STUDY OF THE DISTRIBUTION PATTERN AND INFLUENCING FACTORS OF WATER CULTURAL HERITAGE IN SHAANXI SECTION OF CHINA'S YELLOW RIVER BASIN BASED ON MULTISOURCE DATA

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Abstract. Promoting the scientific conservation and transmission of water cultural heritage in China's Yellow River Basin is a practical approach to fostering coordinated development of regional tourism and ecological functions. This study focuses on the Shaanxi section of China's Yellow River Basin. Based on POI data, 606 water-related cultural resources were categorized into four types: cultural heritage sites, village landscapes, tourist attractions, and heritage listings. Through spatial data analysis, geographic detector, and geographically weighted regression (GWR) models, the distribution patterns, dominant influencing factors, and spatial heterogeneity of these resources were systematically revealed. Results indicate that water cultural heritage in this region exhibits a "dual-core, multi-patch, tributary-linked" pattern of aggregation. The dominant distribution axis runs northeast-southwest, closely aligning with the flow direction of the Yellow River tributaries. Natural factors, such as elevation and river network density, establish the initial distribution foundation, while human factors, including population density, tourist visits, and tourism service facilities, shape the aggregation pattern. Spatial heterogeneity stems from the synergistic driving of multiple factors encompassing "natural environment and socio-economic conditions." This study provides a scientific basis for the differentiated zoning protection of water cultural heritage in the region, thereby offering targeted strategies for its sustainable development and protection.
Keywords: *POI data, spatial patterns, ArcGIS, Geodetector, cultural tourism integration*

Introduction

In recent years, China has clearly articulated a strategy of ecological protection and high-quality development in China's Yellow River Basin, emphasizing its role in promoting the deep integration of culture and tourism. It is evident that documents such as the "14th Five-Year Plan for Water Culture Construction," the "Management Measures for Water Conservancy Scenic Areas," and the "Notice of the Ministry of Culture and Tourism on Promoting the Deep Integration and Development of Intangible Cultural Heritage and Tourism" underscore the significance of water culture-related construction (Central People's Government of the People's Republic of China, 2023; Ministry of Water Resources of the People's Republic of China, n. d. a, b). Consequently, multisource data mining and collaboration within the cultural and tourism industry have emerged as a focal point of attention in academic and practical domains. This collaborative endeavor aims to promote the protection, inheritance, and innovative utilization of water culture landscape heritage. Domestically and internationally, scholars have conducted in-depth explorations of water culture-related fields from various perspectives.

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From the perspective of relevant international research, since 1978, as global heritage conservation concepts have evolved, the Convention established by the United Nations Educational, Scientific and Cultural Organization (UNESCO) has progressively incorporated “water cultural heritage” into its conservation framework (Kong and Liu, 2022) France’s 19th-century Public Waters and Canals Act, a legislative instrument designed to protect the Canal du Midi, is widely regarded as a pioneering model for conserving water cultural heritage (Wan and Wang, 2011). Subsequent research has expanded beyond legal frameworks and preservation measures (Alvarado-Ramírez et al., 2025; ICOMOS, 2022) to explore sustainable development strategies (Ritz, 2024; Abbate et al., 2017), modern technological applications (Rubio et al., 2023; Bucci, 2018), and assessment management methodologies (Quintana-Saavedra et al., 2023).

The history of research on water culture in China dates back to the pre-Qin period, while academic studies on “water culture” began in the 1980s. Domestic research on water cultural heritage has primarily focused on conceptual clarification (Tan, 2012), value assessment, interpretation of its contents (Sui et al., 2018), the distribution characteristics of intangible cultural heritage (Nie et al., 2022), and the history and practices of its protection and utilization (Kong and Liu, 2021). In light of these findings, heritage corridors have been designated (Li et al., 2023; Ji et al., 2025), with a focus on regions such as Jiangsu-Zhejiang and Beijing-Hangzhou (Luo et al., 2024; Wang et al., 2022; Chen et al., 2024b; Shang et al., 2023).

To summarize, it can be seen that research on the distribution patterns and influencing factors of material water cultural heritage in China’s Yellow River Basin, particularly landscape-related heritage, has yet to form a complete system both domestically and internationally. Considering the points above, the present study employs a multisource spatial analysis of the Shaanxi section of China’s Yellow River Basin to investigate the distribution patterns and contemporary characteristics of water cultural heritage—the study endeavors to elucidate the underlying influencing mechanisms and spatial heterogeneity of this phenomenon. From the perspective of research significance, this study makes two notable contributions. Firstly, it enriches the theoretical and methodological framework for research on water cultural heritage in the Shaanxi section of China’s Yellow River Basin. Secondly, it aims to serve as a basis for the evaluation and optimization design of other water cultural heritage sites. Conversely, applying pattern analysis fosters the advancement of the artistic and tourism industry in China’s Yellow River Basin, promoting high-quality integrated development.

Overview of the study area and data processing

Overview of the study area

China’s Yellow River Basin, a vital geographical region, is regarded as the second-longest river in China, spanning a total of 5464 km. The river traverses a total of nine provinces and territories, including Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong, culminating in its confluence with the Bohai Sea within the jurisdiction of Shandong. The Basin encompasses an area of 795,000 km^2. The Shaanxi section of the Yellow River originates at Qiangtou Village in Fugu County, Yulin City (the initial bend where the Yellow River enters Shaanxi Province), and subsequently courses southward through Yan’an and Weinan, ultimately converging with the primary stem of the Yellow River at Tongguan County in Weinan City. The total length of the Shaanxi section is 719 km, constituting 13.2% of the Yellow River’s total length. The

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Shaanxi section spans an area of 133,300 km^2, accounting for 65% of the total area of Shaanxi Province.

The present study primarily focuses on the cities and counties along the Yellow River's main course. The cities encompassed by this study include Xi'an, Baoji, Xianyang, Tongchuan, Weinan, Yan'an, Yulin, the entirety of Hancheng, and Luonan County in Shangluo, totaling eight cities (*Fig. 1*). The Loess Plateau borders the region to the west, the Shanxi-Shaanxi Gorge to the east, and the Weihe Plain to the south.

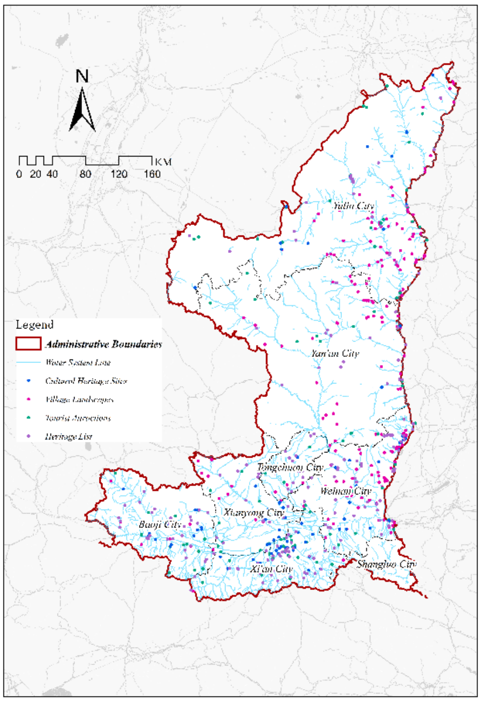

***Figure 1.** Study area and distribution of water cultural heritage sites*

Data sources and processing

Based on heritage-related evaluation criteria (General Administration of Quality Supervision, Inspection and Quarantine, 1999) six initial categories of research subjects were first identified: national and provincial cultural relic protection sites, national and provincial traditional villages, historical and cultural villages, 3A-rated and higher tourist attractions, water conservancy scenic areas, and water cultural heritage sites recognized by the Shaanxi Provincial Department of Water Resources.

Classification preprocessing is then conducted to correct deviations and standardize data, with subjects not meeting recognition tiers or grade standards eliminated. Deduplication screening utilizes unique heritage identifiers. For duplicate records spanning multiple categories, a single affiliation is assigned by prioritizing core attributes to prevent double-counting. Pre-processed categories are merged as follows: (1) national and provincial cultural relic protection units remain standalone; (2) national and provincial traditional villages and historical and cultural villages are merged into the village landscape category; (3) 3A-rated and above tourist attractions and water conservancy scenic areas are merged into the tourist attraction category; and (4) water cultural heritage sites recognized by the Shaanxi Provincial Department of Water

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Resources form a separate heritage listings category. This stepwise merging process ensures each merged category is clearly defined and avoids ambiguity.

Finally, after verification, it was confirmed that all 606 heritage resources were assigned to one of four categories. Errors were corrected, and items were deduplicated to ensure that no omissions or overlaps occurred. The four categories are Cultural Heritage Sites, Village Landscapes, Tourist Attractions, and Heritage Lists (*Table 1*).

The GDE MV3 30 m spatial resolution digital elevation data is sourced from the Geospatial Data Cloud (http://www.gscloud.cn/). Vector data, including rivers and transportation networks, is sourced from OpenStreetMap. The population, GDP, and vegetation indices (NDVI) are derived from the Resource and Environmental Science Data Platform (https://www.resdc.cn/). Vector data, including precipitation, is obtained from the National Earth System Science Data Center (http://www.geodata.cn/). Further economic statistics are derived from the Shaanxi Provincial Statistical Yearbook and Bulletin.

Table 1. *Statistics on water cultural heritage sites in China's Yellow River Basin of Shaanxi Province*

Type	Deadline (batch)	Data source	Quantity/unit
Cultural heritage sites	National Level: October 2019 (Eighth Batch)	Shaanxi Provincial Cultural Heritage Bureau	89
	Provincial Level: July 2018 (Seventh Batch)		
Village landscapes	National Level: March 2023 (Sixth Batch)	Shaanxi Provincial Cultural Heritage Bureau	202
	Provincial Level: August 2022 (Fourth Batch)		
	Historical and Cultural Village: January 2025		
Tourist attractions	3A-rated and above tourist attractions: October 2024	Shaanxi Provincial Department of Culture and Tourism	121
	Water conservancy scenic areas: April 2025	Shaanxi Department of Water Resources	
Heritage list	June 2017	Shaanxi Water Cultural Heritage List	194
Total	—	—	606

Research methods

K-nearest neighbors index

The nearest neighbor index is a conventional method for measuring spatial distribution patterns of point features (clustering, random, or scattered). The fundamental principle of this approach involves comparing the observed mean nearest neighbor distance with the theoretical mean nearest neighbor distance under a random distribution to determine the spatial distribution type (Wu et al., 2023). Specific Steps: (1) Construct a spatial attribute database for 606 water cultural heritage sites using ArcGIS 10.8, including geographic coordinates, categories, and other information, then project to a unified coordinate system; (2) Calculate the Euclidean distance between each heritage site and its nearest neighbor,

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and determine the actual average nearest neighbor distance; (3) Combine this with the total area of the study region to calculate the theoretical average nearest neighbor distance under random distribution; (4) Derive the Nearest Neighbor Index (NNI) by comparing the two values to determine the distribution pattern. The calculation formula is as follows:

$$NNI = \frac{d_{\text{obs}}}{d_{\text{exp}}} \quad \text{(Eq.1)}$$

In the formula: Actual average distance $d_{obs} = \frac{1}{n}\sum_{i=1}^{n} \min_{j \neq i} d(x_i, x_j)$, n denotes the total number of spatial features within the area; $d(x_i, y_j)$ represents the Euclidean distance between the i-th feature and the j-th feature; Theoretical average distance $d_{\text{exp}} = \frac{1}{2\sqrt{\frac{n}{A}}} = \frac{\sqrt{A}}{2\sqrt{n}}$, A denotes the total area of the study region. When *NNI = 1*, it indicates a random distribution of spatial features; when *NNI < 1*, it indicates a clustered distribution; when *NNI > 1*, it indicates a dispersed distribution.

Kernel density analysis

Kernel density analysis has been demonstrated to reflect spatial elements' clustering characteristics and hotspot distribution, thereby revealing their spatial concentration through varying density values (Wu et al., 2023). Specific steps: (1) Using water cultural heritage sites as input data with a Gaussian kernel function; (2) Determining the optimal search radius as 10 km through cross-validation; (3) Calculating density values using the Kernel Density tool in ArcGIS 10.8 to generate a kernel density distribution map; (4) Classifying density values into six levels using the natural breakpoint method to identify hotspot areas. The present study employs this method to investigate the spatial distribution patterns and clustering intensity of water cultural heritage sites in China's Yellow River Basin, specifically in Shaanxi Province. The calculation formula is as follows:

$$\mathrm{f_n}(\mathrm{X}) = \frac{1}{\mathrm{nh}}\sum_{\mathrm{i}=1}^{\mathrm{n}} K\left[\frac{\mathrm{x} - X_{\mathrm{i}}}{\mathrm{h}}\right] \quad \text{(Eq.2)}$$

In the formula: $\mathrm{f_n}(\mathrm{X})$ represents the kernel density estimate, where a higher value indicates greater concentration of elements in that area; k denotes the kernel function; n signifies the total number of elements within the study area; h represents the bandwidth, which is the spatial search radius used when calculating density; $x - X_i$ indicates the distance from element point x to the i-th element point.

Standard deviation ellipse

The standard deviation ellipse is a mathematical tool that can describe the central position of point data spatial distribution. The construction of ellipse parameters is instrumental in unveiling the "core distribution area" and "directional characteristics" of data in space (Gan and Wang, 2021). Specific steps: (1) Input water cultural heritage site

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data and standardize the coordinate system; (2) Calculate parameters, including the center coordinates, major axis, minor axis, and rotation angle of the ellipse; (3) Determine the directionality of distribution based on the ratio of the major axis to the minor axis. The calculation formula is as follows:

$$\frac{\left[\left(x-\bar{x}\right)\cos\theta+\left(y-\bar{y}\right)\sin\theta\right]^2}{\left(k\lambda_1\right)^2}+\frac{\left[-\left(x-\bar{x}\right)\sin\theta+\left(y-\bar{y}\right)\cos\theta\right]^2}{\left(k\lambda_2\right)^2}=1 \quad \text{(Eq.3)}$$

In the formula, the data distribution's geometric center is represented by the ellipse center $\left(\bar{x}, \bar{y}\right)$. It can be demonstrated that the larger the semi-major axis length $\left(\lambda_1, \lambda\right)$, the more dispersed the data distribution is in the corresponding direction, and vice versa. In the event of $\theta \approx 0°$ or $90°$, this indicates the data exhibiting a horizontal or vertical distribution. If θ is any other angle, it indicates that the data distribution in the corresponding direction is more dispersed, and vice versa.

Geodetector

The geographic detector is utilized to quantify the explanatory power of spatial differentiation between independent and dependent variables. The present study employs the geographic detector, with the kernel density values of water cultural heritage sites in China's Yellow River Basin of Shaanxi Province designated as the target variable, to rank the importance of factors influencing spatial distribution characteristics (Wang and Xu, 2017). Specific steps: (1) Use the core density value of water cultural heritage as the dependent variable, with spatial distribution characteristics as independent variables; (2) Classify all independent variables using the natural breakpoint method; (3) Construct a vector fishing net to divide grid units; (4) Calculate the explanatory power q-value and significance p-value for each factor, then rank them by q-value. The calculation formula is as follows:

$$q=1-\frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} \quad \text{(Eq.4)}$$

Within the formula, the variable 'q' denotes the coefficient of explanatory power of factors, with a value range of [0, 1]. A higher value indicates a stronger explanatory power of this indicator for the spatial differentiation of water cultural heritage. L denotes the number of categories of influencing factors. The acronyms N_h and N represent the density value unit count of the h-th category of influencing factors and water cultural heritage, respectively. The acronyms σ_h^2 and σ^2 denote the variance of the h-th category of influencing factors and the density value of water cultural heritage, respectively.

Geogewichted regression analysis

Geographically weighted regression analysis embeds the effect parameters of different factors into distinct grid cells, facilitating local estimation (Brunsdon et al., 1998). Specific steps: (1) Test whether independent variables affect each other, remove those with high overlap (VIF > 7.5), and keep main factors; (2) Use the center points of grid areas as sample locations and link each location's main value with other factors;

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(3) Use flexible statistical methods and choose the best settings based on how well the model fits the data (AICc criterion); (4) Construct a GWR model to obtain the local regression coefficients for each factor, plot the spatial distribution map of these coefficients, and explain the spatial heterogeneity in the distribution of water cultural heritage sites along China's Yellow River Basin in Shaanxi Province. The calculation formula is as follows:

$$y_i = \beta_0(v_i,u_i) + \sum_{k=1}^{p} \beta_k(u_i,v_i)x_{ik} + \varepsilon_i \quad \text{(Eq.5)}$$

The dependent variable, y_i, represents the observed value at sample point i in the aforementioned equation. The independent variable, x_{ik}, denotes the k-th independent variable at sample point i (with a total of p independent variables). The third variable is labelled (v_i,u_i) and denotes the spatial coordinates of sample point i. The fourth variable, labelled $\beta_0(u_i,v_i)$, represents the local intercept at sample point i, reflecting the baseline value at that location that is not explained by the independent variables. The fifth variable is labelled $\beta_k(u_i,v_i)$ and indicates the local regression coefficient of the kth independent variable at sample point i, measuring the strength of influence of that variable on the dependent variable near point i. ε_i is the error term.

Spatial distribution patterns and characteristics of water cultural heritage in China's Yellow River Basin of Shaanxi Province

Spatial agglomeration analysis

The ArcGIS 10.8 technology platform facilitated the construction of a spatial attribute database for the 606 water cultural heritage sites in China's Yellow River Basin of Shaanxi Province, concomitant with the generation of their spatial distribution map (*Fig. 1*). Concurrently, the average nearest neighbor distance between each cultural heritage site was simultaneously calculated. The spatial distribution type of water cultural heritage was determined based on the nearest neighbor index derived from *Equation 1* (*Table 2*).

Table 2. *Nearest neighbor index for water cultural heritage in the Shaanxi Section of China's Yellow River Basin*

Region	Average observation distance	Expected average distance	Nearest neighbor index	Z-score	Distribution type
Overall	10059.58	24400.91	0.412	-27.679	Significant aggregation
Cultural heritage sites	14781.38	23790.35	0.621	-6.834	Mild aggregation
Village landscapes	24320.47	42220.93	0.576	-11.528	Moderate aggregation
Tourist attractions	13488.25	21087.20	0.640	-7.583	Mild aggregation
Heritage list	9560.99	16340.81	0.585	-11.055	Moderate aggregation

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From the perspective of spatial distribution characteristics, Shaanxi Province’s water cultural heritage exhibits a pronounced clustering pattern overall. The NNI index for this period is 0.412, with an absolute z-score value exceeding 1.96 at a significant level. This indicates the profound dependence of water cultural heritage on aquatic environments, including river systems and water conservancy facilities. Within the remaining four categories, $0.4 \leq R \leq 0.6$ is designated as moderate clustering, and $R > 0.6$ is classified as light clustering, to streamline subsequent analysis. The cultural heritage of water in Shaanxi Province exhibits a spatially clustered distribution pattern, both in its totality and across individual categories.

Spatial distribution direction

Equation 3 was applied to compute the standard deviation ellipses for both the overall and categorical water cultural heritage in Shaanxi Province. The results with references to *Figure 2* and *Table 3*. The y-axis length is considerably greater than the x-axis, suggesting that the dispersion of water cultural heritage is significantly higher in the north-south direction than in the east-west direction. This distribution indicates its characteristic geographical distribution along the north-south depth of the Yellow River tributaries. The centers of the ellipses for the overall resources and the various resource categories are located in the central part of the study area. Village landscape resources are located in a more northerly position, particularly in Yan’an City, than other categories. All other resources demonstrate a compact north-south orientation and a distinct northeast-southwest extension. This alignment is near the direction of China’s Yellow River Basin and administrative boundaries.

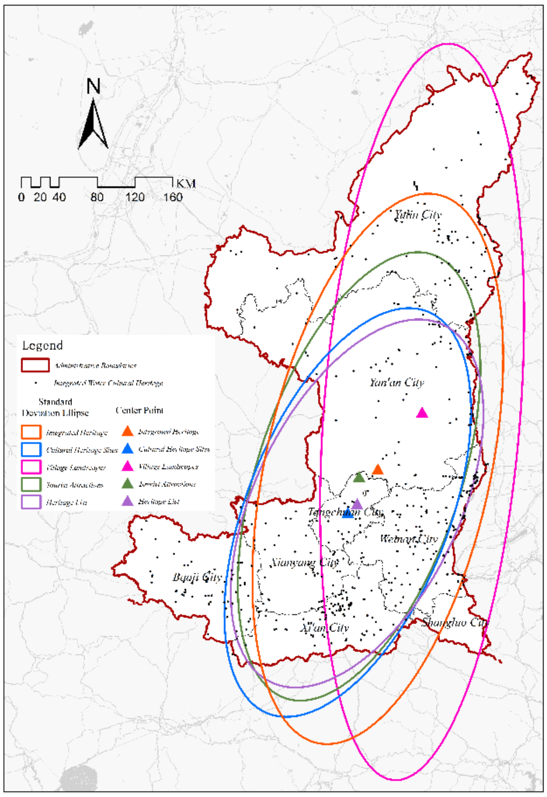

Figure 2. *Distribution of standard deviation ellipses and center points for various types of water cultural heritage in the Shaanxi Section of China’s Yellow River Basin*

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Table 3. *Standard deviation ellipse parameters for water cultural heritage in the Shaanxi Section of China's Yellow River Basin*

Type	Length/KM		Angle/°	Center coordinates	
	X-axis	Y-axis		Longitude	Latitude
Overall	118.91	296.64	12.44	109°20′58″	35°36′33″
Cultural heritage sites	106.83	228.45	21.68	109°1′02″	35°11′54″
Village landscapes	103.83	390.27	4.39	109°51′31″	36°9′27″
Tourist attractions	107.54	246.96	18.28	109°8′30″	35°32′48″
Heritage list	108.04	209.64	25.86	109°7′25″	35°17′02″

Spatial distribution patterns

Using the kernel density analysis tool from *Equation 2*, a visualization analysis was conducted on the water cultural heritage sites in China's Yellow River Basin of Shaanxi Province. This yielded a spatial distribution density map of water cultural heritage sites in China's Yellow River Basin of Shaanxi Province (*Fig. 3*). The map indicates that the core water cultural resources are predominantly concentrated around Xi'an City and along the banks of Weinan City, forming two high-value core zones. These zones radiate to secondary patches in Baoji, Xianyang, and eastern Yulin, presenting a "dual-core, multi-patch, tributary-linked" pattern. From a spatial perspective, the zones of high value extend in a strip-like pattern along the main stem of the Wei River. This is indicative of the spatial linkage role of the Yellow River tributaries in the context of water cultural heritage. The core areas exhibit the highest density values, attributable to dense water networks and frequent human activities. Conversely, central Yan'an and western Yulin exhibit constraints imposed by natural hydrological disadvantages and underdeveloped water cultural heritage foundations, ultimately contributing to the persistent low-density distribution observed in the figure.

The concentration of cultural heritage sites along the Wei River, as national-level water cultural heritage exhibits a single-center spatial structure dominated by Guanzhong. Village landscapes demonstrate greater spatial continuity than other categories, with high-value areas closely following the main Yellow River channel and Wei River tributary valleys in a linear extension, forming a north-south continuous cluster belt from Yulin to Weinan. The tourist attractions exhibit a concentric decline from Xi'an toward Baoji and Weinan, with only scattered low values in Yulin and Yan'an. Heritage-listed sites form a secondary high-value zone along the Wuding River's hydraulic engineering remains, aligning with the northeast-southwest orientation of the standard deviation ellipse. Except for village landscapes, the clustering characteristics of all other categories demonstrate significantly higher values in core areas than in peripheral zones. This finding is indicative of market-driven resource concentration and development.

Development of an indicator system for influencing factors

The distribution and formation process of water cultural heritage results from the combined effects of multiple factors. Considering the distinctive attributes inherent to the research subject (Kong and Liu, 2022; Chen et al., 2024a; Tian et al., 2023; Nie and Zhang, 2025; Li et al., 2021; Zhang et al., 2022; Xue and Gao, 2022), this study

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amalgamates data acquisition with extant research to ascertain the driving factors that influence the spatial distribution of water cultural heritage resources. The kernel density of water cultural heritage in the Shaanxi section of China's Yellow River Basin was selected as the study object. The research identified four primary environmental factors: natural ecological foundation, socioeconomic drivers, cultural tourism development, and resource endowment. From these, 14 secondary factor indicators were selected as independent variables for the study: elevation, slope, vegetation coverage (NDVI), annual precipitation, river network density, population density, GDP per capita, disposable income per capita, transportation accessibility, total tourism revenue, tourist visits, accommodation service core density, catering service core density, and shopping service core density (*Table 4*).

Table 4. *Indicator system and grading criteria for factors influencing the spatial distribution of water cultural heritage in China's Yellow River Basin of Shaanxi Province*

Primary environmental indicators	Secondary factor indicators/unit	Data source	Cut-off time	Classification criteria
Natural Ecological Foundation	Elevation/m (x_1)	GDE MV3 30 m DEM Data	2025	1: <725 m, 2: 725-1094 m, 3: 1094-1376 m, 4: 1376-1839 m, 5: >1839 m
	Slope gradient/° (x_2)	Quadratic Surface Fitting of DEM Data	2025	1: <7°, 2: 7°-14°, 3: 14°-21°, 4: 21°-31°, 5: >31°
	Vegetation coverage/% (x_3) $\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}}$ (Wang et al., 2013)	Resource and Environmental Science Data Platform	2024	1: <0.4, 2: 0.4-0.6, 3: 0.6-0.7, 4: 0.7-0.8, 5: >0.8
	Annual precipitation/mm (x_4)	National Earth System Science Data Center	2014-2023	1: <400 mm, 2: 400-550 mm, 3: 550-600 mm, 4: 600-700 mm, 5: >700 mm
	River network density/km/km² (x_5)	National Earth System Science Data Center 1 km Grid Data	—	1: <0.0001, 2: 0.0001-0.0002, 3: 0.0002-0.0008, 4: 0.0008-0.0009, 5: >0.001
Socioeconomic Drivers	Population density/persons per km² (x_6)	Seventh National Population Census	2020	1: <85, 2: 85-120, 3: 120-180, 4: 181-485, 5: >485
	GDP per capita/yuan per capita (x_7)	Statistical Bulletins of Municipalities under the Shaanxi Provincial People's Government	2014-2023	1: <30000, 2: 30000-50000, 3: 50000-80000, 4: 80000-120000, 5: >120000
	Disposable income per capita/yuan per capita (x_8)	Statistical Bulletins of Municipalities under the Shaanxi Provincial People's Government	2014-2023	1: <20000, 2: 20000-30000, 3: 30000-40000, 4: 40000-60000, 5: >60000

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	Transportation accessibility/km/h (x_9)	Statistical Bulletins of Municipalities under the Shaanxi Provincial People's Government	2020	1: <3, 2: 3-4, 3: 4-5, 4: 5-6, 5: >6
Cultural Tourism Development	Total tourism revenue/100 million yuan (x_{10})	Statistical Bulletins of Municipalities under the Shaanxi Provincial People's Government	2014-2023	1: <50, 2: 50-100, 3: 100-200, 4: 200-500, 5: >500
	Tourist visits/10,000 person-times (x_{11})	Statistical Bulletins of Municipalities under the Shaanxi Provincial People's Government	2014-2023	1: <100, 2: 100-300, 3: 300-500, 4: 500-1000, 5: >1000
Resource Endowment	Accommodation service density/units per km² (x_{12})	Amap POI Data	2024	1: <0.07, 2: 0.07-0.2, 3: 0.21-0.44, 4: 0.45-0.72, 5: 0.73-1.0 6: >1.0
	Food service density/units per km² (x_{13})	Amap POI Data	2024	1: <0.7, 2: 0.7-2.0, 3: 2.0-4.0, 4: 4.0-7.0, 5: 7.0-9.0 6.>9.0
	Shopping service density/units per km² (x_{14})	Amap POI Data	2024	1: <0.01, 2: 0.01-0.02, 3: 0.02-0.04, 4: 0.04-0.07, 5: 0.07-0.1 6: >0.1

Analysis of the mechanisms by which factors across various dimensions influence water cultural heritage

Natural ecological base

Elevation and slope

The natural environment serves as the foundational factor for the distribution of water cultural heritage. After importing DEM data into GIS for elevation and slope analysis (*Fig. 4a, b*), it is evident that in the Guanzhong region, water cultural heritage is concentrated in areas between 300-500 m elevation with slopes <5°. This terrain is flat and abundant in water resources, making it suitable for large-scale human water management activities. In the south, constrained by topography, water cultural heritage is scattered across the river valley lowlands. In the northern Loess Plateau region, heritage sites are distributed along the terraces of the Yellow River's main stem and tributaries. Overall, there is a pattern of "scattered distribution in the north and south, concentrated in the center."

Simultaneously, regional conditions directly determine the state of water cultural heritage. In hilly areas like northern Yan'an, rugged terrain limits the construction of large-scale water conservancy facilities and human settlement, resulting in only one-third as many water cultural heritage sites as in the Guanzhong Plain. In water-scarce regions like western Yulin, where annual precipitation is low and river network density is <0.0001 km/km², sites exist primarily in scattered, isolated states. By contrast, the

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Guanzhong region, with abundant water resources and flat terrain, hosts a concentrated abundance of sites. This phenomenon validates the principle that “geographical conditions determine the distribution areas of water cultural heritage.”

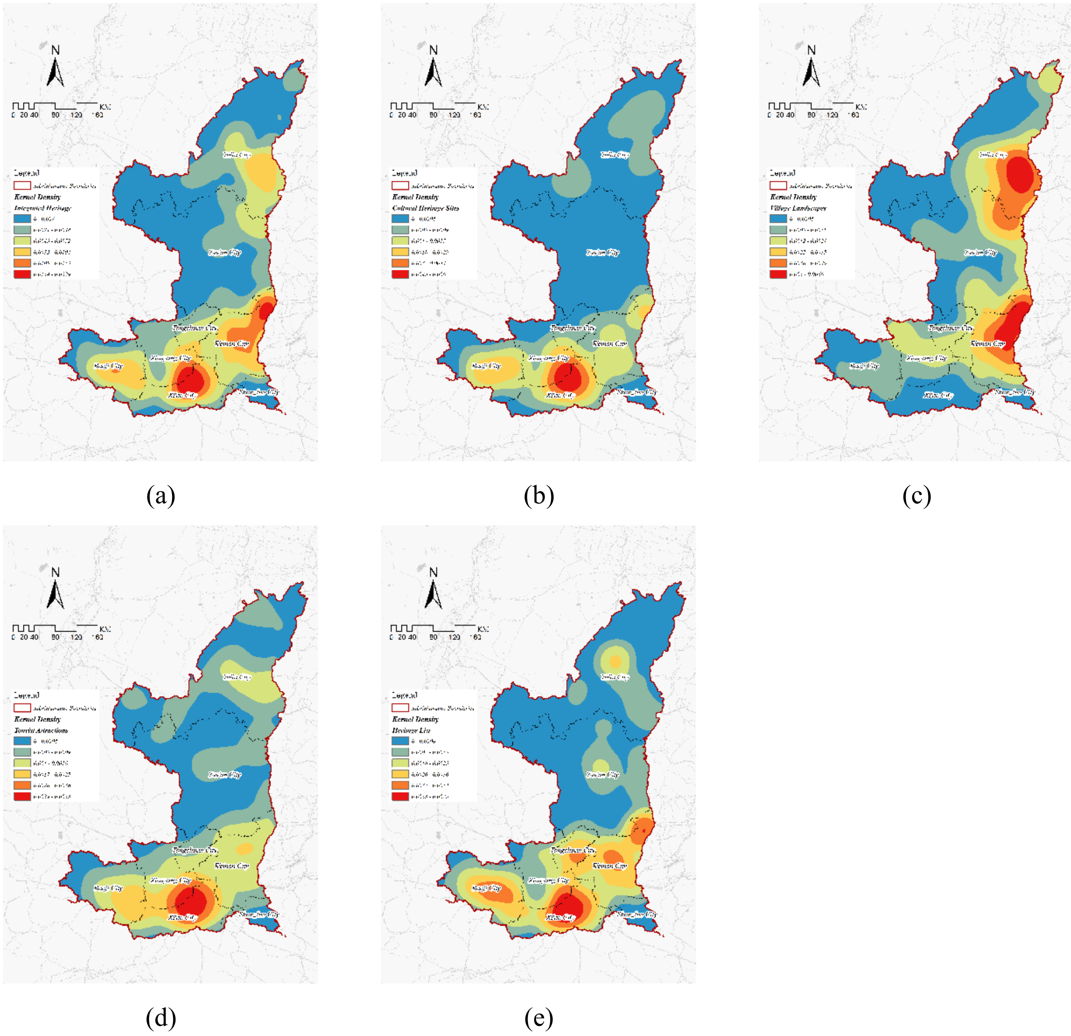

Figure 3. *Kernel density map of water cultural heritage in the Shaanxi Section of China’s Yellow River Basin: (a) integrated water cultural heritage; (b) cultural heritage sites; (c) village landscapes; (d) tourist attractions; (e) heritage list*

Distance from water systems

Although the association between water cultural heritage and water systems is intuitively recognized, existing studies largely lack quantitative empirical evidence on the “distance-presence” relationship and have not clarified the differential response patterns of different heritage types to water system distances (Yuan et al., 2023). To precisely reveal this core correlation, this study constructed multi-ring buffer zones with a 3 km radius (*Fig. 4c, d*) (Sun et al., 2024) using river networks at various levels within the watershed as reference objects. GIS technology was employed to statistically analyze the distribution of water cultural heritage sites within these buffer zones. The results indicate that 507 water cultural heritage sites are distributed within the 3 km buffer zone, accounting for 83.7% of the total,

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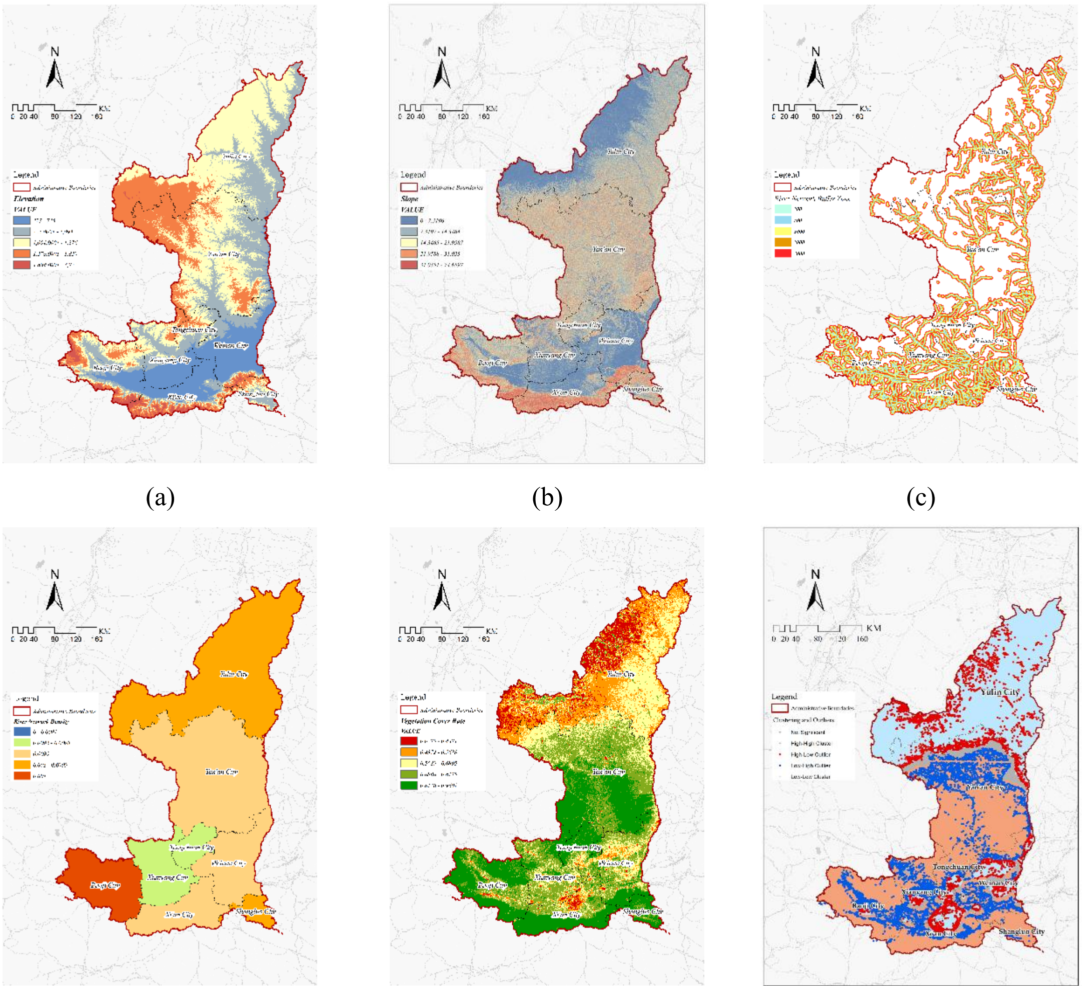
and exhibiting a pronounced distance gradient pattern. The 500 m buffer zone serves as the core zone. with heritage density gradually decreasing as the distance from water systems increases (*Table 5*). By category: Village landscapes were densest near water, exhibiting a relatively gradual decline due to water collection, flood control, and tributary channel support. Tourist attractions, which require direct water-viewing experiences, were highly concentrated within a 500 m radius, with numbers sharply decreasing beyond 2000 m. Heritage listings, encompassing diverse types and influenced by composite water systems, showed a relatively balanced distribution within 2000 m but declined beyond 3000 m due to insufficient support from single rivers. Thus, the distance from water systems influences the range and distribution patterns of different functional types of heritage through a three-tiered gradient: core influence, extended influence, and weak influence.



(a) (b) (c)

(d) (e) (f)

Figure 4. *Schematic diagram of partial influence factors: (a) elevation; (b) slope; (c) river buffer zone; (d) river network density; (e) vegetation cover; (f) NDVI Moran's index*

NDVI vegetation coverage

Areas with high vegetation coverage serve as vital repositories for water cultural heritage due to their robust ecological foundations, and these regions also provide

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essential prerequisites for developing heritage tourism destinations. Analysis of Shaanxi Province's vegetation coverage over the decade from 2015 to 2024 (*Fig. 4e, f*) reveals that water cultural heritage sites primarily remain stable in areas with high vegetation coverage in Guanzhong and southern Shaanxi. A global Moran's I test was conducted on the spatial autocorrelation of vegetation cover, yielding a Moran's I index of 0.786. This result passed the significance level test ($p < 0.01$), indicating a coupling characteristic between water cultural heritage sites and areas of high vegetation cover. The two exhibit a significant spatial clustering pattern.

Table 5. *Statistical analysis of the spatial distribution of water systems in the water cultural heritage of China's Yellow River Basin, Shaanxi Province*

Distance/ category	Cultural heritage sites	Village landscapes	Tourist attractions	Heritage list	Total (number)	Percentage (%)
500 m	26	51	39	51	167	27.56
1000 m	24	44	36	51	155	25.58
2000 m	20	41	22	54	137	22.61
3000 m	10	19	7	12	48	7.92
Total (number)	80	155	104	168	507	83.7

Precipitation

A detailed analysis of Shaanxi Province's average annual precipitation over the past decade (*Fig. 4g*) reveals a correlation between the distribution of water cultural heritage sites and precipitation levels. Precipitation patterns are characterized by higher amounts in the south and lower amounts in the north. Water cultural heritage sites are relatively concentrated in the central and southern regions, reflecting that areas with abundant rainfall are more conducive to water-related activities, thereby preserving a greater number of water cultural heritage sites. By overlaying point distribution maps in GIS, we obtained the distribution quantities and proportions of heritage sites across different precipitation levels (*Table 6*). In the central regions, such as Yan'an and Xianyang, where precipitation falls within the moderate range, water cultural heritage sites are also distributed. This finding suggests that heritage preservation is not confined to regions with extreme precipitation. Regions with moderate rainfall that possess topographical and resource advantages are equally conducive to human activities, facilitating the accumulation of water cultural heritage.

Socioeconomic drivers

Population density

The overlaying of the population density map (*Fig. 4h*) with water cultural heritage sites reveals that the central region, particularly Xi'an City, exhibits the highest population density. As a longstanding political, economic, and artistic hub, Xi'an has undergone extensive water resource development, resulting in a high concentration of water cultural heritage. Conversely, northern areas such as Yulin City and Yan'an City, which are distinguished by sparse populations, exhibit comparatively weaker social foundations for preserving and transmitting water cultural traditions.

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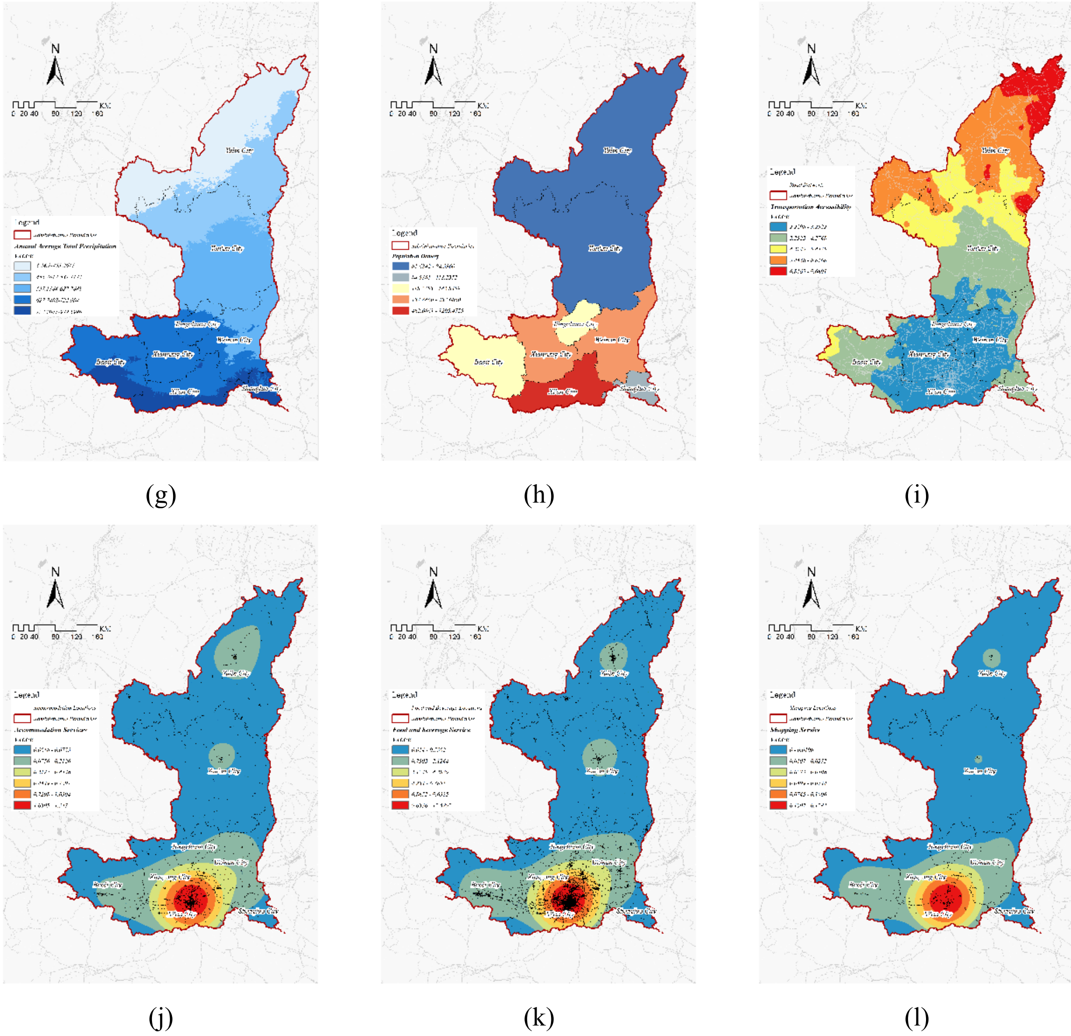

Figure 4. *Schematic diagram of partial influence factors: (g) annual total precipitation; (h) population density; (i) transportation accessibility; (j) accommodation services; (k) food and beverage services; (l) shopping services*

Table 6. *Statistics on spatial distribution of precipitation for water cultural heritage in China's Yellow River Basin, Shaanxi Province*

Precipitation level/category	Cultural heritage sites	Village landscapes	Tourist attractions	Heritage list	Total (number)	Percentage (%)
Level 1: <400 mm	8	15	6	11	40	6.7
Level 2: 400-550 mm	23	45	28	45	141	23.3
Level 3: 550-600 mm	33	82	49	78	242	39.9
Level 4: 600-700 mm	16	42	28	43	129	21.3
Level 5: >700 mm	7	18	10	19	54	8.9
Total (number)	87	202	121	196	606	100.0

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Transportation accessibility

The accessibility data about transportation, when analyzed in conjunction with the spatial distribution data (*Fig. 4i*), evince a discernible gradation in the overall spatial pattern. In the context of contemporary cultural tourism development, sites with superior transportation links are rendered more accessible to visitors, thereby yielding a more pronounced tourism benefit. For instance, the Hancheng Lake Site in Xi'an has attracted a significant number of tourists, prompting the relevant authorities to intensify their efforts in preserving and developing the site. The infrastructure has been constructed, and various exhibition methods are employed to showcase its historical evolution and water cultural significance. Conversely, in less accessible areas of northern Shaanxi, specific water cultural heritage sites have long endured minimal external interference, preserving their original character. For instance, once a defensive settlement, Yulin City's Wubao Stone City features rustic architectural styles. It retains numerous Ming and Qing dynasty structures and facilities, including cave dwellings, temples, and rainwater collection systems.

Per capita GDP and per capita disposable income

The average per capita GDP and per capita disposable income over the past decade reflect, to a certain extent, a region's economic development level and the affluence of its residents. Consequently, improved living standards positively correlate with increased demand for cultural activities. Yulin City and Xi'an City have high per capita GDP, meaning the average income per person is substantial. This points to strong regional economies, which support tourism and the preservation of cultural heritage, including water resources. As a result, resources focus on restoring heritage sites, building facilities, and enhancing the visibility and use of cultural heritage. In contrast, some areas in northern Shaanxi have several water cultural heritage sites, but limited GDP allocation and residents' low purchasing power leave most sites unchanged. Development remains low, and sites are scattered throughout the area. This shows regions with heritage sites attract people and economic activity due to natural or historical advantages, which helps heritage development.

Cultural tourism development

Regions with a high volume of tourism revenue and visitor numbers have the capacity for governments and businesses to develop supporting water cultural tourism infrastructure, thereby rendering water cultural heritage "accessible, tangible, and experiential." The reinvestment of tourism revenue in facility improvements can create a mutually reinforcing cycle of supply and demand. Conversely, economically weaker regions with limited consumer spending power often lack sufficient funds to protect and develop their cultural heritage related to water. Such sites may gradually deteriorate due to a lack of maintenance, struggle to unlock their value through tourism, and remain scattered and obscure, trapped in a vicious cycle of "difficult preservation—weak development—few visitors." Therefore, it can be demonstrated that the core function of tourism-related factors is to activate the utilization value of existing heritage.

Resource endowment

A tripartite categorization of service facilities encompassed the domains of accommodation, catering, and shopping. Concerning the selection of shopping services, both shopping malls and specialty commercial streets were included in the study. Core-density distribution maps were created to reflect the intensity of clustering of regional tourism service facilities (*Fig. 4j, k, l*). Taking the heritage clusters around Xi'an as an example, their initial locations possess tourism appeal due to the natural geographical advantages of the Weihe River Plain. The dense surrounding accommodation and catering services endow water cultural heritage with new functions, transforming the heritage from its original dispersed, primitive, and implicit state into a concentrated, perceptible, and explicit distribution cluster. This ultimately forms a core aggregation belt of this density, serving as the central pillar of the "dual-core" pattern. Evidently, service-related factors significantly influence the degree of cluster manifestation in water cultural heritage, playing a pivotal role in both development and conservation.

Impact factor significance detection

To identify the primary factors affecting the spatial clustering patterns of aquatic cultural heritage, this study employed a 3 km × 3 km grid scale for the Geodetector analysis, as outlined in *Equation 4*. At this scale, spatial aggregation characteristics and differentiation patterns of resource points were most pronounced. The scale also ensured that there were sufficient sample grid points. Consequently, a vector fishing net was constructed to divide the area into 14,783 grid units and detect spatial differentiation of resource points. The optimal influencing factors were ultimately determined by maximizing the explanatory power of independent variables (q-value).

Spatial factor detection

Implementing spatial factor detection in geographic detectors yielded the desired results (*Table 7*). According to extant research (Zhou et al., 2021), factors exhibiting q values greater than 0.5 were identified as dominant influencing factors. The q-values of the elevation, catering, and shopping services are 0.536, 0.532, and 0.535, respectively. These values indicate that these factors dominate the overall distribution of water cultural heritage in the Shaanxi section of China's Yellow River Basin. This finding suggests that natural conditions and the infrastructure for tourism services have a significant impact on the distribution of resources within a region. Additionally, economic and consumption scenarios are closely tied to the characteristics of resources in specific locations. Following a comprehensive review of the extant literature, several factors were identified as moderately influential, with q-values ranging from [0.141,0.499]. These factors, considered important in explaining the phenomenon under investigation, were annual precipitation, population density, per capita GDP, per capita disposable income, transportation accessibility, total tourism revenue, tourist visits, accommodation services, and river network density. Slope and vegetation coverage exhibited significantly lower q-values of 0.033 and 0.053, respectively, than other factors, indicating their relatively weak influence. It is evident that natural factors play a pivotal role in determining the existence of water cultural heritage. Service factors, through their agglomeration and intensification effects, transform water cultural heritage from a dispersed to a concentrated form, thereby influencing the distribution patterns of its form. Together, these two elements constitute the core drivers of its distribution.

A detailed examination of the data reveals that the dominant factors vary significantly across different scenarios. In cultural heritage sites and tourist attractions, accommodation services (q = 0.747/q = 0.800), catering services (q = 0.803/q = 0.820),

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and shopping services (q = 0.822/q = 0.829) exhibit exceptionally high q-values. This finding suggests that the concentration of tourism service facilities directly influences the distribution of cultural heritage sites and tourist attractions. High-quality supporting services have been demonstrated to underpin developing and preserving cultural heritage resources. For village landscapes, all factor q-values were found to be relatively low. This finding indicates that any single factor does not drive spatial differentiation in village landscapes but results from the synergistic effects of natural and cultural factors. The primary factors influencing heritage listings were as follows: population density (q = 0.566), tourist visits (q = 0.527), accommodation services (q = 0.585), catering services (q = 0.637), and shopping services (q = 0.635). The accessibility of transportation and the quality of service facilities have been demonstrated to significantly impact the propensity of visitors to travel, thereby optimizing their tourism experience. This finding indicates that heritage listings are contingent on population and economic foundations, driven by tourism resource endowments.

Table 7. *Spatial Detection Results of Factors Influencing the Distribution of Water Cultural Heritage in the Shaanxi Section of the Yellow River Basin*

Factor indicators	Overall distribution		Cultural heritage sites		Village landscapes		Tourist attractions		Heritage list	
	q	**p**	**q**	**p**	**q**	**p**	**q**	**p**	**q**	**p**
Elevation (x_1)	**0.536**	0	0.448	0	0.219	0	0.492	0	0.442	0
Slope gradient (x_2)	0.033	0	0.050	0	0.004	0	0.048	0	0.029	0
Vegetation coverage (x_3)	0.053	0	0.012	0	0.127	0	0.024	0	0.049	0
Annual precipitation (x_4)	0.226	0	0.339	0	0.201	0	0.316	0	0.419	0
River network density (x_5)	0.141	0	0.273	0	0.061	0	0.355	0	0.256	0
Population density (x_6)	0.385	0	0.428	0	0.150	0	0.483	0	**0.566**	0
GDP per capita (x_7)	0.245	0	0.152	0	0.249	0	0.122	0	0.326	0
Disposable income per capita (x_8)	0.319	0	0.248	0	0.243	0	0.338	0	0.372	0
Transportation accessibility (x_9)	0.253	0	0.283	0	0.011	0	0.368	0	0.431	0
Total tourism revenue (x_{10})	0.298	0	0.312	0	0.084	0	0.362	0	0.463	0
Tourist visits (x_{11})	0.292	0	0.259	0	0.081	0	0.297	0	**0.527**	0
Accommodation service density (x_{12})	0.499	0	**0.747**	0	0.036	0	**0.800**	0	**0.585**	0
Food service density (x_{13})	**0.532**	0	**0.803**	0	0.030	0	**0.820**	0	**0.637**	0
Retail service density (x_{14})	**0.535**	0	**0.822**	0	0.028	0	**0.829**	0	**0.635**	0

Bolded numbers indicate dominant factors with q-values greater than 0.5

Interaction factor analysis

Employing the interaction detection method in geographic detectors yielded the results of factor interaction detection (*Fig. 5*). In conclusion, the interaction between the 14 influencing indicators demonstrated dual-factor enhancement and nonlinear enhancement. This finding suggests that the explanatory power of two-factor interactions in explaining the spatial differentiation of water cultural heritage is stronger than that of single-factor explanations. In other words, the influence of each factor on the spatial differentiation of water cultural heritage is intrinsically interconnected, rather than operating in isolation.

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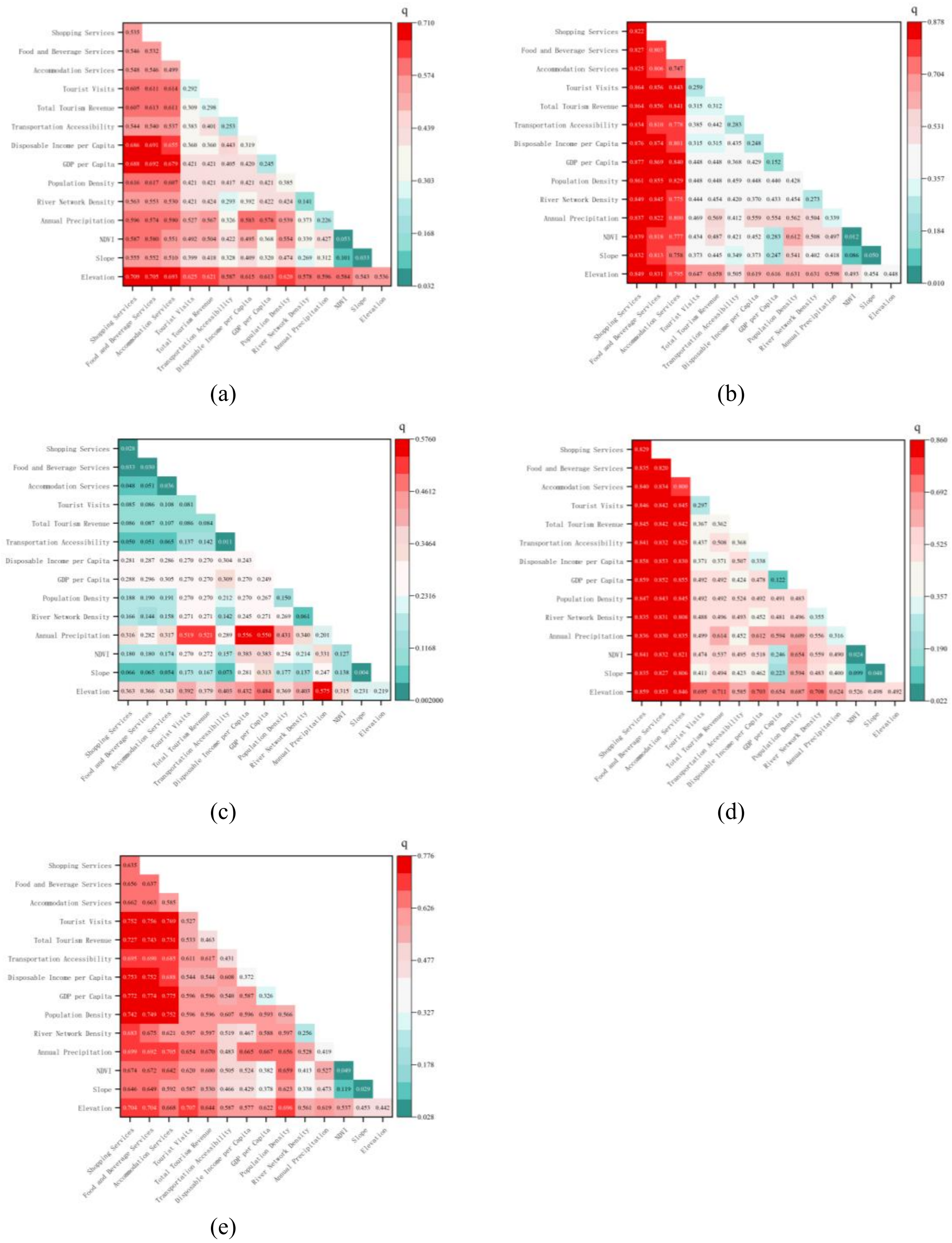

***Figure 5.** Interactive detection results of influencing factors for the overall distribution of water cultural heritage in the Shaanxi Section of China's Yellow River Basin: (a) integrated water cultural heritage; (b) cultural heritage sites; (c) village landscapes; (d) tourist attractions; (e) heritage list*

Specifically, synergistic effects emerge between natural foundations and tourism services for the overall water cultural heritage. Elevation, slope, annual precipitation, and shopping/dining/lodging services exhibit q-values predominantly between 0.5 and 0.7. This indicates that natural topography determines the primary distribution pattern of

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heritage sites, while the clustering of service facilities further enhances the appeal of high-quality heritage areas. The interaction between per capita GDP, disposable income, and shopping/dining services (q-values of 0.6–0.7) reflects how economic levels drive service facility development and heritage utilization. Economically advanced regions possess a greater capacity to invest in heritage construction and development, while improved services enhance heritage value, creating a positive feedback loop that intensifies spatial differentiation. This further confirms the bidirectional relationship between natural factors and the cultural heritage of water. Natural factors initially establish the foundation for the initial distribution. Human factors then influence the development of water cultural heritage. The clustering of heritage sites attracts further concentration of human factors. In summary, the interaction detection results reveal that the spatial differentiation of water cultural heritage results from deep coupling between natural and human factors. Strong interaction combinations precisely point to the differentiation logic of "natural ecological support—human service enhancement."

As previously mentioned, detailed categories also follow the aforementioned patterns. The phenomenon of spatial differentiation in cultural heritage sites, tourist attractions, and heritage listings is predominantly driven by the interaction between service factors and natural or economic factors. Natural factors play a pivotal role in the unique character of heritage sites. For instance, the distinctive topography along the Yellow River gives rise to a unique water cultural heritage. Economic factors have a significant impact on the protectability of heritage sites. Regions with a high GDP have the capacity to develop and restore water cultural heritage. The service and tourism sectors facilitate the enhancement of heritage dissemination, thereby contributing to the promotion of water cultural heritage awareness. A lack of a single dominant interaction characterizes the spatial differentiation of village landscapes. Factor combination q-values are generally low, with relatively prominent interactions between natural and cultural factors. This finding indicates that village landscapes result from long-term synergistic effects between these two factors, influenced by complex multidimensional factors. No singular factor can exert a predominant influence on the differentiation process.

Geographically weighted regression analysis of key influencing factors

Impact factor model screening and comparison

The study utilized ArcGIS spatial autocorrelation analysis tools to examine water cultural heritage sites' overall kernel density values. The results revealed a positive Moran's I index with a P-value of 0.000, thus indicating a positive correlation in the spatial distribution of water cultural heritage at the grid scale. This finding indicates distinct spatial clustering characteristics, thus rendering it suitable for analyzing influencing factors using a geographically weighted regression model (*Table 8*).

Table 8. *Global Moran's I index for aquatic cultural heritage at grid scale*

Item	Item value
Moran's I index	0.994693
Expected index	-0.000447
Variance	0.000239
z-Score	64.353642
p-Value	0.000000

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Before analyzing spatial heterogeneity using the Geographically Weighted Regression model, multiple collinearity tests were conducted for the 14 factors as independent variables using the Ordinary Least Squares model. Indicators with a Variate Inflation Factor (VIF) greater than 7.5 and P-values failing the significance test were excluded (*Table 9*). Following a comprehensive review of the extant literature, six indicators were selected for inclusion in the study as explanatory variables: elevation, slope, vegetation coverage, GDP per capita, disposable income per capita, and transportation accessibility.

Table 9. *Results of collinearity tests for the OLS model*

Dimension	Independent variable	Coefficient	Robust_Pr	VIF
Natural Ecological Foundation	Elevation	-0.000004	0.000000*	2.316527
	Slope gradient	0.000124	0.000000*	3.165642
	Vegetation coverage	-0.007146	0.000000*	4.874530
Socioeconomic Drivers	GDP per capita	-0.000000	0.000002*	5.651216
	Disposable income per capita	0.000000	0.000000*	3.253039
	Transportation accessibility	-0.000143	0.008671*	6.028902

Considering the results obtained above, a Geographic Weighted Regression (GWR) model was constructed using *Equation 5* to examine the spatial variation in the distribution of water cultural heritage resources across the Shaanxi section of China's Yellow River Basin in relation to various factors. A comparative analysis was conducted, which revealed that the GWR model yielded higher R^2 and adjusted R^2 values, along with a smaller AICc, indicating a greater degree of reliability in its analytical outcomes (*Table 10*) (Tian et al., 2024; Niu and Wang, 2024; Chen et al., 2025). In order to facilitate a more intuitive investigation of how different influencing factors shape the spatial differentiation of water cultural heritage resources, the GWR regression coefficients were visualized (*Fig. 6*).

Table 10. *Comparison of OLS model and GWR model test results*

Diagnostic indicators	OLS model	GWR model
AICc criterion	-21397.554	-21529.026
R^2	0.709	0.726
Adjusted R^2	0.707	0.724

Natural ecological foundation

Elevation

The regression coefficient for the northern Shaanxi region is negative with a significant absolute value (*Fig. 6a*), indicating that high elevation exerts a significant negative influence on the distribution of water cultural heritage. Owing to the northern Shaanxi plateau's topography, its rugged terrain, historical water conservancy projects, and settlement development have been constrained by elevation. Conversely, the regression coefficient for the Guanzhong Plain approaches zero, indicative of the negligible impact of elevation on water cultural heritage in plain regions. The region's topography is characterized by a uniform expanse of flat terrain, a feature that significantly impacts

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agricultural irrigation and urban development. In this context, the distribution of water resources is predominantly influenced by human activities, thereby diminishing the constraining effect of elevation.

Slope

Around the Guanzhong Plain, the regression coefficient is negative (*Fig. 6b*). Historically, large-scale irrigation systems and other water conservancy projects were often built on gentle terrain, revealing a negative correlation where “the gentler the slope, the denser the heritage.” Conversely, in areas such as southern Yulin and northern Yan’an, the regression coefficient is positive. This is because on the arid Loess Plateau of Shaanxi north, a particular slope is a natural prerequisite for effectively constructing rainwater harvesting facilities, such as terraced fields and water retention ponds. Consequently, a positive correlation pattern emerges: moderate slopes facilitate water collection, and heritage sites are distributed along slopes. Both patterns align with the core principle that “flatter slopes favor the distribution of water-related cultural heritage.” Regional variations in terrain base merely result in differing effective distribution ranges, leading to localized heterogeneity in correlation.

Vegetation coverage

From the perspective of how vegetation coverage in different regions affects heritage existence, the northern part of Yulin lies within an area of sparse vegetation, exhibiting a positive regression coefficient (*Fig. 6c*). This indicates that water cultural heritage in areas with low vegetation coverage relies more heavily on the “water-vegetation” relationship, with its distribution closely aligned with the region’s limited vegetation resources. The regression coefficient for the densely vegetated areas of Guanzhong and southern Shaanxi is negative, indicating that vegetation resources in these regions are abundant and no longer a key factor constraining the existence of water cultural heritage. Consequently, the influence of vegetation cover on the presence of water cultural heritage is relatively weak in these areas.

Socioeconomic drivers

Per capita GDP

The regression coefficient for the Guanzhong core area is positive (*Fig. 6d*), indicating a positive correlation between regional economic development levels and the preservation and visible utilization of water cultural heritage. Economically developed regions possess greater financial capacity to effectively promote the preservation and restoration of existing water cultural heritage, making their distribution characteristics more pronounced. The regression coefficient for the Northern Shaanxi region approaches zero, reflecting that the region’s economic development achievements have not yet been effectively translated into driving forces for the protection and development of water cultural heritage, resulting in a weaker manifestation effect on existing heritage.

Per capita disposable income

The regression coefficient for the Guanzhong region is positive (*Fig. 6e*), indicating that higher resident incomes drive demand for water cultural heritage. Affluent groups have been demonstrated to exhibit a strong propensity to allocate financial resources

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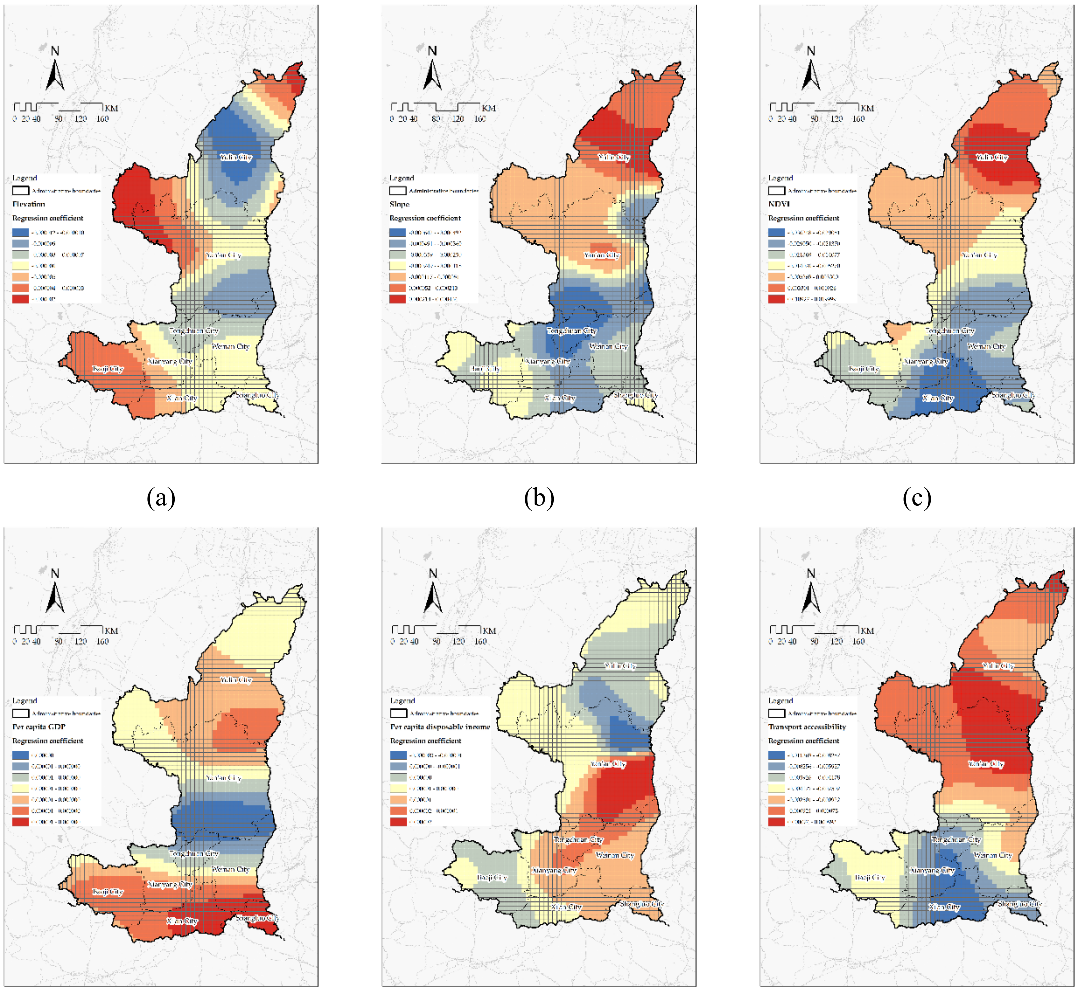
towards cultural experiences, thereby promoting the development of tourism related to water cultural heritage. Conversely, the regression coefficients for Shaanxi's northern and southern peripheral areas are negative, indicating that water cultural heritage in low-income regions is constrained by consumption demand, with residents demonstrating a low demand for non-essential cultural expenditures.



(a) (b) (c) (d) (e) (f)

Figure 6. *GWR model distribution map of regression coefficients for factors influencing spatial differentiation of water cultural heritage: (a) elevation; (b) slope; (c) NDVI; (d) per capita gdp; (e) per capita disposable income; (f) transport accessibility*

Transportation accessibility

The regression coefficient for transportation accessibility in Guanzhong is negative (*Fig. 6f*), indicating that the "transportation-development" conflict influences the distribution of water cultural heritage in Guanzhong. Dense transportation networks characterize cities such as Xi'an. However, urban expansion and construction may result in the damage or displacement of ancient water conservancy facilities. This phenomenon gives rise to the impression of transportation suppression on their distribution; however, it is the consequence of an imbalance between development and conservation.

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Conversely, the northern Shaanxi region demonstrates a positive regression coefficient, signifying comparatively dispersed water cultural heritage with minimal development intensity. Nevertheless, the relative inaccessibility of the sites has resulted in their preservation in relatively undisturbed condition. The enhancement of transportation accessibility has the potential to disrupt geographical isolation, connecting latent water cultural heritage with market forces and facilitating its identification and utilization.

Mechanism of differentiation effects

The six influencing factors reveal that spatial differences in water cultural heritage arise from the interaction between natural constraints and socio-economic drivers. In northern Shaanxi, natural factors shape the distribution of sites, while limited socio-economic investment has not unlocked their heritage value, leaving most sites unchanged. In Guanzhong, socio-economic factors are the dominant ones. Flat terrain reduces natural constraints, and economic and transport advantages promote large-scale, tourism-focused heritage development. However, relying too much on socio-economic growth can overlook natural conditions, risking an imbalance between development and ecological sustainability.

In summary, the spatial heterogeneity of GWR regression coefficients clearly reveals that distinct natural and cultural factors drive the distribution of water cultural heritage across different regions. Northern Shaanxi should prioritize adaptive conservation of natural heritage and increase investment in cultural elements. Central Shaanxi should focus on the coordinated development of its cultural heritage. It should emphasize natural synergy to protect the heritage’s original environment. This complementary strategy enables zoned protection and the use of water cultural heritage in China’s Yellow River Basin. It respects regional differences and avoids the pitfalls of single-track development. This approach provides more precise guidance.

Discussion

Based on the findings from previous research, the spatial pattern of water cultural heritage is characterized by “dual cores with multiple clusters and interconnected tributaries,” the synergistic “nature-service” driving mechanism revealed by geographic detectors, and the spatial heterogeneity reflected in geographically weighted regression analyses, regional conservation and utilization must strictly adhere to the core principle of addressing disparities and strengthening weaknesses. Accordingly, the following conservation models are proposed for four categories of heritage: cultural heritage sites, village landscapes, tourist attractions, and heritage listings:

Cultural heritage sites

In regions exhibiting a high concentration of water-related cultural heritage, priority should be given to the advancement of systematic integration of tourism resources and the innovation of spatial development models (Yang, Y. and Tang, X. L., 2022). Implementing these measures is expected to fully unleash their radiating and driving effects, thereby supporting regional tourism’s comprehensive and coordinated development. The core area along the Weihe River in Guanzhong should be utilized as a case study for the implementation of digital technology in restoring historical functions, controlling service facility size, and preserving the original landscape. This initiative may

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be coordinated with existing village landscape programs. In the Loess Plateau region of northern Shaanxi, integrating cave-dwelling villages with cultural heritage sites can serve as platforms for showcasing water conservancy facilities. The transmission of heritage is facilitated through the villagers' narrations and demonstrations of traditional crafts, ensuring the preservation of cultural knowledge in a living and dynamic manner. In the context of the Guanzhong Plain, it is recommended that "Village Culture Festivals + Heritage Open Days" be organized to strengthen residents' cultural identity.

Village landscape

In the case of traditional villages located within the north-south continuous settlement belt spanning from Yulin to Weinan, it is imperative to preserve the original relationship between villages and water systems. It is imperative to preserve the symbiotic "water-village-field" pattern by implementing ecological compensation measures. In light of the negligible impact of individual factors, establishing spatial industrial coupling models is recommended to stimulate traditional villages' industrial, environmental, and resource components. The creation of distinctive development spaces (Liu et al., 2024) is recommended to guide villagers to operate traditional homestays and integrate service facilities into the village fabric.

Tourist attractions

It is imperative to emphasize the radiating influence of 3A-rated and higher attractions around Xi'an, establishing a linkage with secondary attractions in Baoji and Weinan to enhance synergistic effects. Enhancing the inherent allure of natural elements and the extrinsic impetus of socioeconomic factors is imperative to address cultural and entertainment requirements within scenic areas (Hu et al., 2024). In the high-service-density Guanzhong region, there is a necessity to upgrade smart tourism facilities with a view to enhancing visitor experiences. In the northern reaches of Shaanxi, there is a need to meticulously plan for the development of parking facilities and emergency service stations. This approach is crucial in achieving a balance between enhancing accessibility and ensuring ecological conservation. Furthermore, it is recommended that water conservancy technologies from heritage lists be integrated into tourist attraction experiences, with hydrological legends being woven into scenic narratives to deepen cultural resonance.

Heritage list

The integration of the subject into the watershed corridor protection system is recommended. In densely populated areas, the revitalization and utilization of sites through educational field trips is recommended. In regions exhibiting sparse population density, implementing online exhibitions has been identified as a strategy to reduce conservation costs. Promoting cross-regional resource complementarity between Guanzhong and northern Shaanxi is imperative to achieve equilibrium between regional disparities.

Conclusions

This paper constructs a multi-factor influence system based on research into the spatial distribution of water cultural heritage in the Shaanxi section of China's Yellow River

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Basin. Utilizing a geographically weighted regression model, it reveals the spatial heterogeneity and underlying mechanisms of these influencing factors, leading to the following conclusions:

From a distribution perspective, the overall pattern exhibits clustering, characterized by a “dual-core, multi-spot, tributary-linked” structure. The Guanzhong region serves as the high-density core area for heritage sites, while the northern Shaanxi region, represented by the Wuding River Basin, forms localized clusters. Heritage density in hilly and water-scarce regions is significantly lower than in plains and densely water-networked zones, validating the principle that “geographical conditions dictate the distribution of water cultural heritage.” The primary axis of water cultural heritage distribution runs northeast-southwest, aligning with the flow direction of the Yellow River and its major tributaries, as well as the historical development trajectory of the region. This pattern reflects both the dual influence of natural geography and historical-cultural development on the distribution of heritage, while also embodying the subsequent shaping of heritage clusters through historical and cultural accumulation.

From the perspective of influencing factors, natural and human factors exhibit synergistic effects. (1) At the dominant factor level, natural factors such as elevation and river network density are core drivers for the initial spatial distribution of water cultural heritage sites. Human factors include population density, tourist visits, and tourism service facilities. These shape the effective distribution pattern of water cultural heritage. Their high q-values reflect an amplifying effect on heritage clustering. (2) At the causal relationship level, natural factors mainly exert unidirectional influence. Human factors show bidirectional synergistic characteristics. (3) At the interaction level, the explanatory power of various factors often shows non-linear enhancement or dual-factor amplification relationships. This represents the coupled interaction between natural environments and human tourism support systems, not the effect of any single factor alone.

From the perspective of spatial heterogeneity, the water cultural heritage in the Shaanxi section of China’s Yellow River Basin is the result of a synergistic interplay between multiple factors, including the natural environment and socio-economic conditions. However, the regional impact of specific factors varies significantly. In northern Shaanxi, natural factors predominate, limiting the development of large-scale heritage clusters. Insufficient investment in cultural factors has left most heritage sites in their original state, with their value remaining largely untapped. In the Guanzhong region, the constraints of natural factors have weakened, making cultural factors the core driver. However, transportation factors present a limiting influence, creating potential risks of imbalance between cultural development and the natural baseline.

A comprehensive investigation of the water cultural heritage in the Shaanxi section of China’s Yellow River Basin has revealed that the implementation of four distinct protection models, when utilized in conjunction, optimizes the natural foundation and historical value of safeguarding water cultural heritage. Integrating spatial patterns, influencing factors, and regional heterogeneity has been identified as a key factor in achieving differentiated utilization, thereby promoting the sustainable development of “protection-inheritance-cultural tourism integration” for water cultural heritage in the Shaanxi section of China’s Yellow River Basin.

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