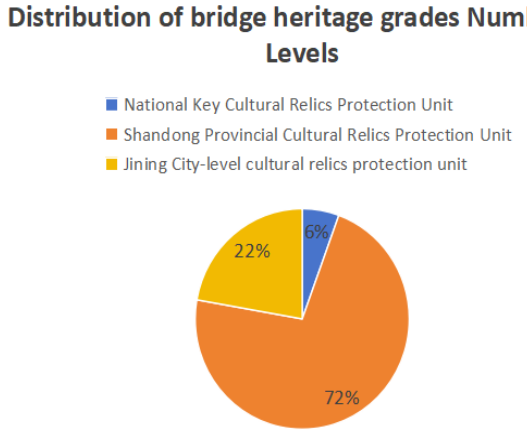
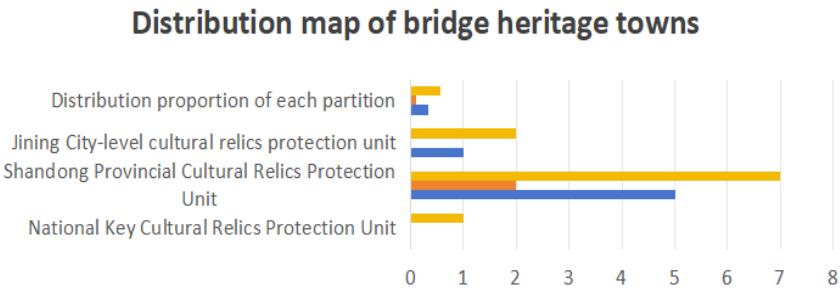


Figure 9. Distribution of bridge heritage grade number of levels



	National Key Cultural Relics Protection Unit	Shandong Provincial Cultural Relics Protection Unit	Jining City-level cultural relics protection unit	Distribution proportion of each partition
Rural Community	1	7	2	56%
Township	0	2	0	11%
Urban Area	0	5	1	33%

Figure 10. Distribution map of bridge heritage towns

5. Findings

This study systematically analyzed the extant bridge heritage in Jining in terms of historical temporal distribution, geographic spatial distribution, riverine system distribution, protection levels, and administrative region distribution, yielding the following conclusions.

5.1. Temporal distribution of bridge heritage

The construction of Jining's extant bridge heritage is primarily concentrated in five historical periods: late Tang, Yuan, Ming, Qing, and the modern era. Bridges built during the Ming and Qing dynasties account for the majority, representing 73% of the total. Analysis using the Standard Deviational Ellipse (SDE) function in ArcGIS Pro shows that, from the Ming dynasty onward, the spatial layout of extant bridges gradually shifted from a core centered in Rencheng District toward the northeast, forming a concentrated distribution zone centered around Qufu and Yanzhou. This shift indirectly reflects the historical transition and relocation of Jining's urban core during the Ming and Qing periods.

5.2. Spatial and riverine distribution of bridge heritage

The extant bridges are predominantly concentrated along the Si River and the Grand Canal, together accounting for 77% of the total. This pattern reflects historically dense populations and frequent waterborne transportation in these areas, which drove the construction of numerous bridges. In terms of administrative regions, bridges are mainly distributed in Rencheng, Qufu, Yanzhou, Sishui, and Zoucheng. Rencheng serves as the core cluster, while Qufu, Yanzhou, and Sishui form secondary clusters, and Zoucheng represents a peripheral area. These spatial patterns underscore the historical importance of these regions as transportation and population centers.

5.3. Protection levels and urban–rural distribution

Among the 18 extant bridges, protection levels are categorized into national, provincial, and municipal tiers. The sole nationally protected bridge—the Bian Bridge in Sishui—accounts for 6% of the total. Provincial-level protected bridges number 13 (72%), while municipal-level protected bridges number four (22%). These high-value

sites, accounting for 78% of the total, highlight the significant cultural and historical value of Jining's bridges and the need for focused preservation and research.

Regarding the urban–rural distribution, 10 bridges (56%) are located in rural areas, six (33%) in urban districts, and two (11%) in townships. The predominance of rural-located bridges, combined with their broad spatial coverage, indicates that bridge heritage not only formed an integral part of historical transportation networks but also served as vital links supporting local residents' daily life and economic activities.

6. Summary

Overall, the study demonstrates that Jining's bridge heritage exhibits clear temporal, spatial, and protection-level patterns. The majority of bridges were constructed during the Ming and Qing dynasties, with their spatial distribution gradually shifting from a core in Rencheng to the northeast. Bridges are mainly concentrated along major waterways and urban centers, and high-value protected sites dominate the heritage landscape. The findings provide a comprehensive understanding of the historical evolution, spatial characteristics, and preservation status of Jining's bridges, offering a solid foundation for future conservation, management, and research initiatives.

7. Current Status and improvement measures for the protection of bridge heritage in Jining

As a cradle of Qilu culture, Jining preserves a number of historic bridges that embody profound socio-cultural value and considerable potential for revitalized use. Yet, despite existing legal frameworks at both national and local levels, many of these sites face severe conservation challenges, highlighting the urgency of systematic scholarly attention.

7.1. Deficiencies in the "four haves" and improvement strategies

Implementation of the "Four Haves"—defined boundaries, explanatory signage, archival records, and dedicated management—remains uneven. Boundaries are often limited to physical delineation without considering the broader historical environment, resulting in conflicts with urban development, such as illegal construction near Qufu's Bao'an Bridge [7]. Explanatory signage is typically superficial, failing to convey historical, structural, or cultural depth; for instance, the Bian Bridge in Sishui provides only basic information despite its national heritage status. Archival documentation is fragmented, with inadequate surveying data and repair records, while unreliable online information further obscures value assessment. Finally, management suffers from blurred responsibilities and insufficient resources [8].

To address these gaps, protection boundaries should be scientifically defined, with intrusive structures removed. Comprehensive interpretive systems, including detailed signage, digital databases, and mobile applications, should be established to ensure authenticity and enhance public education. A specialized heritage task force, integrating professionals, local authorities, and community representatives, is essential for coordinated and responsive management [9–10].

7.2. Challenges in revitalized use and improvement strategies

Current utilization remains confined to static presentation, neglecting integration with waterways, routes, and settlements, thereby weakening cultural interpretation and restricting functions in education, tourism, and

community participation. Given the concentration of bridge heritage in Rencheng, Yanzhou, and Qufu—areas already rich in tourism resources—bridges could be developed as cultural focal points within integrated tourism zones, drawing on models such as Zhaozhou and Xiaoqikong [11]. Cultural and creative industries linked to bridge heritage would further enhance visibility and diversify use. Such initiatives can transform conservation from static display toward dynamic, multifunctional cultural regeneration, simultaneously advancing local economies and resident livelihoods while safeguarding heritage values [12–13].

8. Conclusion

Through ArcGIS Pro–based spatial analysis, this study identifies the temporal distribution, spatial clustering, hydrological context, and protection status of Jining's bridge heritage. The findings reveal both their richness and their embodiment of regional culture, shaped by Confucian and canal traditions. However, deficiencies persist in boundary delineation, archival and signage systems, management mechanisms, and revitalization models. Targeted improvements are therefore proposed to establish a sustainable and systematic conservation framework that integrates preservation with innovative reuse, thereby achieving both cultural continuity and regional development.

Disclosure statement

The author declares no conflict of interest.

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