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Basin-Scale Spatial Differentiation and Influencing Factors of Village Toponymic Cultural Landscapes: A Case Study of the Xin'an River Basin

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Abstract

Village toponyms record environmental characteristics, settlement development, and historical-cultural processes. This study analyzes 7963 village toponyms in the Xin'an River Basin using semantic classification, spatial analysis, GeoDetector, and block-restricted label permutations. The results show that (1) village toponyms are significantly clustered (ANN = 0.968, $p < 0.001$), forming a "one-axis, four-core" pattern. Natural-landscape and human-landscape toponyms account for 48.15% and 51.85%, respectively. (2) River network density ($q = 0.247$) and elevation ($q = 0.227$) have the highest individual explanatory power for overall grid-level counts, and their joint stratification yields the highest q value (0.343). (3) Highland and mountain toponyms have higher relative elevation than expected under permutation, while several water-related groups exhibit river proximity. The predefined associations for lowland and hollow, gentle-terrain, and waterfront toponyms are unsupported. Aspirational toponyms also exhibit river proximity, showing that this association is not exclusive to water-related meanings. Historical cases document water infrastructure construction, waterborne transport, and toponym continuity following village relocation. These findings provide conditional evidence of semantic–environmental correspondence and support historical-toponym documentation and cultural landscape conservation across administrative boundaries.

Keywords: Xin'an River Basin; village toponyms; spatial differentiation; GeoDetector; cultural heritage conservation; sustainable landscape management

Academic Editors: Jianming Cai, Francesca Di Turo and Giacomo Fiocco

Received: 28 September 2026
Revised: 8 November 2026
Accepted: 13 November 2026
Published: 16 November 2026

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1. Introduction

Toponyms are cultural records of how communities have adapted to and transformed their environments. Their naming logics are conditioned by natural features such as terrain and hydrology while remaining embedded in historical processes of migration, economic activity, and political contestation [1]. Toponyms preserve information related to environmental perception, collective memory, and long-term human–environment interaction [2].

They are an important part of intangible cultural heritage and have value for protection [3]. In China, the Chinese Society for Toponymy was established in 1988. In 2004, the

Chinese Toponymic Cultural Heritage Protection Project was started to support the protection and study of toponyms. In recent years, laws and local policies have also stressed the need to protect toponyms with historical and cultural value.

At the international level, UNESCO has adopted conventions to protect cultural heritage and intangible cultural heritage. The United Nations has also developed standards for geographical names. These efforts support the protection of toponyms. However, globalization and rapid development have caused problems such as poor management, loss of toponymic meaning, repeated place names, and loss of local cultural features [4]. Since the Convention for the Safeguarding of the Intangible Cultural Heritage was adopted in 2003 [5], more attention has been given to the protection of toponymic cultural heritage.

International toponymic research has moved beyond etymology and taxonomy toward critical and landscape-based perspectives. Critical toponymic studies examine how naming practices encode power, identity, and social memory [6]. Landscape researchers have used toponyms to identify landscape character in New Zealand [7], map disappearing agricultural features in Spain [8], reconstruct historical land use in Switzerland [9], and trace rural Mediterranean landscape transformations [10]. These studies demonstrate that toponyms can serve simultaneously as cultural texts and spatial evidence. Recent case studies published in international journals have similarly combined classification with GIS-based kernel-density and nearest-neighbor analyses, with some also applying geographical detector models to relate toponymic patterns to natural and human processes [11,12]. Together, these studies use toponymic meanings, spatial data, and historical records to examine landscape characteristics and changes.

The study of toponymic cultural landscapes originated in cultural geography. Sauer conceptualized cultural landscapes as the material expression of human activity on the Earth's surface and recognized toponyms as information-rich cultural forms [13]. Subsequent research has used toponyms to trace cultural distributions and environmental change [14]. In China, research has expanded from semantic matching and classification methods [15] to GIS-based analyses of spatial pattern and historical evolution. Studies have identified contrasts between natural and human toponyms in Beijing [16], traced distributional change in Xinhui [17], reconstructed land reclamation from settlement names [18], and analyzed cultural-landscape genomes and settlement patterns at regional scales [19,20].

Village research has focused mainly on national [21,22], provincial [23], cross-provincial [24,25], and local scales, with less attention to the spatial distribution of village toponyms at the basin scale. Using the river basin as the unit of analysis allows terrain, river networks, and settlement patterns to be examined together across administrative boundaries [26]. Within this framework, the study examines whether selected toponym meanings correspond to local landscape features when existing village locations are held fixed.

The Xin'an River Basin contains mountains, hills, basins, and river-valley plains and therefore provides a representative setting in which natural and cultural processes overlap. The basin's varied environmental settings and documented settlement history provide a suitable context for examining both the spatial distribution of village toponyms and the historical information associated with their names. Accelerating urbanization is altering the original settings of many villages and obscuring the meanings of historical toponyms. Systematically identifying their distribution and influencing factors is therefore relevant to cultural inheritance, rural revitalization, and sustainable cultural landscape management.

Using 7963 village toponyms in the Xin'an River Basin, this study addresses three questions:

(1) How are village toponyms compositionally classified and spatially distributed across the basin?

(2) Which environmental factors best explain their spatial differentiation, and how do those factors interact?

(3) With village locations and local category counts held constant, do specific semantic groups exhibit the expected environmental differences, and how can historical documents help interpret the activities and name continuity associated with these groups?

2. Materials and Methods

2.1. Study Area

The Xin'an River Basin spans Anhui and Zhejiang Provinces, China, between 117°10′–120°05′ E and 28°10′–30°20′ N. The Xin'an River rises at Liugujian in Xiuning County, Huangshan City, Anhui Province, and flows eastward through Tunxi District and Shexian, Xiuning, Yixian, and Qimen Counties in Huangshan City; Jixi County in Xuancheng City; and Chun'an County and Jiande City in Hangzhou, Zhejiang Province. At Meicheng Town in Jiande, it joins the Lan River and becomes the Fuchun River before ultimately entering the Qiantang River (Figure 1). The river is approximately 373 km long, and its basin covers about 11,632 km^2. As an ecological and cultural corridor linking the mountains of southern Anhui with the plains of northern Zhejiang, the basin includes mountains, hills, basins, and river-valley plains. It is encircled by the Huangshan, Tianmu, Baiji, and Wulong mountain ranges, between which the Xiuning–Shexian, Yixian, and Qimen basins developed [27].

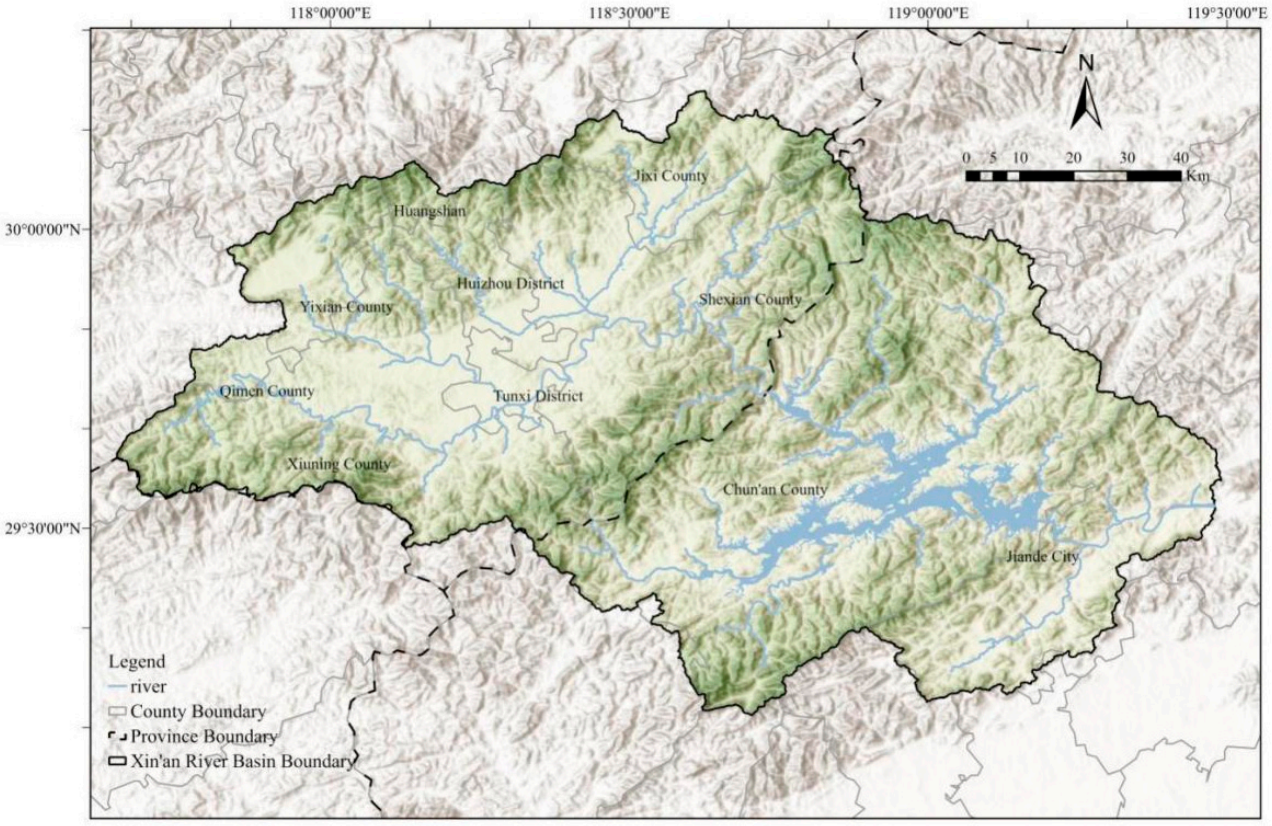


Figure 1. Location and administrative extent of the Xin'an River Basin.

2.2. Data Sources and Toponym Classification

2.2.1. Data Sources

The National Geographic Information Resource Directory Service System (http://www.webmap.cn/, accessed on 20 March 2026) was used as a reference during spatial preprocessing. The location search API of the Baidu Map Open Platform (https://lbs.baidu.com/, accessed on 20 March 2026) was used to collect village points of interest (POIs) in the Xin'an River Basin. After duplicate records and 283 village toponyms of untraceable origin were removed, 7963 valid village toponyms remained. Their origins were checked against local gazetteers, including the *Huizhou Five Thousand Villages* series.

A 30 m digital elevation model (DEM) was obtained from the public 30 m DEM provided by the Geospatial Data Cloud Platform (https://www.gscloud.cn/search; accessed on 20 March 2026). The elevation data was directly extracted from the DEM, while the slope and aspect were calculated using the "Slope" and "Aspect" tools in ArcGIS 10.2. The topographic relief was calculated as the difference between the maximum and minimum elevations within each grid cell. The annual average temperature and annual precipitation data were obtained from the "2024 China 1-km Annual Average Temperature Dataset" and the "2024 China 1-km Annual Precipitation Dataset," both provided by the National Earth System Science Data Center, with a spatial resolution of 1 km (http://www.geodata.cn/main/; accessed on 20 March 2026). River network data were obtained from OpenStreetMap (www.openstreetmap.org, accessed on 20 March 2026).

2.2.2. Toponym Classification

Toponyms can convey information about regional landforms, water features, history, and settlement culture [28]. A systematic classification framework facilitates the identification of these features and the analysis of the semantic composition and spatial differentiation of village toponyms.

Following previous village-toponym studies [29–31], the toponyms were semantically coded into two broad classes. Natural-landscape toponyms comprised landform, flora and fauna, hydrological, and natural-resource subcategories; human-landscape toponyms comprised color, meteorological, degree and quantity, direction, architecture, economic activity, military, hydraulic infrastructure, surname, and aspirational subcategories (Table 1).

Table 1. Semantic classification framework and operational definitions of village toponyms.

Toponym Category	Subtype	Tertiary Semantic Category	Definition
Natural landscape	Landform		Toponyms referring to landforms or terrain features.
	Flora and fauna		Toponyms referring to animals, plants, or biological features.
	Hydrological	Waterfront	Toponyms referring to riverbanks, lake shores, islets, shoals, and bays.
		surface water	Toponyms referring to lakes, deep pools, ponds, springs, and other water features distinct from rivers and streams.
		Linear waters	Toponyms referring to rivers, streams, and other flowing-water features.
	Natural resource		Toponyms referring to rocks, minerals, or natural resources.
Human landscape	Color		Toponyms based on color terms or color characteristics.
	Meteorological		Toponyms referring to weather, atmospheric, or celestial phenomena.
	Degree and quantity		Toponyms referring to quantity, size, age, or other relative measures.
	Direction		Toponyms indicating location, direction, or spatial order.
	Architecture		Toponyms derived from buildings, structures, or built landmarks.

Economic activity		Toponyms associated with production, trade, transport, or livelihoods.
Military	Defensive structures	Toponyms referring to mountain settlement defense, local public security, or military remains.
	Transport routes and passes	Toponyms referring to mountain passes, transport nodes, or the control of regional routes.
	Military garrisons and administrative units	Toponyms explicitly derived from military garrisons, military agricultural settlements, administrative structures, or historical military activities.
Hydraulic infrastructure		Toponyms derived from hydraulic facilities or water-management practices.
Surname		Toponyms derived from family surnames or lineage settlements.
Aspirational		Toponyms expressing wishes, values, or auspicious meanings.

Toponyms were classified by to the core meaning. For names with multiple or unclear meanings, local gazetteers and other historical records were consulted to identify the core meaning. To avoid double counting, each toponym was assigned to a single category that best matched this meaning. When the present-day meaning differed from the historical naming meaning, the latter was used as the basis for classification.

2.3. Analytical Methods

The analysis comprised four stages (Figure 2). First, village toponyms were classified by meaning and summarized using category counts and proportions. Second, average nearest neighbor analysis and kernel density estimation characterized spatial patterns, and GeoDetector assessed associations between grid-level counts and environmental variables. Third, block-restricted label permutations tested semantic–environmental correspondence while holding village locations and within-block category counts fixed. Finally, historical records helped interpret the activities and changes reflected in selected toponyms.

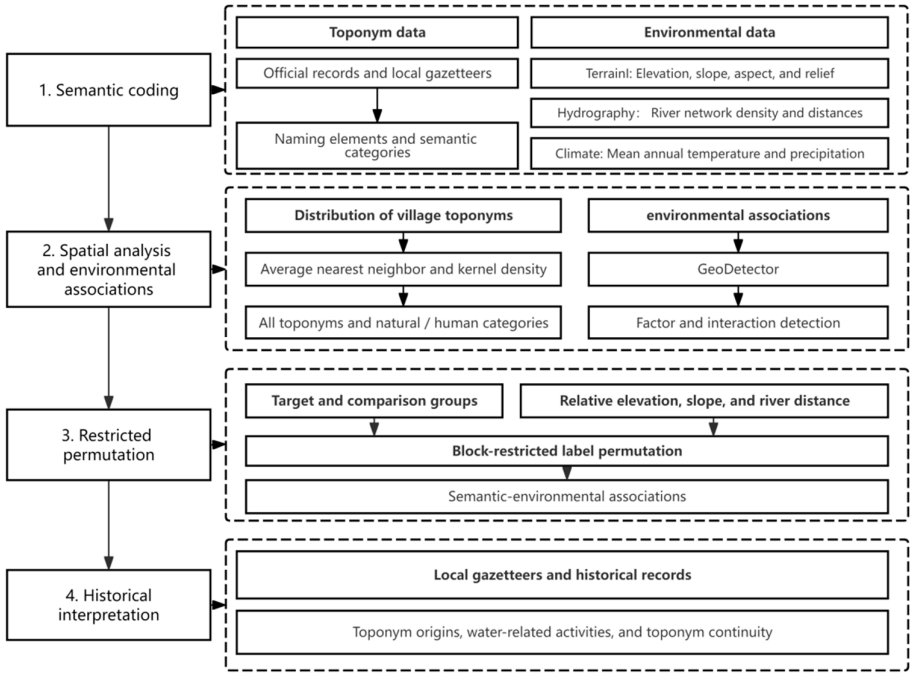


Figure 2. Analytical workflow for examining basin-scale village toponyms.

2.3.1. Average Nearest Neighbor Analysis

Average nearest neighbor (ANN) analysis was used to quantify the spatial pattern of village toponyms in the Xin'an River Basin [32], The calculation is as follows:

$$\overline{D}_0 = \frac{1}{n}\sum_{i=1}^{n} d_i \quad (1)$$

$$\overline{D}_e = \frac{\sqrt{\mathrm{A/n}}}{2} \quad (2)$$

$$\mathrm{ANN} = \frac{\overline{D}_0}{\overline{D}_e} \quad (3)$$

where $\overline{D}_0$ is the observed mean nearest-neighbor distance; d_i is the distance between toponym point i and its nearest neighbor; n is the total number of village-toponym points; $\overline{D}_e$ is the expected mean nearest-neighbor distance under complete spatial randomness; A is the study-area size.

2.3.2. Kernel Density Estimation

Kernel density estimation was performed on village toponym points using ArcGIS 10.2. A consistent search radius was used to identify concentration areas and compare the spatial densities of natural- and human-landscape toponyms [33]. The estimator is:

$$\mathrm{F_n}(x) = \frac{1}{nh}\sum_{i=1}^{n} k\left(\frac{x - x_i}{h}\right) \quad (4)$$

where $\mathrm{F_n}(x)$ is the kernel-density estimate; n is the number of villages in the corresponding toponym category; k is the kernel function; h is the bandwidth $h > 0$; $x - x_i$ is the distance from estimation location x to sample point x_i.

The main high-density clusters and overall spatial pattern remained broadly consistent at search radii of 5, 10, 15, and 20 km. The final analysis used a 10 km search radius and a 500 m output cell size to preserve local variation while limiting fragmentation of the density surface.

2.3.3. Optimal Parameters-Based Geographical Detector (OPGD)

GeoDetector assesses spatial heterogeneity and quantifies the explanatory power and interactions of potential drivers [34]. Factor detection was used to assess the explanatory power of terrain, hydrographic, and climatic variables for the spatial distribution of each toponymic category, while interaction detection assessed whether pairs of factors enhanced or weakened one another. The factor-detector statistic is:

$$q = 1 - \frac{1}{N\sigma^2}\sum_{h=1}^{L} N_h\,\sigma_h^2 \quad (5)$$

where q represents the explanatory power of the explanatory variable for the spatial hierarchical heterogeneity of the dependent variable; N is the total number of sampled points; N_h is the sample size in stratum h; ${\sigma_h}^2$ and σ^2 represent the variances of the dependent variable within stratum h and across all sampling points, respectively. q ranges from 0 to 1, with larger values indicating greater explanatory power.

The GD package in R 4.6.1 was used to optimize discretization separately for each combination of a response variable (Y1–Y17) and a continuous explanatory variable (X1–X7). Five methods were tested with 3–8 strata: equal intervals, quantiles, natural breaks, geometric intervals, and standard deviation. Factor and interaction detection used the optimal settings listed in Table 2.

Table 2. Optimal discretization parameters of environmental variables for different village-toponym categories.

Toponym Category	Elevation X1	Slope X2	Aspect X3	Topographic Relief X4	Mean Annual Temperature X5	Annual Precipitation X6	River Network Density X7
All toponyms Y1	G-8	N-8	G-8	G-8	N-8	N-8	G-8
Natural-landscape total Y2	N-7	N-8	G-8	E-8	E-8	N-7	N-7
Natural—landform Y3	G-8	N-8	G-8	E-8	N-8	N-7	N-7
Natural—flora/fauna Y4	Q-8	N-8	G-8	E-8	E-8	N-8	N-7
Natural—hydrological Y5	Q-8	N-6	G-8	N-7	Q-7	Q-7	E-8
Natural—resource Y6	N-8	N-8	G-8	E-5	Q-8	Q-7	G-8
Human-landscape total Y7	G-8	N-8	G-8	G-8	Q-6	N-8	G-8
Human—color Y8	G-8	Q-7	G-7	Q-8	Q-6	N-8	E-8
Human—meteorological Y9	Q-7	G-8	G-8	N-5	Q-7	Q-8	Q-8
Human—degree/quantity Y10	G-8	Q-8	G-8	G-8	N-6	Q-6	E-8
Human—direction Y11	G-7	G-6	G-7	G-8	Q-8	N-8	G-8
Human—architecture Y12	G-6	G-7	G-6	G-7	Q-8	Q-8	G-8
Human—economic activity Y13	Q-8	G-8	G-8	Q-8	Q-8	Q-7	Q-8
Human—military Y14	Q-8	N-7	G-8	N-8	N-7	Q-8	E-8
Human—hydraulic infrastructure Y15	G-7	G-7	G-7	G-8	Q-7	Q-8	N-8
Human—surname Y16	G-8	N-8	G-8	G-7	N-6	N-8	Q-7
Human—aspirational Y17	Q-8	Q-8	G-8	G-6	Q-6	Q-7	G-8

Note: E, equal interval; N, natural breaks; Q, quantile; G, geometric interval. Numbers indicate the optimal number of classes.

2.3.4. Tests of Semantic–Environmental Correspondence

Block-restricted label permutations were used to test whether village toponym meanings corresponded to local environmental characteristics. For each target semantic group, the observed environmental statistic was compared with the null distribution generated by permuting labels within blocks.

(1) Naming elements and predefined hypotheses

Each village toponym was assigned to a primary category as described in Table 1. Within each category, test groups were defined based on the meanings of naming elements in individual village toponyms. The corresponding environmental indicators and expected directions were specified for each group (Table 3).

Table 3. Predefined hypotheses for testing semantic–environmental correspondence.

Test ID	Category	Semantic Group	Examples of Naming Elements	Environmental Indicator	Expected Direction
H1	Landform	Lowlands and hollows	*mountain hollow* (坞), *ravine* (坑)	$RE_{1\,km}$	Lower than in reference villages
H2		Highlands and mountains	*mountain* (山), *ridge* (岭), *peak* (峰), *hill* (丘)	$RE_{1\,km}$	Higher than in reference villages
H3		Gentle terrain	*flat ground* (坪), *cultivated valley land* (畈), *flat land* (坦)	Slope	Lower than in reference villages
H4	Hydrological	Linear waters	*River* (江), *river* (河), *mountain stream* (涧), *stream* (溪)	D_{river}	Lower than in reference villages
H5		Waterfront	*Waterfront* (滨), *islet* (洲), *shoal* (滩), *bay* (湾)	D_{river}	Lower than in reference villages

H6		Surface water	*lake* (湖), *deep pool* (潭), *pond* (池)	D_{river}	Lower than in reference villages
H7	Hydraulic infrastructure	Hydraulic infrastructure	*dam* (坝), *weir* (堨), *canal* (渠), *water-powered pestle* (碓)	D_{river}	Lower than in reference villages
H8	Economic activity	Ferry and water-transport facilities	*harbor* (港), *port* (浦), *ferry crossing* (渡), *wharf* (埠)	D_{main}	Lower than in reference villages
C1	Color	Color（Comparison category）	*red* (红), *scarlet* (赤), *yellow* (黄), *blue-green* (青), *purple* (紫)	D_{river}	No predefined direction
C2	Meteorological	Meteorological（Comparison category）	*light* (光), *wind* (风), *glow* (霞), *sun* (阳), *rainbow* (虹)	$RE_{1\ km}$	No predefined direction
C3	Aspirational	Aspirational（Comparison category）	*blessing* (福), *prosperity* (富), *abundance* (丰), *prosperity* (昌), *peace* (太平), *unity* (团结), *victory* (胜利), *peace* (和平)	D_{river}	No predefined direction

Note: H1–H8 denote predefined directional hypotheses, whereas C1–C3 denote comparison categories without predefined directional expectations. Reference villages are those without the corresponding naming element within the same 10 km block. $RE_{1\ km}$ denotes relative elevation within a 1 km neighborhood; D_{river} is the Euclidean distance from a village to the nearest river. D_{main} is the minimum Euclidean distance from the village to the Xin'an River main stem, the Lian River, or the Heng River.

(2) Village-level environmental indicators

Neighborhood relative elevation was used to represent each village's position relative to the surrounding terrain [35]:

$$RE_r(i) = z_i - \bar{z}_r(i) \quad (6)$$

where z_i is the elevation of the 30 m DEM cell containing village i, and $\bar{z}_r(i)$ is the mean elevation of DEM cells within radius r of the village. The main analysis used r = 1 km. Positive and negative relative elevations indicate that a village is above and below the neighborhood mean, respectively.

(3) Block-restricted label permutations

The analysis used a square grid with 10 km cells and an origin at projected coordinates (0,0). The block indices for village i were calculated as:

$$g_{xi} = \left\lfloor \frac{x_i - x_0}{L} \right\rfloor, \quad g_{yi} = \left\lfloor \frac{y_i - y_0}{L} \right\rfloor \quad (7)$$

where x_i and y_i are the projected coordinates of village toponym point i, x_0 and y_0 define the grid origin, and L = 10,000 m.

(4) Effect sizes and statistical significance

Each test used B = 9999 within-block label permutations [36]. Village locations, environmental values, and target-group counts were held fixed. Labels were shuffled only in blocks containing both target and reference villages. The median from permutation b was denoted by T_b, and the complete set of permutation statistics was denoted by $T = \{T_1, \ldots, T_B\}$. Let T_{obs} denote the observed median for the target group. The difference between the observed value and the median of the null distribution was calculated as:

$$\Delta = T_{obs} - \text{median}(T_1, \ldots, T_B) \quad (8)$$

The null median and the 2.5th and 97.5th percentiles were reported, with percentiles calculated using R's quantile function (type = 7). The standardized effect size (SES) was calculated as [37]:

$$SES = d\frac{T_{obs} - mean(T)}{sd(T)} \quad (9)$$

where mean(T) and sd(T) are the mean and standard deviation of the null distribution, respectively. The direction coefficient was $d = 1$ when the expected direction was "higher" and $d = -1$ when it was "lower." For H1–H8, a positive SES indicated a deviation consistent with the expected direction. For the comparison categories, $d = 1$, retaining the original sign.

For the Monte Carlo permutation test [38], r_L and ru denote the numbers of permuted medians at or below and at or above T_{obs}, respectively. The one-sided probabilities and the two-sided p-value were calculated as follows:

$$p_L = \frac{r_L + 1}{B + 1}, \qquad p_U = \frac{r_U + 1}{B + 1} \quad (10)$$

$$P = \min\{1, 2\min(p_L, p_U)\} \quad (11)$$

Within each analytical setting, Holm correction was applied separately to H1–H8 and C1–C3 [39]. An adjusted $p < 0.05$ indicated statistical significance. For H1–H8, a result supported the predefined direction if it was statistically significant and had $SES > 0$.

(5) Robustness checks and results

Robustness was assessed using 5 and 20 km blocks and by shifting the 10 km grid origin to (5000, 0), (0, 5000), and (5000, 5000) m. Across all block sizes and grid origins, H2, H4, H6, H7, H8, and C3 remained significant, and the other groups remained nonsignificant. For H8, the absolute deviation from the null median increased from 0.535 km with 5 km blocks to 1.871 km with 20 km blocks.

3. Results

3.1. Classification and Composition

The classification yielded four natural-landscape and ten human-landscape subcategories (Table 4).

Table 4. Semantic classification of village toponyms in the Xin'an River Basin.

Toponym Category	Subtype	Tertiary Semantic Category	Typical Naming Elements	Count	Total	Percentage (%)
Natural landscape	Landform		*mountain hollow* (坞), *ravine* (坑), *flat ground* (坪), *cultivated valley land* (畈), *mountain* (山), *valley* (川), *hill* (丘)	2242	2242	28.16
	Flora and fauna		*swallow* (燕), *crane* (鹤), *pig* (猪), *cattle* (牛), *sheep* (羊), *chicken* (鸡), *horse* (马), *lion* (狮), *snake* (蛇), *fish* (鱼), camphor tree (樟), maple (枫), *bamboo* (竹), *tea* (茶), *flower* (花), *lotus* (莲), *fir* (杉), *pine* (松), *cypress* (柏), *hackberry* (朴), *chestnut* (栗), *plum* (梅), *persimmon* (柿)	579	579	7.27
	Hydrological	Waterfront	*Waterfront* (滨), *islet* (洲), *shoal*(滩), *bay* (湾)	56	740	9.29
		surface water	*lake* (湖), *sea* (海), *deep pool* (潭), *pond* (池), *spring* (泉), *marsh* (沼)	371		
		Linear waters	*River* (江), *river* (河), *mountain stream* (涧), *waterfall* (瀑), *rapids* (濑), *torrent* (湍), *stream* (溪), *river* (川), *broad expanse of water*(沆)	313		
	Natural resource		*stone* (石), *gold* (金), *silver* (银), *iron* (铁), *copper* (铜), *sand* (沙)	273	273	3.43
Human landscape	Color		*red* (红), *scarlet* (赤), *yellow* (黄), *blue-green* (青), *purple* (紫), *black* (乌), *white* (白)	100	100	1.26

Meteorological		*light* (光), *wind* (风), *glow* (霞), *sun* (阳), *rainbow* (虹), *moon* (月), *star* (星), *cloud* (云)	74	74	0.93
Degree and quantity		*large* (大), *small* (小), *double* (双), *half* (半), *one* (一), *two* (二), *three* (三), *four* (四), *five* (五), *six* (六), *ten* (十), *hundred* (百), *thousand* (千), *ancient* (古), *elder* (老), *high* (高), *long* (长), *deep* (深), *new* (新), *old* (旧)	474	474	5.95
Direction		*upper* (上), *lower* (下), *middle* (中), *edge* (边), *inner* (里), *outer* (外), *front* (前), *rear* (后), *east* (东), *west* (西), *south* (南), *north* (北), *end* (头), *bottom* (底)	1258	1258	15.80
Architecture		*bridge* (桥), *gate* (门), *pagoda* (塔), *pavilion* (亭), *house* (屋), *dwelling* (舍), *residence* (宅), *hall* (堂), city (城), *temple* (寺), *shrine* (庙), *nunnery* (庵), *tower* (楼), *hall* (厅), *pavilion* (阁)	225	225	2.83
Economic activity		*field* (田), *shop* (店), *workshop* (坊), *shop* (铺), *firm* (行), *market* (市), *street* (街), *harbor* (港), *port* (浦), *ferry* (渡), *wharf* (埠), *fishing* (渔), *granary* (仓), *pawnshop* (典), *merchant* (商), *selling* (卖), *press* (榨)	228	228	2.86
Military	Defensive structures	*fortified village* (寨), *fort* (堡), *fortress* (城), *rampart* (垒)	11	33	0.41
	Transport routes and passes	*pass* (关), *narrow pass* (隘), *post station* (驿)	15		
	Military garrisons and administrative units	*administrative seat* (府), *military camp* (营), *military* (军), *soldier* (兵), *administrative unit* (甲), *administrative office* (司)	7		
Hydraulic infrastructure		*dam* (坝), *weir* (堨), *canal* (渠), *water channel* (槽), *water-powered pestle* (碓), *bamboo water conduit* (枧), *well* (井), *polder* (圩), *pond* (塘)	380	380	4.77
Surname		*Cheng* (程), *Wang* (汪), *Ye* (叶), *Yang* (杨), *Wang* (王), *Hu* (胡), *Zhu* (朱), *Chen* (陈), *Zhang* (张), *Hong* (洪), *Tang* (汤), *Jin* (金), *Fang* (方), *Zhou* (周), *He* (何), *Wu* (吴), *Huang* (黄), *Jiang* (江), *Li* (李), *Liu* (刘), *Xiang* (项), *Xu* (徐), *Xu* (许), *Luo* (罗), *Pan* (潘), *Zha* (查), *Bao* (鲍), *Zhang* (章), *Yu* (余), *Lin* (林), *Song* (宋)	1076	1076	13.51
Aspirational		*blessing* (福), *prosperity* (富), *flourishing* (兴), *peace* (安), *virtue* (贤), *official* (官), *abundance* (丰), *prosperity* (昌), *unity* (联), *dragon* (龙), *phoenix* (凤), *peace* (太平), *unity* (团结), *victory* (胜利), *peace* (和平), *youth* (青春), *success* (成功), *Guanyin* (观音)	281	281	3.53
Total			7963	7963	100

Note: Parentheses contain Chinese characters corresponding to English terms. Pinyin romanization is used for surnames and Huizhou-dialect terms where appropriate.

3.1.1. Natural-Landscape Toponyms

Natural-landscape toponyms number 3834 and account for 48.15% of the dataset (Table 4). They describe the basin's physical geography and reveal how settlement builders perceived and used local environments. Landform toponyms are the largest subcategory (28.16%), commonly containing terms such as wu (enclosed valley), keng (ravine), ping (level ground), fan (cultivated valley land), and shan (mountain).

Hydrological toponyms account for 9.29% of all village toponyms and are further divided into three semantic subtypes. Waterfront toponyms refer to riverbanks, islets, shoals, and bays. Surface-water toponyms refer to features such as lakes, pools, ponds, and springs, whereas linear-water toponyms refer to rivers, streams, and other flowing-

water features. Such toponyms preserve cultural information about water-related landscapes within the basin's dense drainage network.

Flora-and-fauna toponyms account for 7.27% and include terms such as yan (swallow), fu (wild duck), yu (fish), zhang (camphor), and zhu (bamboo). Fuyuan Village in Qimen County uses fu, an older reference to wild ducks common in Huizhou waters [40], illustrating how locally salient species were used as environmental markers. Natural-resource toponyms form the smallest natural subcategory (3.43%) and commonly include shi (stone), jin (gold), yin (silver), and tie (iron).

3.1.2. Human-Landscape Toponyms

Human-landscape toponyms number 4129 and account for 51.85% of the dataset (Table 4). Their naming logics are embedded in Huizhou lineage traditions, economic systems, and social change. Directional toponyms are the largest human subcategory (15.80%) and commonly use *shang* (upper), *xia* (lower), *qian* (front), *hou* (rear), *li* (inner), and *wai* (outer). Paired names such as *Qiancun*/*Houcun* (Front/Rear Village), *Waicheng*/*Licheng* (Outer/Inner Cheng), and *Shangzhuang*/*Xiazhuang* (Upper/Lower Zhuang) encode relational spatial positions and locally valued ideas of order and balance.

Surname toponyms account for 13.51% and involve approximately 156 surnames, including *Cheng*, *Wang*, *Ye*, *Yang*, and a second homophonous Wang surname. Degree-and-quantity toponyms account for 5.95% and contain terms such as *da* (large), *xiao* (small), *ban* (half), and *jiu* (old) [41]. Hydraulic-infrastructure toponyms account for 4.77% and frequently contain *ba* (dam), *yan* (weir), *qu* (canal), and *cao* (trough) [42]. Aspirational toponyms account for 3.53%. In a region shaped by migration, warfare, and natural hazards, names such as *Heping* (peace), *Fucheng* (prosperous city), and F*enghuang* (phoenix) express hopes for security and abundance [43].

Economic-activity toponyms account for 2.86% and often contain *tian* (field), *dian* (shop), *fang* (workshop), and *yu* (fishing) [44]. Architecture toponyms account for 2.83% and commonly reference bridges, gates, pagodas, temples, or halls. Color toponyms account for 1.26%; Ziyang Village in Shexian County was named for its position below Ziyang Mountain and the purple-toned dawn scenery described in local tradition [44]. Meteorological toponyms account for 0.93%; Yuncun in Tunxi was formerly called Yunyuan because clouds and mist frequently filled the surrounding valley [45].

Military toponyms are least common (0.41%) and include terms such as *jun* (army), *bing* (soldier), *guan* (pass), *zhai* (fortified settlement), and *ying* (encampment). Although relatively few in number, these toponyms contain information about historical defense, transportation, and territorial administration [46].

3.2. Spatial Distribution Patterns

For all village toponyms, the ANN index is 0.968, with $z = -5.524$ and $p < 0.001$ (Table 5, Figure 3). The index below 1 and the negative z-score support a clustered pattern at the study scale; they do not by themselves establish the mechanism producing the pattern.

Table 5. Nearest neighbor index results for all village toponyms in the study area.

Type	N	Observed Mean Distance (m)	Expected Mean Distance (m)	Nearest Neighbor Ratio (R)	Z-Score	*p*-Value	Distribution Type
All village toponyms	7963	584.8	604.3	0.968	−5.524	<0.001	Clustered

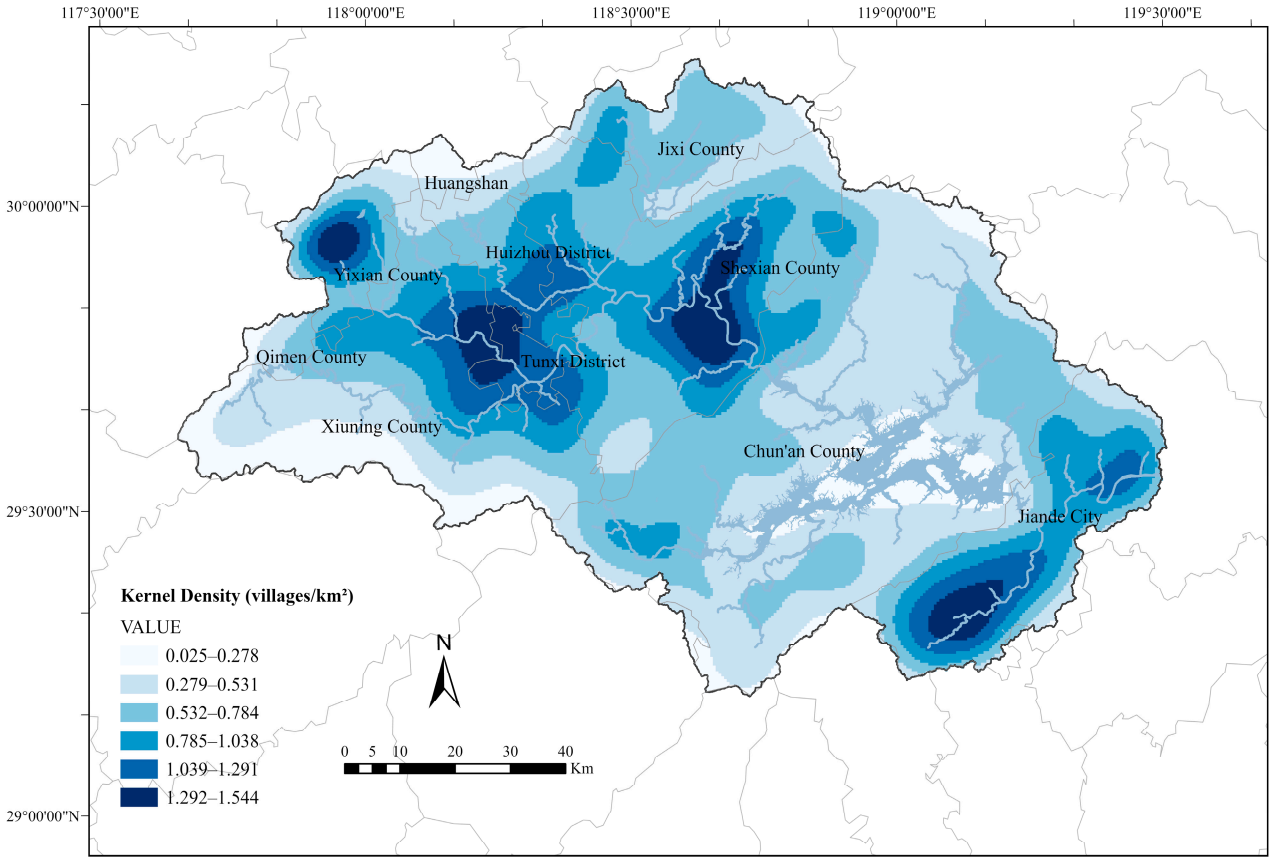


Figure 3. Kernel-density surface for all village toponyms. Projection: WGS 1984 UTM Zone 50N (EPSG: 32650).

Village toponyms in the Xin'an River Basin exhibit a "one-axis, four-core" pattern (Figure 4). The axis follows the main stem of the Xin'an River and its major tributaries, including the Lian and Heng rivers. The four high-density cores lie at the junction of Tunxi District, Huizhou District, and Xiuning County, in eastern Shexian County, in Yixian County, and in Jiande City. Their expansion along valleys and transport corridors reflects both physical accessibility and the historical development of Huizhou lineages and merchant networks.

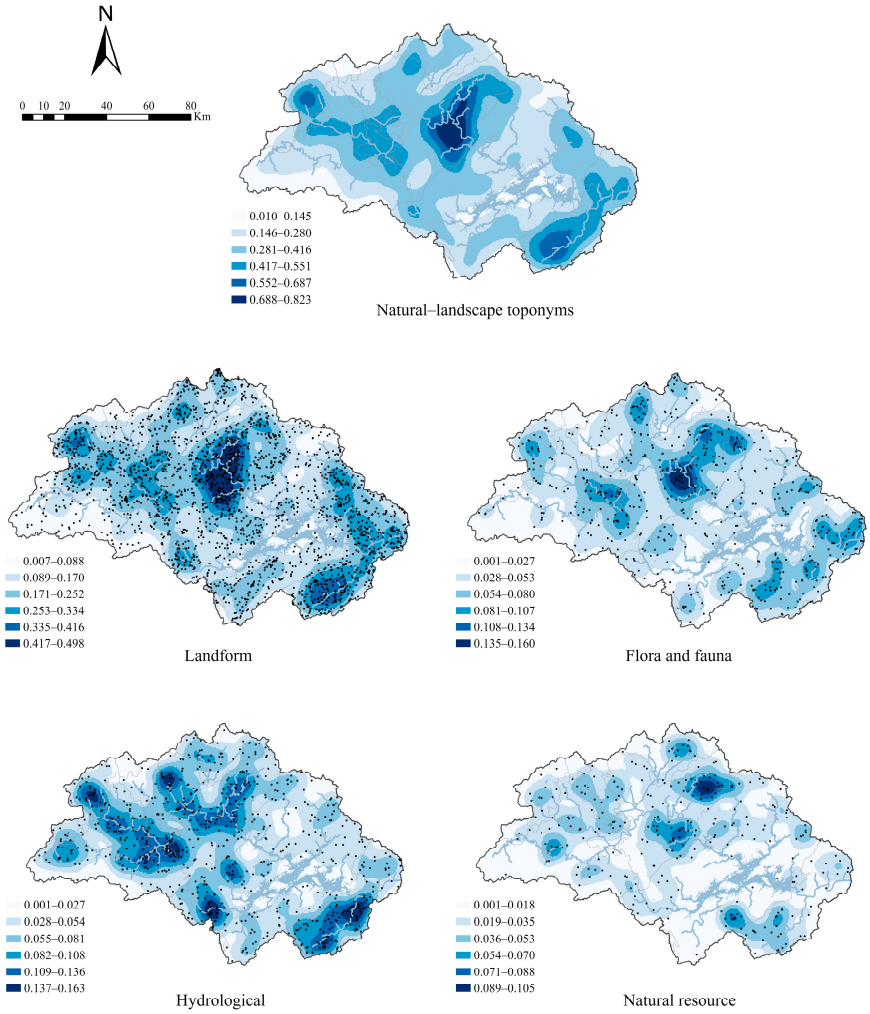


Figure 4. Kernel-density surfaces for natural-landscape toponyms and their subcategories. Projection: WGS 1984 UTM Zone 50N (EPSG: 32650).

3.2.1. Spatial Distribution of Natural-Landscape Toponyms

Natural-landscape toponyms also exhibit a clustered pattern (Table 6). Their highest densities occur in the central basin, especially in Shexian County, with smaller concentrations in Yixian County, Tunxi District, and Jiande City (Figure 4).

Table 6. Nearest neighbor index results for Natural-landscape toponyms in the study area.

Type	N	Observed Mean Distance (m)	Expected Mean Distance (m)	Nearest Neighbor Ratio (R)	Z-Score	*p*-Value	Distribution Type
Overall	3834	827.6	870.9	0.95	−5.897	<0.001	Clustered
Landform	2242	1032	1138.9	0.906	−8.502	<0.001	Clustered
Flora and fauna	579	1982.7	2241.1	0.885	−5.307	<0.001	Clustered
Hydrological	740	1745	1982.4	0.88	−6.231	<0.001	Clustered
Natural resource	273	2993.2	3263.8	0.917	−2.620	0.009	Clustered

Landform toponyms are concentrated in the transition between upstream mountains and river valleys, with a secondary presence in downstream plains. Terms such as ling

(ridge) and feng (peak) mark major relief, whereas wu (enclosed valley) and fan (flat cultivated land) distinguish finer landforms along basin margins. Flora-and-fauna toponyms occur mainly in mountainous and valley settings, particularly near the boundary between Shexian and Chun'an Counties. Hydrological toponyms show a basin-scale distribution broadly aligned with the drainage network throughout the basin and are most concentrated along upstream tributaries. Natural-resource toponyms are concentrated upstream and are less common downstream.

3.2.2. Spatial Distribution of Human-Landscape Toponyms

Human-landscape toponyms are significantly clustered (Table 7). Their highest densities occur in the central-western basin, especially in Tunxi District, Huizhou District, and Xiuning County, with smaller concentrations in Yixian County, Shexian County, and Jiande City (Figure 5).

Table 7. Nearest neighbor index results for Human-landscape toponyms in the study area.

Type	N	Observed Mean Distance (m)	Expected Mean Distance (m)	Nearest Neighbor Ratio (R)	Z-Score	*p*-Value	Distribution Type
Overall	4129	734.1	839.2	0.875	−15.403	<0.001	Clustered
Color	100	4882.7	5392.6	0.905	−1.809	0.070	Non-significant
Meteorological	74	5908.9	6268.8	0.943	−0.945	0.345	Non-significant
Degree and quantity	474	2216.0	2476.9	0.895	−4.388	<0.001	Clustered
Directional	1258	1211.9	1520.4	0.797	−13.768	<0.001	Clustered
Architectural	225	3476.0	3595.1	0.967	−0.950	0.342	Non-significant
Economic activity	228	3009.3	3571.3	0.843	−4.546	<0.001	Clustered
Military	33	6568.1	9387.3	0.700	−3.300	<0.001	Clustered
Hydraulic infrastructure	380	2397.1	2766.4	0.867	−4.977	<0.001	Clustered
Surname	1076	1382.1	1644.0	0.841	−9.995	<0.001	Clustered
Aspirational	281	2884.9	3217.0	0.897	−3.310	<0.001	Clustered

Color toponyms are associated with perceived environmental colors and are distributed mainly in downstream valleys and near upstream waterways. Meteorological toponyms generally follow mountain areas where elevation contributes to variable local weather. Degree-and-quantity toponyms cluster in upstream mountains and downstream valleys: mountain names often include terms meaning "deep" or "high," whereas valley names more often include "level" or "distant." Directional toponyms are frequently combined with other name elements and are widely distributed. Architecture toponyms cluster in the upper-basin Xiuning–Tunxi Basin and Lian River Plain and follow tributaries around Qiandao Lake downstream. Dense upstream waterways encouraged bridge-related names, while elevated hills and terraces provided relatively flood-safe sites for ancestral halls and memorial archways [47].

Economic-activity toponyms concentrate along the Xin'an River and its tributaries and in upstream basins, corresponding to Huizhou merchant transport routes. The radial drainage network connected the Yangtze, Qiantang, and Poyang Lake systems and supported commodity circulation. Military toponyms concentrate upstream, where mountain barriers and defensible basins provided strategic sites [48]. Hydraulic-infrastructure toponyms occur chiefly in upstream valleys and secondarily in downstream valleys. Seasonal rainfall variability in the subtropical monsoon climate [49] encouraged terrain-adapted water-control works for flood management and agriculture. Surname toponyms cluster in basins and valley plains but are scattered in mountain areas. Aspirational toponyms are concentrated in core settlement areas and become sparse toward the basin margins.

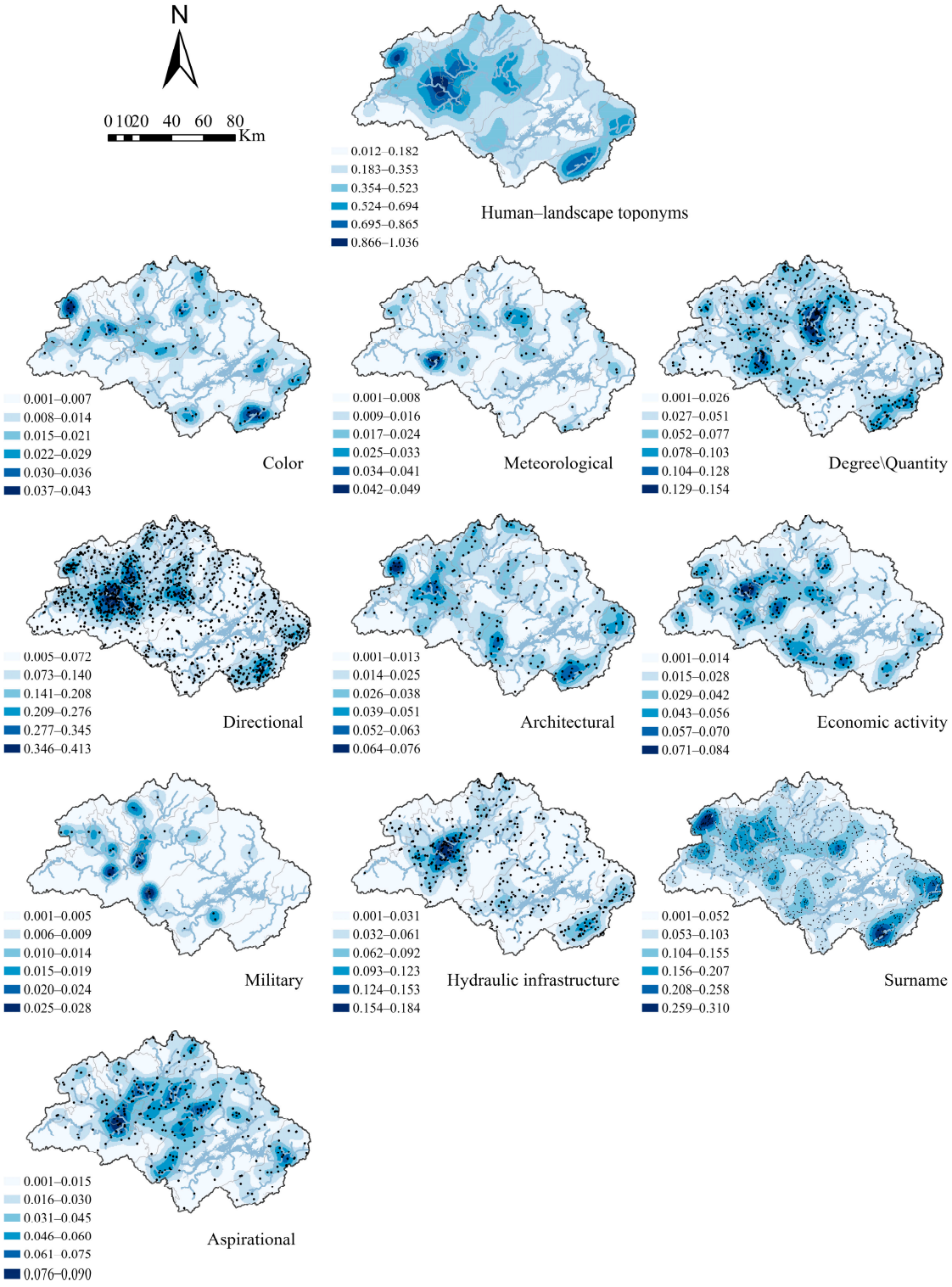


Figure 5. Kernel-density surfaces for Human-landscape toponyms and their subcategories. Projection: WGS 1984 UTM Zone 50N (EPSG: 32650).

3.3. Environmental Associations of Village Toponym Distribution

3.3.1. Environmental Variables

Based on previous research [50,51], seven potential explanatory factors were selected: elevation (X1), slope (X2), aspect (X3), topographic relief (X4), mean annual temperature

(X5), annual precipitation (X6), and river network density (X7). Together these variables represent topographic, hydrographic, and climatic conditions that may structure the spatial distribution of toponymic categories (Table 8).

Table 8. Environmental explanatory variables used in the GeoDetector analysis.

Variable	Dimension	Indicator	Calculation Method	Unit
Dependent variable	Toponymic landscape	All village toponyms (Y1)	Number of all village toponyms in each 5 km × 5 km grid cell.	count
		Natural-landscape toponyms (Y2)	Number of natural-landscape village toponyms in each 5 km × 5 km grid cell	count
		Human-landscape toponyms (Y7)	Number of human-landscape village toponyms in each 5 km × 5 km grid cell	count
Independent variables	Topography	Elevation (X1)	Mean elevation within each grid cell, calculated from the 30 m DEM.	m
		Slope (X2)	Mean slope within each grid cell, derived from the 30 m DEM.	°
		Aspect (X3)	Circular mean aspect within each grid cell, derived from the 30 m DEM.	°
		Topographic relief (X4)	Difference between the maximum and minimum elevations within each grid cell.	m
	Climate	Mean annual temperature (X5)	Mean value of the 2024 annual mean temperature raster within each grid cell.	°C
		Annual precipitation (X6)	Mean value of the 2024 annual precipitation raster within each grid cell.	mm
	Hydrology	River network density (X7)	Total river length within each grid cell divided by its area.	km/km²

3.3.2. Single-Factor Results

Based on the results of the single-factor detection, the q values (Table 9) were obtained indicating the explanatory power of each indicator on the distribution in the Xin'an River Basin.

For all village toponyms (Y1), river network density had the highest explanatory power (q = 0.247). Elevation, slope, aspect, topographic relief, and river network density were significant, whereas mean annual temperature and annual precipitation were not. This result indicates that the overall distribution of toponyms is mainly constrained by the terrain pattern and water system environment [52].

Table 9. GeoDetector single-factor results for village-toponym categories.

Toponym Category	Elevation X1	Slope X2	Aspect X3	Topographic Relief X4	Mean Annual Temperature X5	Annual Precipitation X6	River Network Density X7
All toponyms Y1	0.227 **	0.075 **	0.034 *	0.052 **	0.018	0.019	0.247 **
Natural-landscape total Y2	0.170 **	0.048 **	0.017	0.027 *	0.014	0.015	0.187 **
Natural—landform Y3	0.143 **	0.043 **	0.022	0.026 *	0.024 *	0.014	0.143 **
Natural—flora/fauna Y4	0.054 **	0.024 *	0.018	0.022 *	0.011	0.012	0.076 **
Natural—hydrological Y5	0.113 **	0.038 *	0.014	0.025 *	0.018	0.021 *	0.116 **
Natural—resource Y6	0.050 **	0.012	0.015	0.018	0.015	0.010	0.047 **
Human-landscape total Y7	0.228 **	0.093 **	0.049 **	0.095 **	0.021 *	0.018	0.250 **
Human—color Y8	0.043 **	0.050 **	0.011	0.016	0.013	0.009	0.041 **
Human—meteorological Y9	0.024 *	0.008	0.012	0.007	0.011	0.007	0.006
Human—degree/quantity Y10	0.048 **	0.015	0.023 *	0.018	0.015	0.014	0.068 **
Human—direction Y11	0.144 **	0.076 **	0.036 *	0.101 **	0.016	0.011	0.157 **
Human—architecture Y12	0.040 **	0.030 *	0.013	0.020 *	0.020 *	0.010	0.075 **
Human—economic activity Y13	0.109 **	0.063 **	0.018	0.044 **	0.012	0.016	0.084 **
Human—military Y14	0.024*	0.049 **	0.006	0.025*	0.012	0.025 *	0.032 *
Human—hydraulic infrastructure Y15	0.191 **	0.096 **	0.072 **	0.132 **	0.016	0.028 *	0.156 **

Human—surname Y16	0.153 **	0.049 **	0.027 *	0.050 **	0.022 *	0.017	0.155 **
Human—aspirational Y17	0.066 **	0.029 *	0.025 *	0.031 *	0.017	0.013	0.077 **

Note: * $p < 0.05$; ** $p < 0.01$.

(1) Factors Influencing Natural-Landscape Toponyms

River network density and elevation had the highest explanatory power for natural-landscape toponyms overall (Y2), with q values of 0.187 and 0.170, respectively. Slope and topographic relief were also significant, whereas aspect and the two climatic variables were not.

The relative importance of these factors varied among subcategories. Elevation and river network density were equally explanatory for landform toponyms (Y3, q = 0.143). River network density was the strongest factor for flora-and-fauna toponyms (Y4, q = 0.076) and hydrological toponyms (Y5, q = 0.116), while elevation ranked highest for natural-resource toponyms (Y6, q = 0.050).

(2) Factors Influencing Human-Landscape Toponyms

River network density and elevation also had the highest explanatory power for human-landscape toponyms overall (Y7), with q values of 0.250 and 0.228, respectively. Topographic relief, slope, aspect, and mean annual temperature were significant, although the explanatory power of temperature was low. Annual precipitation was not significant.

River network density ranked highest for degree-and-quantity (Y10), directional (Y11), architectural (Y12), surname (Y16), and aspirational toponyms (Y17). Among these categories, its explanatory power was greatest for directional and surname toponyms (q = 0.157 and 0.155, respectively). Elevation was the strongest factor for economic-activity toponyms (Y13, q = 0.109) and hydraulic-infrastructure toponyms (Y15, q = 0.191). Color and military toponyms were most strongly associated with slope, but their q values were low (0.050 and 0.049, respectively). Meteorological toponyms likewise showed low explanatory power across the tested variables, with elevation yielding the highest value (Y9, q = 0.024).

3.3.3. Interaction Results

(1) All village toponyms in the Xin'an River Basin

In the overall toponymic cultural landscape (Y1), the interaction between elevation (X1) and river network density (X7) is the strongest, with a q value of 0.343, followed by elevation (X1) and topographic relief (X4), with a q value of 0.336 (Figure 6).

(2) Natural-landscape toponyms

For natural-landscape toponyms as a whole (Y2), elevation and river network density had the strongest interaction (q = 0.280). Topographic relief and river network density ranked second (q = 0.263). This shows that the distribution of natural-landscape toponyms is mainly related to terrain and water-system conditions (Figure 7).

For landform toponyms (Y3), the main interaction was between elevation and aspect (q = 0.208). Elevation and topographic relief ranked second (q = 0.204). The spatial distribution of landform toponyms is associated with combinations of elevation, aspect, and topographic relief.

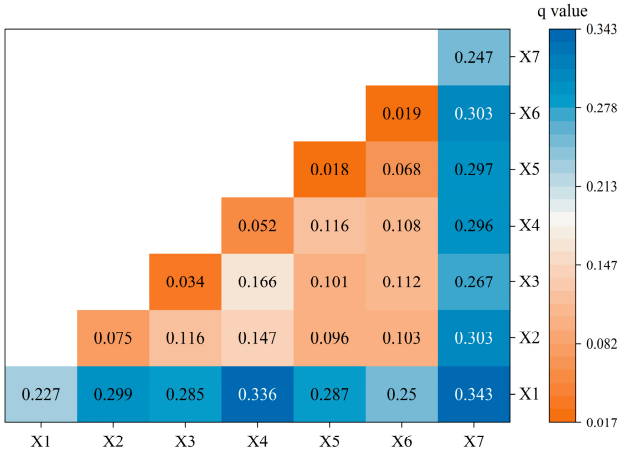


Figure 6. GeoDetector interaction results for the overall distribution of village toponyms (Y1).

For flora and fauna toponyms (Y4), aspect and topographic relief had the strongest interaction (q = 0.148). Slope and river network density ranked second (q = 0.139). Hydrological toponyms (Y5) were mainly related to the interactions between mean annual temperature and river network density (q = 0.244) and between elevation and mean annual temperature (q = 0.221).

For natural-resource toponyms (Y6), elevation and river network density had the strongest interaction (q = 0.185). Aspect and river network density ranked second (q = 0.152).

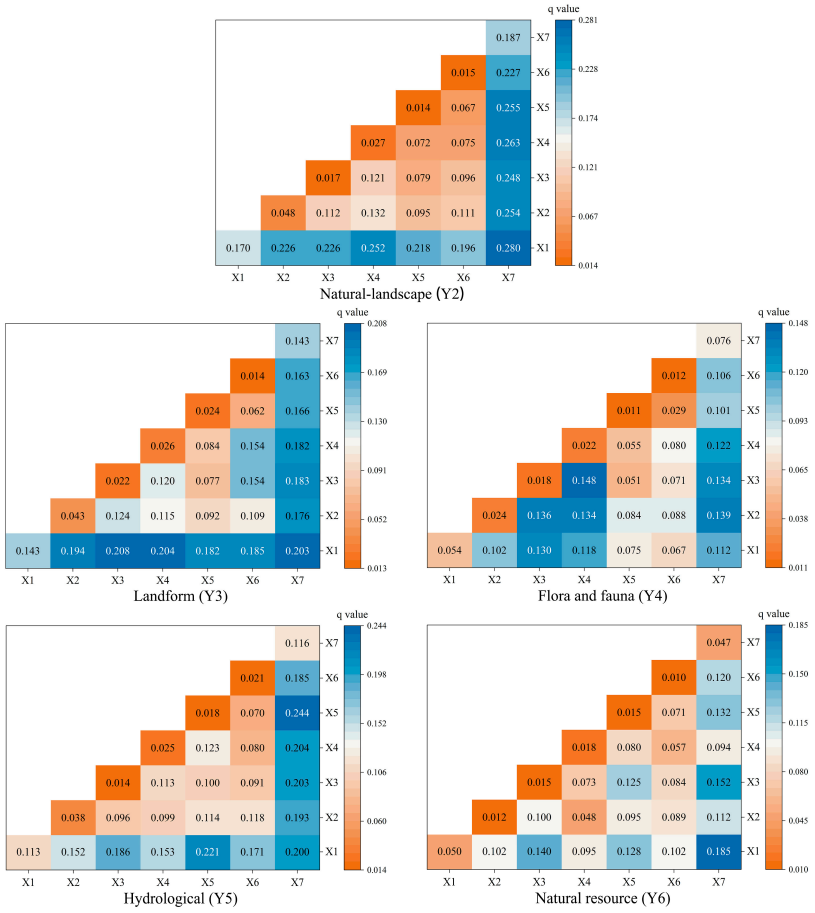


Figure 7. GeoDetector interaction results for natural-landscape toponyms (Y2) and their semantic subcategories (Y3–Y6).

(3) Human-landscape toponyms

In the overall category of human-landscape toponyms (Y7), the interaction between elevation (X1) and slope (X2) had the highest explanatory power (q = 0.342). The interaction between elevation and river network density (X7) ranked second (q = 0.315). This shows that the spatial distribution of human-landscape toponyms is related to the topographic and hydrological conditions of settlement locations (Figure 8).

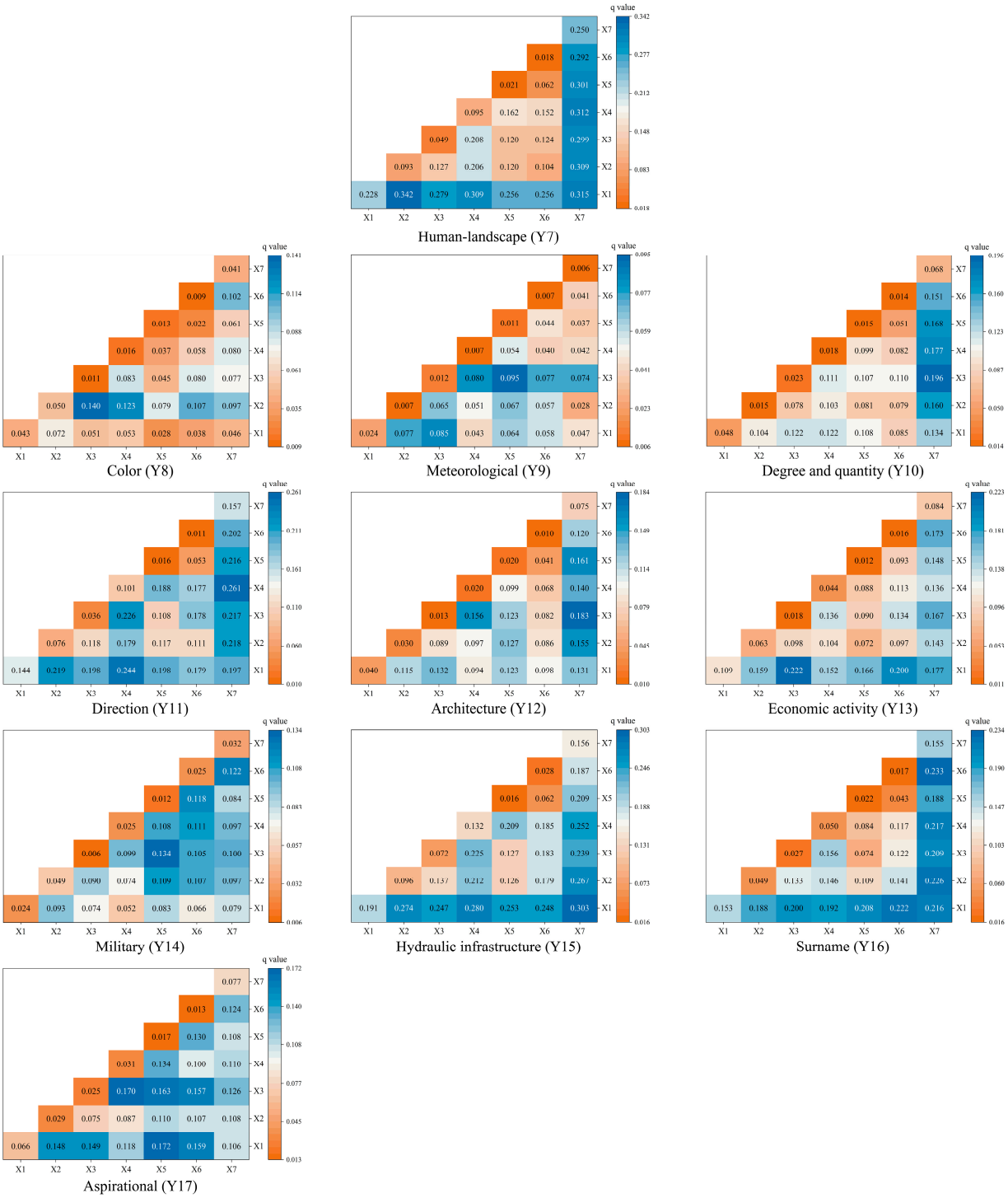


Figure 8. GeoDetector interaction results for human-landscape toponyms (Y7) and their semantic subcategories (Y8–Y17).

For color toponyms (Y8), the strongest interaction was between slope and aspect (q = 0.140). The interaction between slope and topographic relief ranked second (q = 0.123). For meteorological toponyms (Y9), the interaction between aspect and mean annual temperature was strongest (q = 0.095), followed by elevation and aspect (q = 0.085). The low q values show a weak relationship with local environmental conditions.

Degree-and-quantity toponyms (Y10) were mainly related to the interactions between aspect and river network density (q = 0.196) and between topographic relief and river network density (q = 0.177). For directional toponyms (Y11), the interaction between topographic relief and river network density was strongest (q = 0.261), followed by elevation and topographic relief (q = 0.244). For architectural toponyms (Y12), the main interactions were aspect and river network density (q = 0.183) and mean annual temperature and river network density (q = 0.161). Economic-activity toponyms (Y13) were mainly related to elevation and aspect (q = 0.222) and elevation and annual precipitation (q = 0.200).

For military toponyms (Y14), the strongest interaction was between aspect and mean annual temperature (q = 0.134). Annual precipitation and river network density ranked second (q = 0.122). For hydraulic-infrastructure toponyms (Y15), elevation and river network density formed the main interaction (q = 0.303), followed by elevation and topographic relief (q = 0.280). Surname toponyms (Y16) were mainly related to annual precipitation and river network density (q = 0.233) and slope and river network density (q = 0.226). For aspirational toponyms (Y17), elevation and mean annual temperature had the highest explanatory power (q = 0.172), followed by aspect and topographic relief (q = 0.170).

3.4. Semantic–Environmental Correspondence and Historical Interpretation

Village toponyms contain information about the natural environment, production, daily life, and local history. Their semantic classification and spatial distribution provide clues for understanding human–environment relationships [53]. This section first tests the correspondence between natural-landscape meanings and local terrain and water systems, then combines the results with documentary records to examine environmental use and cultural memory recorded in historical-cultural landscape names.

3.4.1. Natural-Landscape Meanings and Environmental Features

Highland and mountain toponyms (H2) have a median 1 km neighborhood relative elevation of −29.03 m, compared with a permutation-null median of −36.93 m (Δ = 7.90 m; SES = 4.55; Holm-adjusted p = 0.0016). This indicates that, under random label exchange within blocks, villages in this category occupy relatively higher local terrain positions than expected. However, their median relative elevation remains negative, indicating that these villages generally lie below the mean elevation of their respective neighborhoods (Table 10; Figure 9a).

Lowland and hollow toponyms (H1) have a median relative elevation of −44.04 m, compared with a null median of −42.21 m, yielding an actual deviation of −1.83 m. Gentle-terrain names (H3) have a median slope of 8.11°, compared with a null median of 8.27°, yielding an actual deviation of −0.16°. Both groups deviate in the expected directions, but neither reaches statistical significance. Terrain constraints concentrate villages in the Xin'an River Basin in valleys and on gentle terrain, where access to water and transport is easier [54,55]. As a result, villages in different toponymic semantic groups may occupy similar terrain.

Linear-water toponyms (H4) have a median nearest-river distance of 74.06 m, compared with a null median of 142.09 m, yielding an actual deviation of −68.03 m (SES = 5.44). The corresponding distance for surface-water toponyms (H6) is 85.30 m, compared with a null median of 137.00 m, yielding an actual deviation of −51.70 m (SES = 4.69). Both

groups exhibit river proximity consistent with the expected direction. However, waterfront toponyms (H5) have an observed median distance of 144.90 m, compared with a null median of 149.34 m, yielding an actual deviation of −4.44 m that is not statistically significant (Figure 9c).

Among the comparison categories, color (C1) and meteorological toponyms (C2) showed no significant deviations from the permutation null distribution. Aspirational toponyms (C3) were significantly closer to rivers than expected (Δ = −33.10 m, Holm-adjusted p = 0.0084), indicating that river proximity extends beyond toponyms with hydrological meanings. These associations are conditional on village locations and within-block category counts.

Local records identify the features behind specific toponyms. In Songkeng (竦坑), *keng* denotes a stream valley, while *tan* in Pingtan(平坦) denotes flat land [56]. Pukou(浦口) refers to a waterfront at a river confluence, and Yuetan (瀹潭) takes its name from the nearby Yueyuan River and a deep pool in the Xin'an River [40].

Table 10. Tests of semantic–environmental correspondence (Spatially restricted label permutations within 10 km blocks, B = 9999).

Test	n	Metric	Observed Median	Null Median (95% Quantile Range)	Actual Deviation Δ	SES	P (Holm)
H1	995	1 km relative elevation (m)	−44.04	−42.21 (−45.20, −39.12)	−1.83	1.15	0.7560
H2	1067	1 km relative elevation (m)	−29.03	−36.93 (−40.22, −33.81)	7.90	4.55	0.0016
H3	180	Slope (°)	8.11	8.27 (6.82, 9.73)	−0.16	0.20	1.0000
H4	313	Nearest-river distance (m)	74.06	142.09 (119.23, 171.00)	−68.03	5.44	0.0016
H5	56	Nearest-river distance (m)	144.90	149.34 (104.31, 225.57)	−4.44	0.28	1.0000
H6	371	Nearest-river distance (m)	85.30	137.00 (116.16, 160.62)	−51.70	4.69	0.0016
H7	146	Nearest-river distance (m)	64.77	151.12 (119.90, 195.21)	−86.35	4.57	0.0016
H8	45	Specified river distance (km)	0.45	1.434 (0.826, 2.135)	−0.98	2.88	0.0032
C1	100	Nearest-river distance (m)	124.62	155.27 (114.60, 216.32)	−30.65	−1.27	0.3600
C2	74	1 km relative elevation (m)	−39.59	−39.76 (−53.22, −27.20)	0.17	0.06	0.9758
C3	281	Nearest-river distance (m)	109.10	142.20 (118.25, 171.61)	−33.10	−2.53	0.0084

Note: The 95% range represents the 2.5th and 97.5th percentiles of the null distribution.

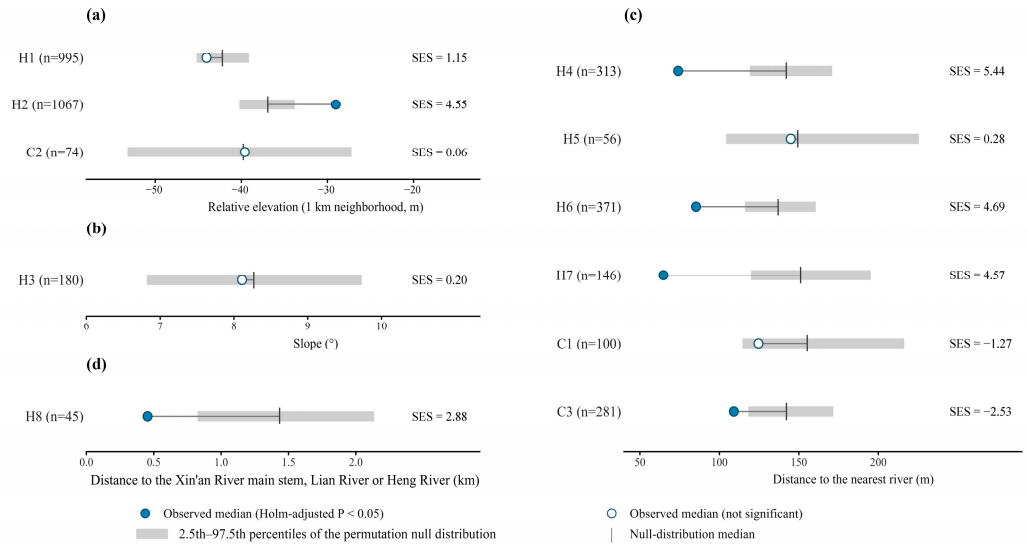


Figure 9. Tests of semantic–environmental correspondence in village toponyms. (**a**) 1 km neighborhood relative elevation, (**b**) slope, (**c**) distance to the nearest river, and (**d**) distance to the nearest of the Xin'an River main stem, the Lian River, and the Heng River.

3.4.2. Hydraulic-Infrastructure and Ferry-Transport Meanings and Environmental Use

Hydraulic-infrastructure and ferry or water-transport toponyms record how people have used and modified water environments. The composition and distribution of water-related names are shaped by both natural conditions and socioeconomic factors [57]. Hydraulic-infrastructure names (H7) have a median nearest-river distance of 64.77 m, compared with a null median of 151.12 m, yielding a difference of −86.35 m (SES = 4.57). Ferry or water-transport names (H8) have a median distance of 0.454 km to the nearest of the Xin'an River main stem, the Lian River, and the Heng River, compared with a null median of 1.434 km, yielding a difference of −0.980 km (SES = 2.88). Both deviations are consistent with the expected directions in Table 3, indicating spatial associations between these facility-related meanings and rivers (Table 10; Figure 9c,d).

Historical records connect these meanings with specific activities. A *hui* (塝) is a type of weir characteristic of Huizhou. Chengjiahui (程家塝) was named after a weir built by residents of the Cheng lineage, preserving a record of both the builders and the structure [42]. The Xin'an River network historically connected Huizhou with Hangzhou and markets in the Jiangnan region [58]. Yuliang (渔梁) takes its name from a dam across the river and was once an important gateway for Huizhou merchants [44]. The element *du* in Censhandu (岑山渡) denotes a ferry crossing, and historical records document its role in the distribution of goods [40].

3.4.3. Name Continuity and Historical Interpretation

Toponym meanings and their evolution can shed light on local livelihoods, cultural identity, and settlement history. Of the 56 villages with waterfront toponyms (H5), 25 (approximately 45%) lie more than 500 m from the nearest present-day river. Two factors may help explain this pattern. Heavy rainfall in the Xin'an River Basin can cause rapid fluctuations in mountain river levels, which may have encouraged settlement farther from riverbanks [59]. Waterfront toponyms also often refer to minor tributaries or small waterfront features. Over time, some of these watercourses may have shifted, shrunk, or disappeared because of sedimentation, land reclamation, culvert installation, or reservoir construction [52].

Historical records show that Jiushi (旧市) retains the element *shi*, referring to its former marketplace [41]. Jiekou (街口) retained its name after reservoir construction prompted its relocation farther inland, linking the former and current village sites [44]. Huangdun was known at different times as Yaojiadun (姚家墩), Huangdun (黄墩), and Huangdun (篁墩). During the Ming dynasty, Cheng Minzheng restored the form 篁墩 and associated it with the deeds of his ancestors [40]. These cases illustrate how village names can preserve earlier settlement functions, persist after relocation, or acquire new interpretations.

4. Discussion

The "one-axis, four-core" spatial pattern of village toponyms in the Xin'an River Basin is associated with natural environmental conditions and contains information about settlement development and historical human activities. This study examines village toponyms at both the basin-wide distribution and local semantic levels, identifying associations between toponymic concentrations and environmental factors such as terrain and river networks, while testing the correspondence between village-toponym meanings and local environmental characteristics. Historical documents are further used to interpret human–environment relationships and cultural memory reflected in water management, waterborne transport, and toponym continuity.

4.1. Environmental Constraints and Human Adaptation

Compared with toponymic studies focused on individual villages or administrative units, a basin-scale approach integrates river networks, valleys, settlements, and their historical connections across administrative boundaries. Previous research has identified basin-wide coherence in the distribution of traditional waterside settlements and their cultural heritage in the Nanxi River Basin [60]. This study extends the basin-scale approach to village-toponym analysis, combining basin-wide spatial distributions with local semantic–environmental tests to examine the environmental and historical-cultural characteristics reflected in toponymic spatial patterns.

The results show that river network density and elevation have the highest single-factor explanatory power for village-toponym distributions, followed by slope, with the strongest interaction occurring between elevation and river network density. Block-restricted label permutations further indicate that highland and mountain toponyms have higher relative elevations than expected under permutation, while linear-water and surface-water toponyms exhibit shorter river distances than expected. These findings reveal both the environmental context of overall toponymic concentrations and the correspondence between specific naming elements and local environmental characteristics.

Landform toponyms occur mainly in mountain–valley transition zones, while hydrological and hydraulic-infrastructure toponyms reflect local water conditions and water-management practices. Climate may also influence toponym formation indirectly through hydrology, vegetation, and agricultural activities. Similarly, research in western Hunan found that natural-landscape toponyms were primarily associated with terrain, water systems, and vegetation, whereas cultural-landscape and hydraulic-infrastructure toponyms reflected both environmental conditions and historical processes [53]. By combining semantic–environmental tests with historical records of water management and ferry transport, this study further supports the interpretation of some toponyms as historical records of human–environment interactions [61], although their specific formation processes require additional historical evidence.

4.2. Historical Layering of Human Activities

The spatial relationships identified in this study can be interpreted through the perspective of "environmental filtering, human selection, and cultural inscription" [62]. Natural environmental conditions provide the basis for settlement development, while human activities influence the identification and naming of locally significant features. The continuation or reinterpretation of toponyms may preserve historical information even after settlement functions or spatial patterns change. Military toponyms are mainly distributed in the upper basin, whereas economic-activity toponyms tend to concentrate along rivers, indicating spatial associations between historical activities and geographical settings [63,64]. Migration, lineage, and religious traditions also provide historical and cultural contexts for understanding toponyms [65], although their specific influences require further verification. These patterns share some similarities with findings on toponymic cultural heritage in Jiangsu Province [66]. In both regions, toponyms tend to concentrate in densely populated and economically active areas, suggesting associations between historical toponyms, population concentration, settlement expansion, and socioeconomic activities.

Water management and waterborne transport provide important clues for understanding the historical and cultural meanings of village toponyms. Block-restricted label permutations indicate that hydraulic-infrastructure and ferry or water-transport toponyms have shorter river distances than expected under permutation, while historical records provide additional evidence of their naming contexts. Hydraulic-infrastructure toponyms may record local water-use and management practices, whereas ferry and water-

transport toponyms preserve information about historical river transport and settlement connections. In addition, some toponyms have persisted following settlement relocation or changes in settlement functions, suggesting that they can retain memories of earlier settlement activities. Previous research has shown that the continued use of toponyms contributes to the transmission of place meanings and collective memory [67]. Thus, village toponyms not only reflect historical human–environment relationships but may also preserve local cultural information through name continuity.

4.3. Implications for Cultural Heritage Sustainability

Toponyms reflect long-term links between the natural environment, settlement growth, and social practices. The findings provide information about terrain, water systems, production, daily life, and social memory [67].

The results have practical implications for cultural heritage sustainability. First, the "one-axis, four-core" pattern can help coordinate toponym documentation across administrative boundaries. Second, semantic categories can inform interpretation routes, village signage, and digital gazetteers that connect names with local terrain, water management, lineages, and livelihoods. Third, conservation should retain both the name and its spatial setting, particularly along river corridors where landscape change may sever the relationship between a toponym and the feature or practice it records [68]. Such measures can integrate historical-toponym protection with rural revitalization while avoiding the homogenization of local cultural identity.

4.4. Limitations and Future Research

This study has several limitations. First, the cross-sectional toponym dataset cannot capture historical changes in settlement names, locations, or administrative boundaries, and the completeness of Baidu Maps API records remains uncertain. Second, present-day environmental conditions may differ from historical landscapes, while river distance may not adequately reflect historical hydrology or original village toponym meanings. Third, block-restricted label permutations held village locations and within-block category counts fixed, but local confounding may remain. The results therefore represent conditional associations. Furthermore, historical records cover selected cases, limiting conclusions about naming processes across the basin. Intercoder agreement in semantic classification has yet to be independently assessed. Future research should integrate historical maps, gazetteers, archival records, oral histories, and field investigations to examine toponymic evolution and its social and environmental contexts.

5. Conclusions

Analysis of 7963 village toponyms in the Xin'an River Basin revealed spatial variation in their distribution, environmental factors associated with that variation, and links between name meanings and local environments. The main findings are as follows:

(1) The 7963 village toponyms in the Xin'an River Basin are significantly clustered (ANN = 0.968, z = −5.524, $p < 0.001$), forming a "one-axis, four-core" pattern along the main stem and major tributaries.

(2) River network density ($q = 0.247$) and elevation ($q = 0.227$) have the highest single-factor explanatory power for the spatial variation in overall grid-level village toponym counts, followed by slope (q = 0.075). Elevation and river network density have the strongest interaction for both all village toponyms ($q = 0.343$) and natural-landscape toponyms ($q = 0.280$), whereas elevation and slope have the strongest interaction for human-landscape toponyms ($q = 0.342$).

(3) Permutation tests indicate that highland and mountain toponyms have higher relative elevation than expected under permutation, while linear-water, surface-water,

hydraulic-infrastructure, and ferry or water-transport toponyms exhibit river proximity. The tests do not support the predefined environmental associations for lowland and hollow, gentle-terrain, or waterfront toponyms. Aspirational toponyms also show significant river proximity. Historical records identify the features and activities behind individual names and show how names can persist after settlement functions or locations change.

The findings can inform historical-toponym documentation, coordinated conservation across administrative boundaries, and rural landscape planning. Future research should combine systematic historical records, field verification, and cross-basin comparisons to assess the scope of these findings.

Author Contributions: Conceptualization, F.J. and C.Y.; methodology, F.J. and C.Y.; software, C.Y. and L.T.; validation, F.J., C.Y. and L.T.; formal analysis, C.Y.; investigation, C.Y. and L.T.; resources, F.J.; data curation, C.Y. and L.T.; writing—original draft preparation, C.Y.; writing—review and editing, F.J., C.Y. and L.T.; visualization, C.Y. and L.T.; supervision, F.J.; project administration, F.J.; funding acquisition, F.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Key Project of the Anhui Provincial Philosophy and Social Science Fund, grant number AHSKD2024D021.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The environmental datasets used in this study are available from the data sources described in Section 2.2.1. Village toponym data were derived from the Baidu Maps Open Platform and cross-validated using local gazetteers and historical sources. The processed datasets supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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