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How does historical culture shape the village clusters: Multi-dimensional Network and cluster analysis in Xinghua rural areas, China

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Abstract

This study aims to explore how historical and cultural heritage can serve as a key spatial force to reshape the network structure and agglomeration patterns of village clusters. Taking Xinghua City in China as a case study, this study systematically compares geographical and cultural factors to reveal the core role of historical culture in filling the limitations of a purely geographical perspective and promoting coordinated development of villages. The study constructed a dual analytical framework that integrates geographical foundations and cultural context. Firstly, a gravity model is constructed based on geographical factors such as village size, water system, and cultivated land, and geographic network and cluster analysis are conducted. Subsequently, incorporating the relationship between tangible and intangible cultural heritage, statutory cultural protection areas, and place name culture into the gravity model, constructing a cultural network, and conducting cluster identification. By comparing the spatial patterns, node levels, and connectivity structures of geographic networks and clusters with cultural networks and clusters, the unique influence of cultural factors is revealed. Research has found that: (1) There is a significant spatial mismatch between geography and cultural clusters, and cultural influence can transcend geographical barriers and form continuous cultural radiation belts; (2) Historical Culture, as a mechanism of selective reinforcement, significantly deepens the gravitational differences among individual villages, enabling villages with profound historical accumulation such as *Duotian* Aquatic Village to surpass their geographical limitations and become high-level nodes in the cultural network; (3) Historical and cultural gravity effectively repairs the discontinuity in connectivity strength in geographic networks by generating medium strength connections based on shared historical memory, reshapes the pattern of inter village associations, and presents a higher centripetal force and structural density in the network. The research provides a key scientific basis for the concentrated and contiguous protection of traditional Chinese villages and rural revitalization: planning practices must go beyond simple geographical proximity, prioritize the identification and activation of cultural networks based on common historical context, and guide resource optimization and regional coordinated development.

Key Words: historical culture; traditional village clusters; rural space; spatial network; morphology agglomeration; gravity model

1 Introduction

In recent years, sustainable development and cultural heritage preservation in rural areas have become core issues in global policy and academic research. To address the common challenges of insufficient rural vitality and lagging development (Aguirre & Bermúdez, 2025; García et al., 2024; García, 2024), the international community has formed a multi-level protection from macro goals to specific practices. At the strategic level, the United Nations Sustainable Development Goals (SDGs), particularly Goal 11, explicitly require "strengthening the protection and defense of world cultural and natural heritage" (United Nations, 2015). At the regional practice level, the EU has deeply integrated cultural heritage protection into rural landscape management, biodiversity maintenance, and community economic revitalization through its Common Agricultural Policy such as the Rural Development Policy, forming a

systematic path of promoting development through heritages (Andersen et al., 2020). At the same time, UNESCO promotes the recognition and protection concept of "cultural landscapes", elevating the overall historical environment and intangible cultural traditions of rural areas to the same important status as world-class individual heritage sites (UNESCO, 2015). These international initiatives collectively point towards an integrated conservation model that goes beyond the static preservation of individual rural monuments and emphasizes cultural heritage as an endogenous driving force for activating rural social resilience and promoting comprehensive revitalization (Perkins et al., 2023; Piras, Pan, et al., 2024; Rey-Pérez & Domínguez-Ruiz, 2020).

In China, the understanding and practice of rural heritage have entered a new stage, characterized by a shift from focusing on individual villages to emphasizing centralized and contiguous regional protection (Huang & Wang, 2023; Z. G. Wang et al., 2024; Xue & Huang, 2024). Traditional villages, as the largest and most widely distributed living cultural heritage system, do not exist in isolation (Liu et al., 2022). They interweave with each other in terms of natural geography, historical evolution, and cultural connections, together forming a complex system with hierarchical structure and internal connections. Therefore, research that only starts from administrative boundaries or individual forms is insufficient, and it is necessary to deeply reveal the deep spatial logic formed by the long-term superposition of natural and cultural elements behind them. This centralized and contiguous protection aims to provide a more solid theoretical and practical foundation for achieving sustainable rural revitalization and cultural heritage inheritance by exploring the systematic connections between villages (Liu & Li, 2017; Zhang et al., 2021).

Previous studies have shown that discussions on rural areas mainly focus on the following key areas. This includes the study on the geographic spatial distribution characteristics of rural areas (H. L. Liu et al., 2024; Sun et al., 2025; Xu et al., 2024; Yang et al., 2022). Early study on the spatial distribution of rural settlements mainly focused on morphological description and pattern recognition, mainly using GIS spatial analysis tools including kernel density analysis and nearest neighbor index (Chen et al., 2024; Chen & Li, 2024; Liu et al., 2023; Wang & Zhang, 2021) to quantitatively characterize the distribution types, density differentiation, and location characteristics of settlements. With the deepening of research, scholars have gradually shifted from descriptive analysis to mechanistic interpretation, paying attention to the role of multiple factors such as socio-economic and policy systems in shaping the spatial pattern of settlements (Guo et al., 2021; Wang et al., 2023). For example, by introducing spatial regression models, geographic detectors, and other methods, study has found that the distribution of rural settlements is not only constrained by natural background conditions, but also closely related to factors such as industrial development (Geng et al., 2025), population mobility, land policies, and historical evolution. Meanwhile, the international academic community's analysis of the morphological structure of rural settlements (Löschenbrand et al., 2023; Piras et al., 2024; Rao et al., 2025) also experienced an expansion from individual buildings to groups, gradually shifting from early single building protection to a centralized and contiguous protection and development model that emphasizes regional coordination, landscape integrity, and community participation. Tao et al. (2024) systematically reviewed the evolution of rural settlement study in China from individual buildings to group patterns, and pointed out that current study is shifting from "point analysis" to "networked association" (Liu et al., 2024; Yuan et al., 2025).

It is this perspective of "networked connections" that leads study towards exploring the deep historical and cultural dynamics behind it.

However, existing research on the causes of village spatial agglomeration often focuses on quantitative analysis of economic and geographical factors or forms. Due to the difficulty in quantifying historical documents and local knowledge, there is still a lack of systematic integrated research on how historical and cultural heritage, as endogenous elements, interacts with geographical environments and jointly shapes the internal mechanisms of village spatial networks. Therefore, this study emphasizes that understanding the structural connections between villages must pay attention to their common historical and cultural layering processes. The potential for collaborative development in many villages is not only due to their geographical proximity, but also because they share a natural evolutionary history and have deep cultural connections. Based on this understanding, this study attempts to systematically sort out and spatially integrate scattered historical and cultural information on the basis of traditional village form and scale analysis, aiming to construct an analytical framework that integrates geographical basis and cultural context (Fig. 1), and reveal how the two jointly drive the agglomeration of traditional villages. This exploration not only helps to compensate for the lack of cultural mechanism explanation in current research, but also provides a new perspective based on historical logic and spatial correlation for the regional overall protection and revitalization of traditional village cultural heritage.

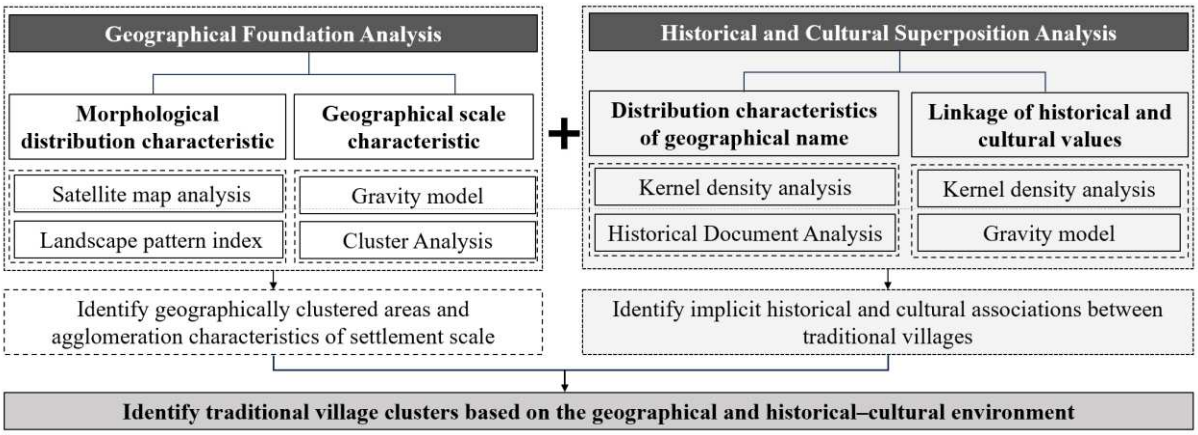


Figure 1. The technical route of the study

2 Study region and background

Xinghua is a county-level city in Jiangsu Province, administered by Taizhou City, China. It is located in the central part of Jiangsu Province, between the Yangtze River and the Huai River (Fig. 2). The city covers an area of 2,393 square kilometers and has administrative jurisdiction over 26 townships, 3 streets, and 678 villages. Xinghua lies in the *Lixia River* Plain, characterized by low-lying depressions formed on former tidal flats (Fig. 3). The region's unique landscape offers strong potential for collaborative agglomeration and development. Currently, Xinghua has achieved full coverage of development-oriented village planning and plays a crucial role in national-level rural revitalization initiatives, including the construction of characteristic rural demonstration areas and traditional villages. This study uses Xinghua as a case to illustrate the practical characteristics of rural space, offering insights and practical guidance for delineating regional collaborative agglomeration units.

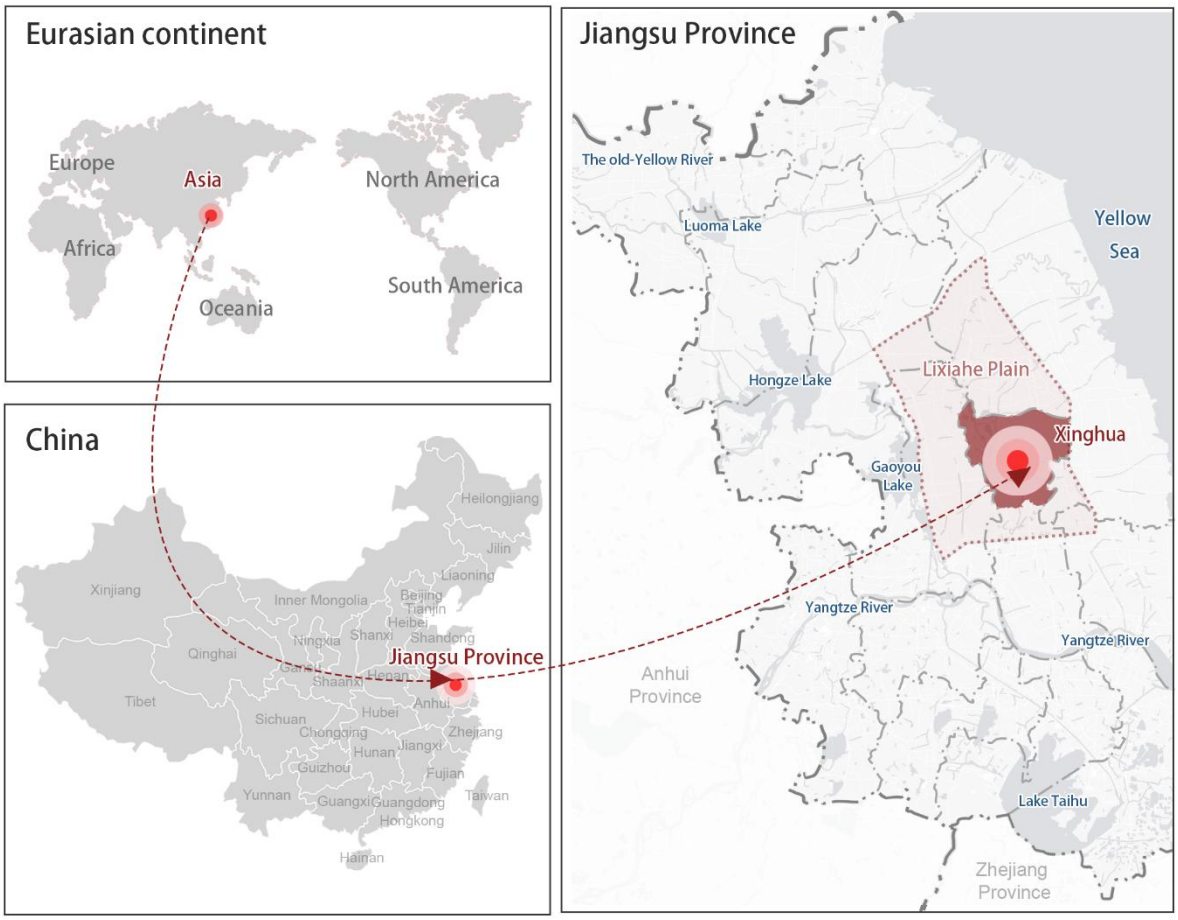


Figure 2. The location of Xinghua



Figure 3. Features of Xinghua rural spaces

2.1 The landform of the same origin is gradually differentiating, with distinctive features

Regions with similar geomorphic foundations gradually develop differentiation under the combined influence of natural evolution and human intervention. For example, Xinghua lies in the hinterland of the *Lixia* River, where, since ancient times, a dense river network has interwoven with lakes and marshes. Although the terrain is generally uniform, historical changes in the river network and human activity have gradually produced distinctive landscapes, including raised fields[1] (Fig. 4), *wei*-fields[2] (Fig. 5), and wetlands (Yuan, 2025). In earlier periods, inhabitants adapted to the water environment by building embankments and fields, piling soil to form raised fields. This laid the foundation for the region's agricultural practices (Shi et al., 2022; Yuan & Wang, 2019). With the growth of water transportation and the rise of river docks, commerce and handicrafts flourished, leading to corresponding changes in settlement patterns (Hu, 2024). In areas with dense river networks, streets and markets developed alongside thriving commerce and trade. Along the lakeshores, fishing villages emerged with the growth of aquaculture. By contrast, regions with less dense river networks remain dominated by traditional agriculture.



Figure 4. The feature of the raised field

[1] Raised field: It is a piled up high field formed by excavating deep trenches or small rivers with a network of soil. The terrain is high and the soil is fertile and loose, making it suitable for planting various dry crops, especially for producing melons and vegetables.

[2] Wei-fields: It is formed by people building embankments and dams on shallow swamps or silted beaches of rivers and lakes, enclosing fields in the middle and blocking water outside the embankments. People open ditches and set up culverts in the polder fields, with both drainage and irrigation.



Figure 5. The feature of the *wei*-field

2.2 Settlements are difficult to cluster due to their scattered and disordered distribution

Traditional small-scale farming and dispersed rural industries have together resulted in inefficient village spatial structures. This is reflected in small residential areas and dispersed resource allocation, which hinder the formation of agglomeration effects. Despite ongoing rural development policies in recent years, issues of low land-use efficiency and fragmented spatial layouts remain unresolved. For example, rural areas in Xinghua continue to face problems of small scale and spatial fragmentation. During the Ming Dynasty, scattered raised fields from *wei*-field development led farmers to settle nearby, forming a "one *wei*-field, one village" pattern. Some villages are arranged in a bead-like pattern along tributaries such as the *Bangyan* and *Luting* rivers. The average size of these villages is much smaller than that of incorporated villages in Jiangsu Province, where a typical village has about 350 households. The absence of central agglomeration areas, combined with hollowing-out trends and idle homestead land, has further aggravated problems of small-scale and spatial fragmentation.

2.3 The phenomenon of insufficient resource utilization and uneven development of villages and towns is prominent

Limited use of characteristic resources, policy differences, and diverse development drivers have led to a multi-level, differentiated development pattern in the region (Wang et al., 2024). For instance, rural development in Xinghua shows clear differences in driving forces, resulting in an unbalanced spatial pattern. Cultural and tourism-driven areas, such as *Shagou* Town and *Qianduo* Town, draw on historical–cultural resources and raised-field landscapes to develop tourism-related industries in surrounding villages. However, because their influence is

geographically limited, villages located more than 5 kilometers away remain largely unaffected and continue to rely on traditional industries. As a result, village development remains both insufficient and uneven.

3 Geographical foundation analysis

3.1 Morphological distribution characteristics

3.1.1 Construction of the morphological characteristics method system

To assess whether villages and towns share similarities in morphological resources and characteristics, the analysis is conducted across two dimensions, incorporating terrain, land use, resource endowment, and related attributes. First, eight types are identified based on patch and class agglomeration characteristics to examine morphological distribution and clustering patterns. Second, from the perspective of the overall spatial pattern, these types are assigned contrast values to measure the degree of differentiation across indicators. Through this process, the aggregation, cohesion, and fragmentation characteristics of the geographical distribution of villages and towns are determined, allowing for the synthesis of the region's overall morphological features (Fig. 6).

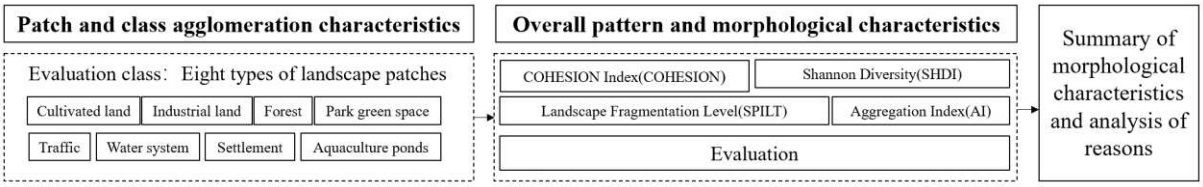


Figure 6. Technical route for evaluating morphological distribution characteristics

The study evaluated the region using the landscape pattern index in **Fragstats**, where SHDI, AI, COHESION and SPILT are four typical index which can show the diversity, aggregation, cohesion and fragmentation level (Table 1). While the moving window algorithm was applied for image generation and processing. Its algorithm operates by opening an analysis window centered on each pixel, calculating the selected indicators within that window, and assigning the results back to the central pixel. By repeating this process across all pixels, a new raster surface is generated, representing the gradient of the local landscape structure. This method effectively captures the fine-scale characteristics of landscape patterns and reveals spatial differences within the study area.

Table 1. Patch and class agglomeration characteristics and overall pattern and morphological characteristics indicators

Index	Formula	Formula description	Index explanation
Shannon Diversity （SHDI）	$SHDI = -\sum_{i=1}^{m}(P_i \times \ln P_i)$	Measurement index based on information theory, reflecting landscape heterogeneity.	In a landscape system, the richer the land use and the higher the degree of fragmentation, the greater the content of uncertain information, and the higher the calculated SHDI value.
Aggregation Index （AI）	$AI = \left[\frac{g_{ii}}{max - g_{ii}}\right](100)$	Used to describe the degree of aggregation of different patches or regions in a	More aggregation indicates that patches of the same type are clustered together, while a lower degree of aggregation indicates

		landscape, as well as the connectivity between patches of each landscape type.	that they are more dispersed and can be used to evaluate the agglomeration patterns of patches of the same type in the landscape.
Cohesion Index（COHESION）	$CO = \left[1 - \frac{\sum_{j=1}^{m} p_{ij}}{\sum_{j=1}^{m} p_{ij}\sqrt{a_{ij}}}\right]\left[1 - \frac{1}{\sqrt{A}}\right]^{-1} \times 100$ p_{ij} represents the circumference of the num. j patch in the num. i type landscape，A is the total area of the landscape	Used to describe the degree of aggregation of spatial structures within patches in a landscape, the index reflects the spatial connectivity or aggregation within patches of the same type.	A higher COHESION value indicates that different types of plaques are more concentrated or densely distributed together, forming a more compact spatial structure.
Landscape Fragmentation Level（SPILT）	$S = \frac{N_i}{A_i}$ N_i is the number of patches in landscape i，A_i is the total area of landscape i	The degree of fragmentation or fragmentation of a landscape refers to the degree of separation between different patches in the landscape.	When the landscape is divided into multiple smaller segments, the degree of fragmentation is higher; When the landscape maintains large continuous patches, the degree of fragmentation is lower.

3.1.2 Morphological characteristics of land-use

In analyzing patch and class agglomeration characteristics (Fig. 7), this study quantified the distribution patterns of eight types of landscape patches in Xinghua cultivated land, aquaculture ponds, water systems, forests, transportation, settlements, green space, and industrial land based on the aggregation index. Supplementary

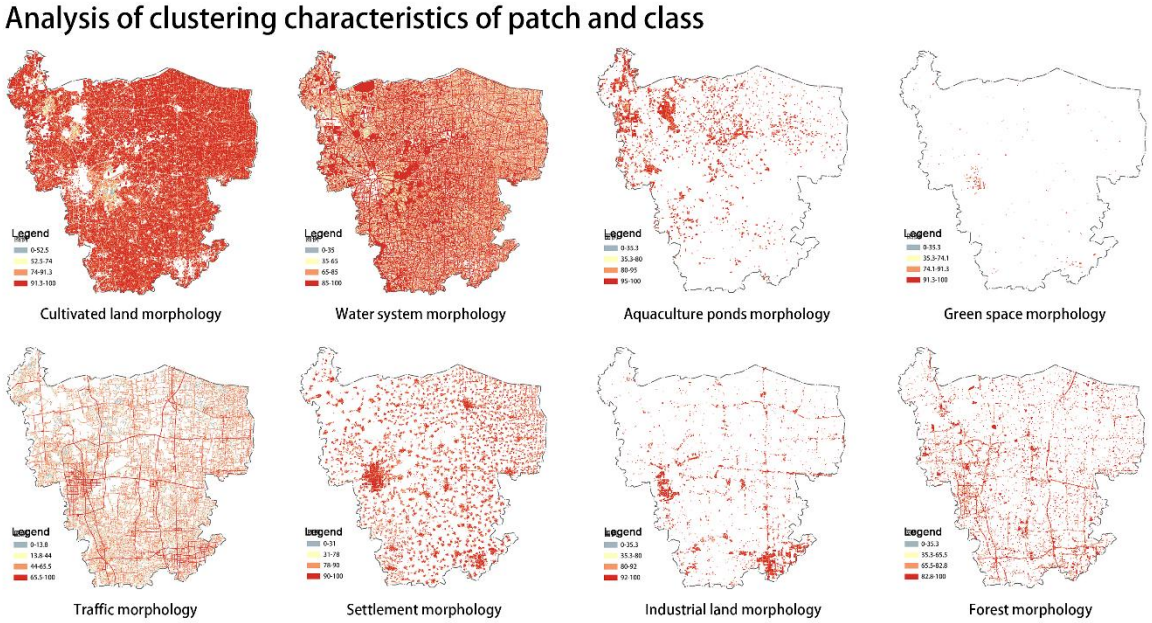


Figure 7. Patch and class agglomeration characteristics

The results show that the degree of agglomeration is higher in the eastern, southern, and southwestern regions, but weaker in the central, western, and northwestern parts. A complementary feature is the high concentration of aquaculture ponds and water systems in the northwest. Aquaculture ponds are uniformly clustered in small patches in the north, while they are sparsely distributed in the south. Water systems display an overall uniform agglomeration pattern in the east and south, but are more scattered in the central and northwestern areas, where irregular large water bodies are distributed.

In terms of settlement patterns, Xinghua exhibits three major agglomeration cores. The first is a radiating cluster centered on the central urban area, mainly in the central and western regions. The second is an industrial-led cluster around *Dainan* Town in the southeast, which consists of several secondary agglomeration points. The third is a small-scale cluster centered on *Anfeng* Town in the northwest. Other settlements are scattered and lack a clear centripetal structure. The transportation network closely mirrors these settlement patterns, with major agglomerations in the central and western regions, as well as in the southwest, southeast, and northeast. Transportation nodes are evenly distributed in the east, but are sparse in the northwest.

This spatial differentiation is closely tied to geomorphological features (Fig. 8). The geomorphology of Xinghua can be divided into five sub-regions: swamps, western raised fields, southern *wei-fields*, central small *wei-fields*, and eastern large *wei-fields*. The widespread presence of *wei-fields* reflects the low-lying terrain and long-standing reliance on artificial reclamation to convert swamps into farmland. Consequently, the clustering level of cultivated land is relatively consistent across the region. Within this system, the northeast has large *wei-fields* shaped by both natural water systems and artificial embankments for flood control and irrigation, while the south is dominated by evenly distributed small *wei-fields*. In contrast, swamps dominate the central and northwestern regions, where wetlands, lakes, *wei*-fields, and aquaculture ponds form composite landscapes. These areas have not only been transformed for traditional agriculture but also diversified toward aquaculture and wetland tourism, resulting in

multi-level utilization of swamp and wetland resources.

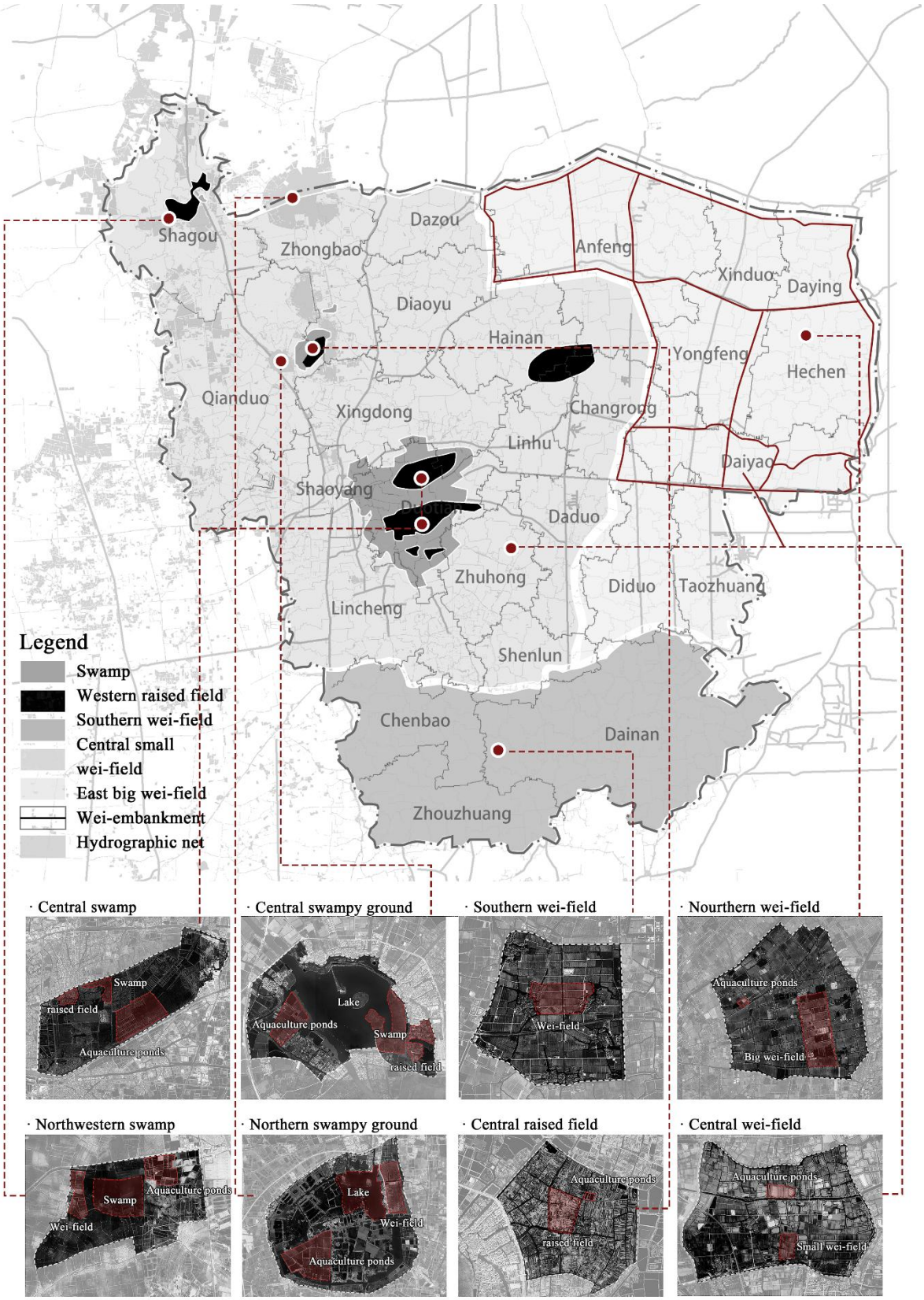


Figure 8. Explanation for the agglomeration characteristic of the patch and class

To capture the overall spatial pattern and morphological characteristics (Fig. 9), four

landscape pattern indices were employed: the Aggregation Index (AI), Cohesion Index (COHESION), Shannon Diversity Index (SHDI), and Landscape Fragmentation Index (SPLIT). These indices quantify regional structure in terms of patch agglomeration, spatial connectivity, land use diversity, and landscape segmentation. The results indicate that Xinghua's overall aggregation degree is relatively high, with the east and south showing strong clustering of homogeneous land-use patches, largely due to large-scale agricultural layouts. However, three areas of low aggregation occur in the central and northwestern regions, influenced by swamp terrain and the historical development of raised fields and scattered *wei*-fields.

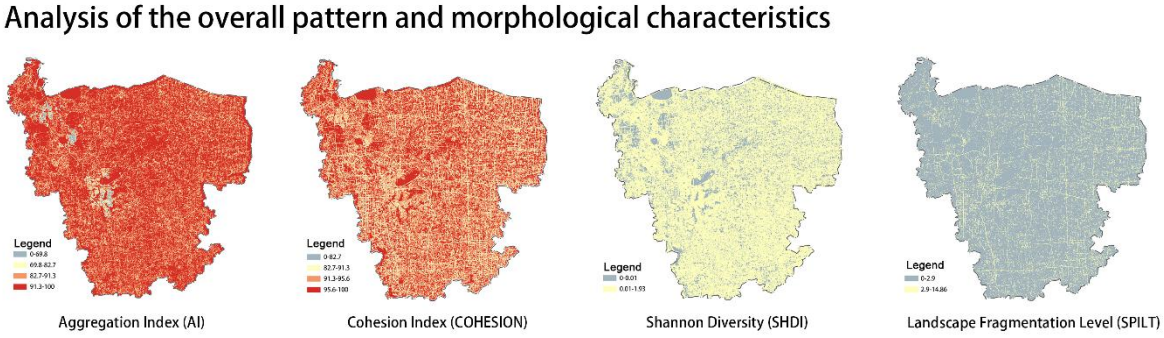


Figure 9. Overall pattern and morphological characteristics

The cohesion index demonstrates strong overall spatial connectivity, with values generally above 82.7, but also significant spatial variation. Notably, the central and northwestern regions show abnormally high cohesion, reflecting compact but interwoven patch structures formed under the traditional raised-field agricultural system. In contrast, the east and south have moderate cohesion, suggesting looser patch combinations and a need for stronger spatial connectivity.

The SHDI results show that overall diversity is relatively low, consistent with Xinghua's agricultural dominance. However, the northwest exhibits higher values, indicating the coexistence of multiple land-use types and the formation of a complex mosaic landscape. This heterogeneity arises from both its transitional geographical location and its diversified land-use practices, including raised-field cultivation, aquaculture, and *wei-field* farming. Such landscape uncertainty requires attention in future planning.

Finally, the fragmentation index reveals that the region's landscape integrity is strong, with relatively low overall fragmentation. This integrity is largely maintained by the extensive water system, which both divides and connects different landscape units. Nevertheless, localized fragmentation is evident around towns mainly due to human disturbances such as land reclamation and construction activities.

3.2 Geographical scale characteristics

3.2.1 Construction of a geographic scale network based on the gravity model

In response to the problems of scattered scale and spatial fragmentation, we introduce and improve "network methods" such as gravity models and social network analysis based on the various scale characteristics and transportation accessibility of villages and towns. By doing so, we can characterize the connectivity of rural communities from multiple dimensions, identify high-level nodes, and determine the "center" and "edge" of the region. And the study emphasizes network connectivity for the purpose of identifying rural areas that are spatially dispersed and have integrated elements under low-density conditions.

The gravity model can measure the interaction between two spatial entities and is widely

used in the study of regional spatial structures. Based on the spatial scale characteristics of rural areas, the following improvements are made to the traditional gravity model to measure the network correlation strength of the geographical scale between villages and towns. The study replaces the "comprehensive quality parameter" with the "comprehensive geographic scale of villages and towns" as the core parameter for measuring the attractiveness and radiation effect of villages and towns. Traditional gravity models typically use single indicators such as total population and GDP to represent mass parameters. However, rural areas are different from cities in that their population size is small and the differences are not significant. In addition, Xinghua has always had a landscape with dense river networks and intertwined lakes. Therefore, the study comprehensively considers the size of villages and towns, water systems (Table 2), cultivated land, and population, and incorporates them into the gravity model.

$$R_{ij} = K_{ij}\frac{M_i M_j}{D_{ij}^2} \tag{1}$$

$$K_{ij} = \frac{g_i}{g_i+g_j} = \frac{G_i/p_i}{G_i/p_i+G_j/p_j} \tag{2}$$

R_{ij} is the strength of the connection between village node i and village node j. M_i and M_j respectively represent the comprehensive calculation results of the indicator items of a certain village node, which is the gravity value of the village. D_{ij} represents the distance between node i and village node j. K_{ij} is the correction coefficient. G_i and G_j represent the area of the town or street where the village is located. p_i and p_j represent the population of the township or street where a village is located. The correction coefficient is used to adjust the geographic scale of villages based on township data.

Table 2. Index of comprehensive geographic scale

Type	Element	Index	Unit	Data sources	Weight
Comprehensive index gravity value	Area Scale	Total area of the administrative village	km^2	Survey data on land use	0.19077
		Proportion of land area for village construction	%	Survey data on land use	0.28968
	Water System Scale	The total length of the water system flowing through the village area	km	*List of Backbone Rivers in Jiangsu Province*（*Revised in 2018*）, OpenStreetMap	0.11764
		Proportion of water area within the village area	%	OpenStreetMap	0.05271

	Cultivated Land Scale	Proportion of cultivated land area in villages	%	Survey data of land-use	0.14101
	Population scale	Population of administrative villages	/	Jiangsu Government Service Network (https://www.jszwfw.gov.cn/）, *Layout planning of towns and villages in Xinghua（Revised in 2022）*	0.20819
correction coefficient	Area Scale	The area of the town or street where the village is located	Km^2	Survey data of land-use	/
	Population scale	The seventh population census of the township or street where the village is located	/	*Statistical Review of Xinghua*	

3.2.2 Data standardization processing and weighting

The study employed the Min-Max normalization method to standardize variables such as village area and river length. The entropy weight method and analytic hierarchy process (AHP) were then applied to calculate the weights of each indicator, both separately and in combination, to determine the overall weight for each variable. These weights were subsequently used to compute the gravity value of each village node. Using the gravity model formula described above, the strength of connections between any two villages was calculated.

During data processing, network-related values often exhibited a heavy-tailed distribution, in which a large number of very small connection values obscured the underlying core structure. To address this, a heavy-tail extraction method was applied: connections exceeding the mean value were retained, while those below the mean were considered negligible and excluded. The resulting gravity model produces an undirected matrix representing pairwise connections between villages. These connections were visualized on the ArcGIS platform, with connection strengths classified using the natural breakpoint method to construct a clear network association pattern reflecting the geographic scale of villages and towns.

3.2.3 Measurement of the network correlation pattern of geographical scale

A preliminary assessment of village and town centrality was conducted based on the comprehensive geographic scale to determine the hierarchical level of each settlement and to clarify unit centers and the network correlation patterns among villages and towns. Firstly, centrality was calculated for each village and town, dividing them into three levels. From the perspective of node attributes (Fig. 10), high-centrality settlements are concentrated in the central urban area of Xinghua, *Dainan* Town in the southeast, and *Anfeng* Town in the northeast, forming a multi-core structure. Villages and towns with moderate centrality are arranged in a circular pattern around these core nodes, while low-centrality settlements are scattered in the

northwest and peripheral areas, forming the end nodes of the network system. This core–edge spatial differentiation reflects the uneven agglomeration of regional geographic scale factors.

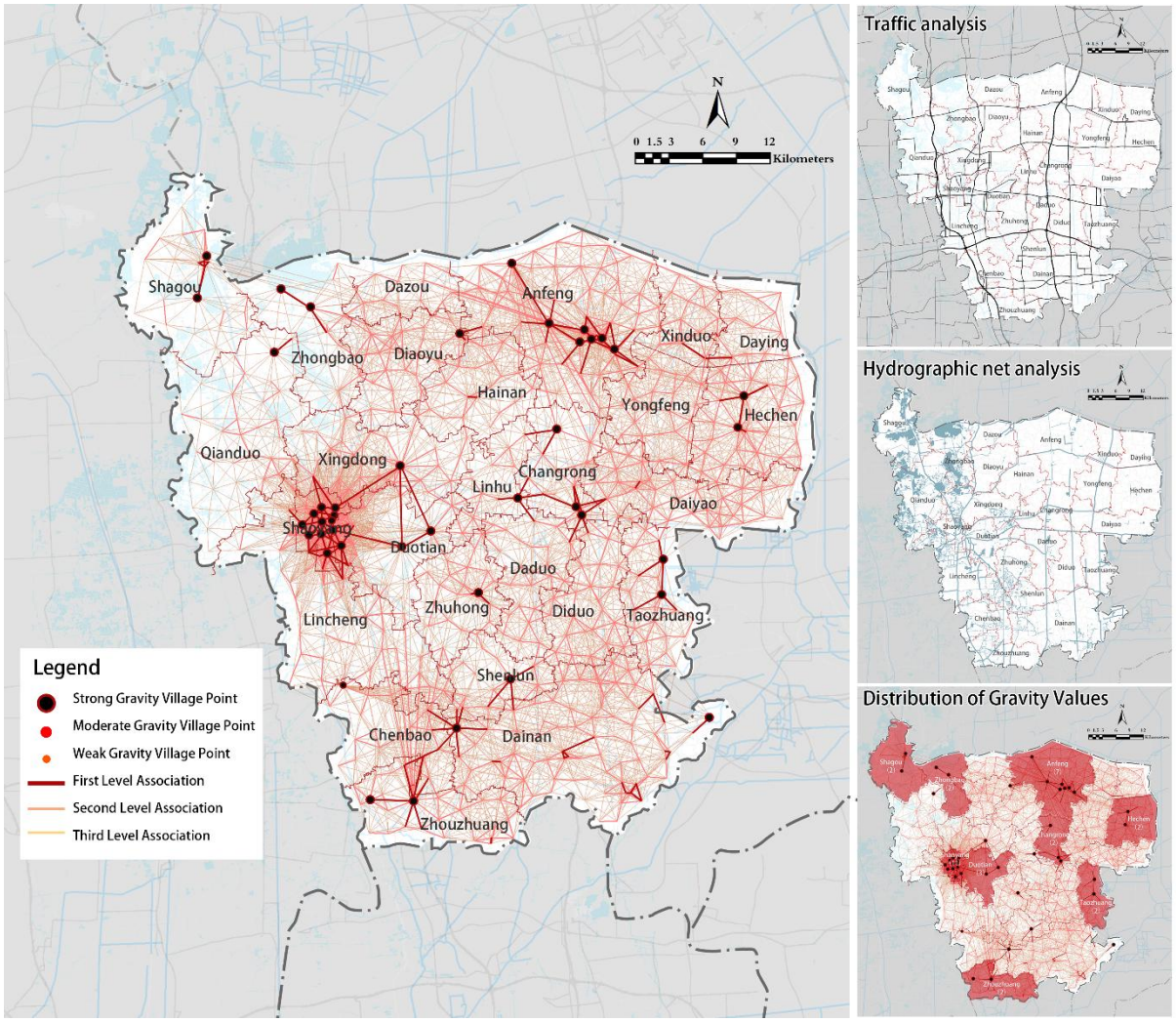


Figure 10. Geographical scale network correlation gravity model for villages and towns. The area near *Shaoyang* shows strong gravity.

Network association strength also exhibits a clear core–edge differentiation. High-intensity correlations are concentrated in two core areas: the central and western regions around Xinghua's urban center, and the southeastern *Dainan* Town area. These two cores form the primary axis of the regional network, while medium-intensity nodes surround the cores, connecting secondary centers such as *Anfeng* Town and *Zhouzhuang* Town, though their connectivity patterns are less regular. Low-intensity associations occur sporadically in the northwest's dense water network zones and in the eastern agricultural areas, characterized by short-distance, low-density connectivity. Overall, the hierarchical structure of the network and the role of secondary aggregation centers remain limited.

The formation of these patterns is influenced by topography and hydrology. High-intensity association areas are primarily located in the central and southern small *wei-field* zones, which have well-connected water systems but moderate water network density. Low-intensity associations are concentrated in the northwest's lakes and depressions, where complex water networks reduce regional connectivity. Settlement distribution further reinforces these patterns:

high-level nodes coincide with large, densely clustered settlements, consistent with the core agglomeration principles of central place theory, while small, scattered settlements at the edges exhibit weaker network connectivity. Accessibility to transportation also plays a key role, with high-strength corridors aligned with major roads and waterways, including provincial highways and the *Yanjing* River. In contrast, the northwest's sparse land transportation network and segmented water systems limit node interaction. From a historical perspective, the central urban area, *Dainan* Town, and *Anfeng* Town have long served as traditional regional centers, accumulating infrastructure and public service advantages that make them natural network hotspots. Peripheral areas, constrained by natural geography and limited transportation access, exhibit relatively lagging development.

3.2.4 Geographic modular clustering

Using the Louvain community discovery algorithm proposed by Blondel et al. in Gephi for geographic modular clustering, 19 clusters appeared with scattered spatial distribution. From the visualization of the clustering network (Fig. 11), it can be seen that communities represented by different colors exhibit a relatively clustered but staggered distribution pattern in space. Although a continuous regional structure has been formed, the number of 19 modules indicates that relying solely on geographical scales to divide the internal connections of regions has strong fragmented characteristics.

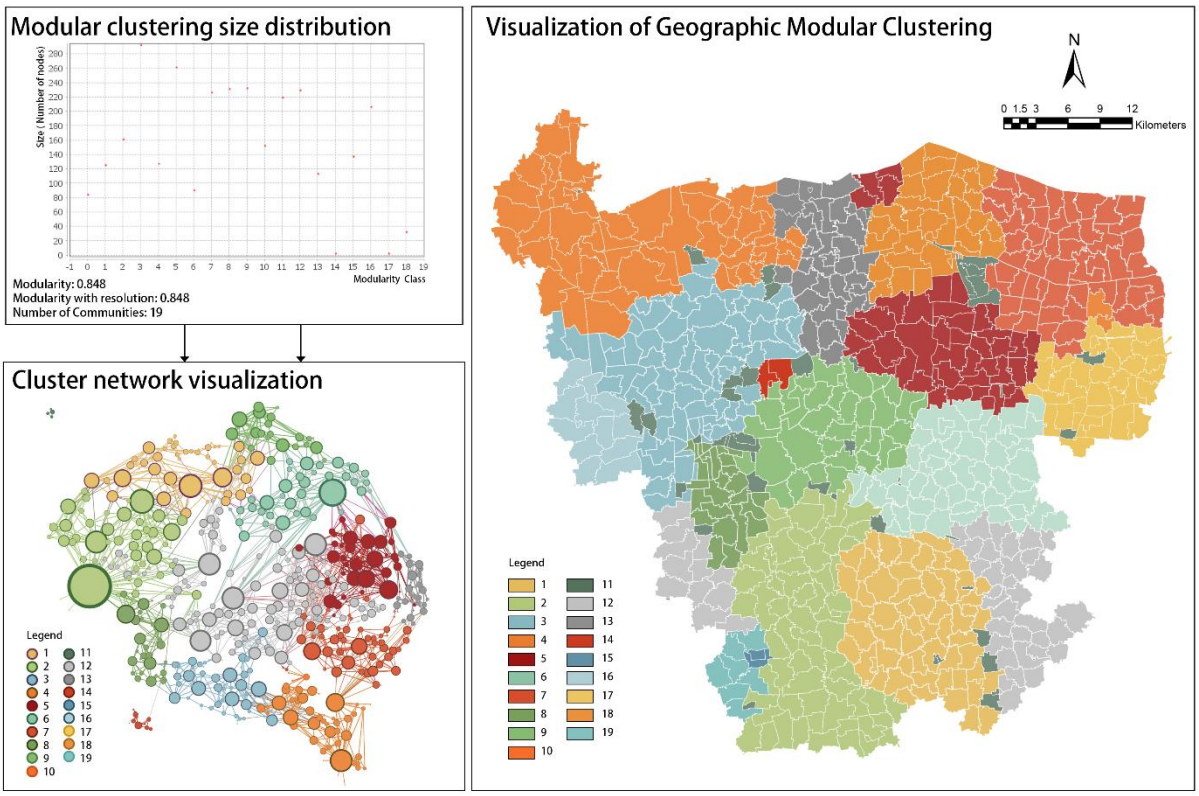


Figure 11. Nineteen geographic modular clusters

From the perspective of algorithm principles, standard algorithms are sensitive to small or weakly connected networks, making it easy to identify a large number of locally dense subgraphs. And in the constructed geographic correlation matrix, weak connections dominate, meaning that the attraction values between most villages are generally low. The algorithm tends to identify each slightly stronger local connection as an independent community, resulting in

some prominent patches in the process of geographic visualization.

Based on the characteristics of geographic data, the geographic network structure in Xinghua area presents typical spatial heterogeneity and core periphery differentiation features. The dense water network system, especially the lake and depression areas in the northwest, constitutes a natural geographical barrier, significantly weakening the overall connectivity of the region, resulting in a fragmented pattern of "short radius strong connections, long radius weak connections" in the relationships between villages. At the same time, high centrality nodes have a significant gravitational siphon effect on surrounding villages, further strengthening spatial polarization. These core nodes not only gather most of the regional resources, but also weaken the potential connections between edge villages and distant nodes.

From the perspective of network structure (Fig. 10), this region exhibits two key characteristics: firstly, the hierarchical structure is not significant, and a continuous hierarchical structure of "*core-sub-core-edge*" has not been formed, indicating a fault in regional development and insufficient cultivation of intermediate level nodes. Secondly, there is a significant discontinuity in the connection strength, with nodes mostly having strong or weak connections, and a lack of medium strength connections as network bridges, which further exacerbates the fragmentation of the overall structure and makes it difficult for the network to achieve smooth transition and connection from the core to the end.

4 Historical and cultural superposition analysis

4.1 Distribution characteristics of geographical name categories

The classification of place names and the distribution of settlements in the Xinghua area reflect strong geomorphic adaptability and distinct historical characteristics. Settlements can be categorized into four types: water-dominated, agricultural, commercial, and defensive (Table 3). Their spatial distribution is closely linked to the region's unique swamp and *wei*-field landforms, as well as historical and cultural influences.

Table 3. Geographical name classification explanation

Type of place name		**Main Words**	**Settlement type**	**Description**
Natural geographical name	River system	ditch	Water dominated settlement	Flowing water channel
		sea		The waters near the connection between the mainland and the ocean
		jiang		The general term for large rivers
		river		Natural or artificial large waterways
		port		A river bay that can be anchored
		marsh		Shallow water lake, a depression with accumulated water and grass
		bay		Bend of river

		sand		Arable land by the water's side
		bridge		A bridge, a building erected on water or in the air for passage
		dam		Buildings used to reinforce embankments in hydraulic engineering
	Agriculture	duo	Agricultural settlement	A raised high field formed by excavating a network of deep trenches or accumulating soil along a lake or river network
		pasture		Fields in suburb
		wei		Rice paddies surrounded by earthen embankments
		mount		The towering part formed by the ground, the soil slope
		forest		Clusters of trees
		yard		Vegetable garden, orchard
Humanistic place name	Business	yao	Commercial settlement	Places for firing bricks, tiles, and ceramic vessels, coal kilns
		zao (stove)		Salt boiling household
		chang		Flat open space, threshing ground
	Defensive	fort	Defensive type settlement	Small fort, a market town or shop with a city wall
		ton		A few smaller households are established, with surnames added in front of them
		manor		The post station belongs to the official and garrison fields, as well as some official villages
		guan		Temporary stationed barracks
		town		The walls surrounding the city are used for defense
		barrack		Living and camping around the soil

The distribution of settlements and place names in the Xinghua area clearly reflects the combined influence of natural landforms and historical culture (Fig. 12). Water-dominated settlements are concentrated in regions with dense river networks, and place names containing words like "port" and "bay" indicate residents' adaptation to the aquatic environment. Agricultural settlements, often identified by characters such as "*duo*", are concentrated in artificially transformed *wei*-field and raised-field areas, reflecting the ingenuity of wetland agricultural practices. Defensive settlements, denoted by terms like "fort" and "ton", are mainly found in the northern region, linked both to flood control needs and historical events such as *Zhang Shicheng*'s uprising at the end of the Yuan Dynasty, with some settlements possibly representing remnants of wartime activity. Commercial settlements, indicated by names such as "*yao*" and "*zao*", are scattered and reflect the spatial organization of salt and handicraft industries dependent on water transport. Overall, this settlement pattern illustrates the close interaction between humans and the land, shaped jointly by the natural wetland environment and historical–cultural factors. Supplementary

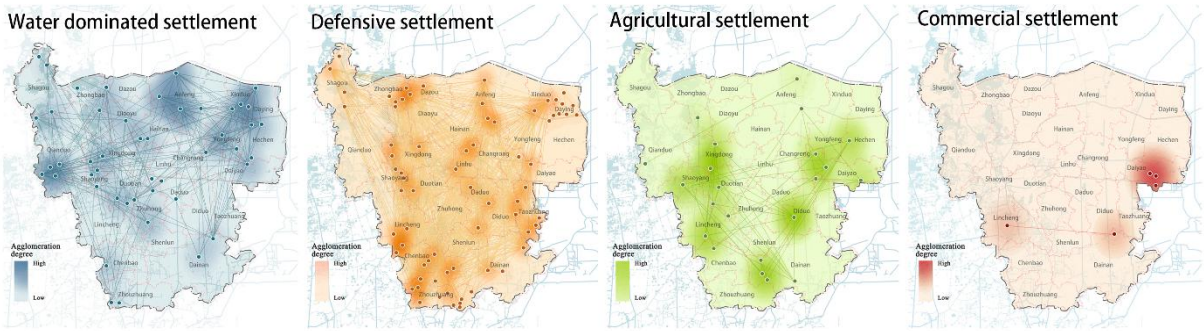


Figure 12. Geographical name analysis results

4.2 Distribution characteristics of historical and cultural values

4.2.1 Measurement of the network correlation pattern of culture

This study takes historical and cultural value as the core indicator (Table 4) for evaluating the attractiveness of villages, covering dimensions such as cultural heritage site, intangible cultural heritage sites (Table 5), statutory characteristic cultural areas, and villages associated with geographical name culture. The selection of these indicators is mainly based on their spatial carrier role in systematically reflecting the historical and cultural context of Xinghua. The location of material heritage and intangible cultural heritage directly reflects the temporal and spatial level of cultural existence. Statutory characteristic cultural areas represent officially recognized cultural value clusters. The cultural association of geographical names reveals the hidden historical continuity in language, memory, and local identity. In the process of selecting indicators, potential indicators such as the frequency of cultural activities recorded in local literature and the level of contemporary cultural industry development, although having reference value, were not included in this model due to differences in data availability, difficulty in unifying quantitative standards, or weak correlation with historical space.

It should be noted that historical and cultural value is used as the only measurement indicator (Table 5) in this evaluation, so some villages that do not have cultural sites have a value of 0 in the gravity model, reflecting that these villages have not yet formed measurable cultural influence in the current cultural spatial structure. This result highlights the uneven distribution of cultural resources and clarifies the blank areas that need to be focused on in future cultural protection and regional integration.

The spatial distribution of culture was analyzed using kernel density and gravity models, revealing a pattern centered on the urban area and radiating along major water systems. Two high-density zones were identified. The first is the core cultural circle centered on Xinghua Ancient City, which includes numerous Ming and Qing Dynasty buildings and residences of historical Fig.s. The second is a sub-center cultural circle around *Shagou* Ancient Town, characterized by modern commercial architecture and revolutionary sites. These two areas are interconnected via the water transportation network, forming the primary cultural axis of the region and exhibiting significant cultural radiation effects. National-level heritage sites in the central region, such as the *Jiangzhuang* Site and Xinghua *Duotian*, together with provincial-level sites, serve as major sources of cultural attraction, influencing surrounding cultural resources (Fig. 13).

Table 4. Historical and cultural elements

Heritage type	**Category**	**Quantity**	
Cultural relics	Archaeological Sites	5	337
	Traditional architectural group	9	
	List of Historical Buildings	197	
	Traditional street and alley spaces	19	
	All levels of cultural heritage preservation units	107	
Intangible cultural heritage	Traditional skills, folk customs, traditional music, traditional dance, traditional drama, folk literature, traditional medicine	124	

Table 5. Index of cultural value

Type	**Element**	**Index**	**Unit**	**Data sources**	**Weight**
Comprehensive index gravity value	Culture value	Heritage	Quantity	Taizhou public data open platform *(http://opendata.taizhou.gov.cn/oportal/catalog/B00073E89D0C4A92A35E89A7CCAB851A)*	0.6
		Statutory characteristic cultural areas	Quantity	Taizhou government (https://www.taizhou.gov.cn/xwzx/sqdt/art/2025/art_1f2dea7bbdf6415bae9466bccd1067fd.html)	0.4
correction coefficient	Area Scale	The area of the town or street where the village is located	Km^2	Survey data of land-use	/
	Population scale	The seventh population	/	*Statistical Review of Xinghua*	

		census of the township or street where the village is located			

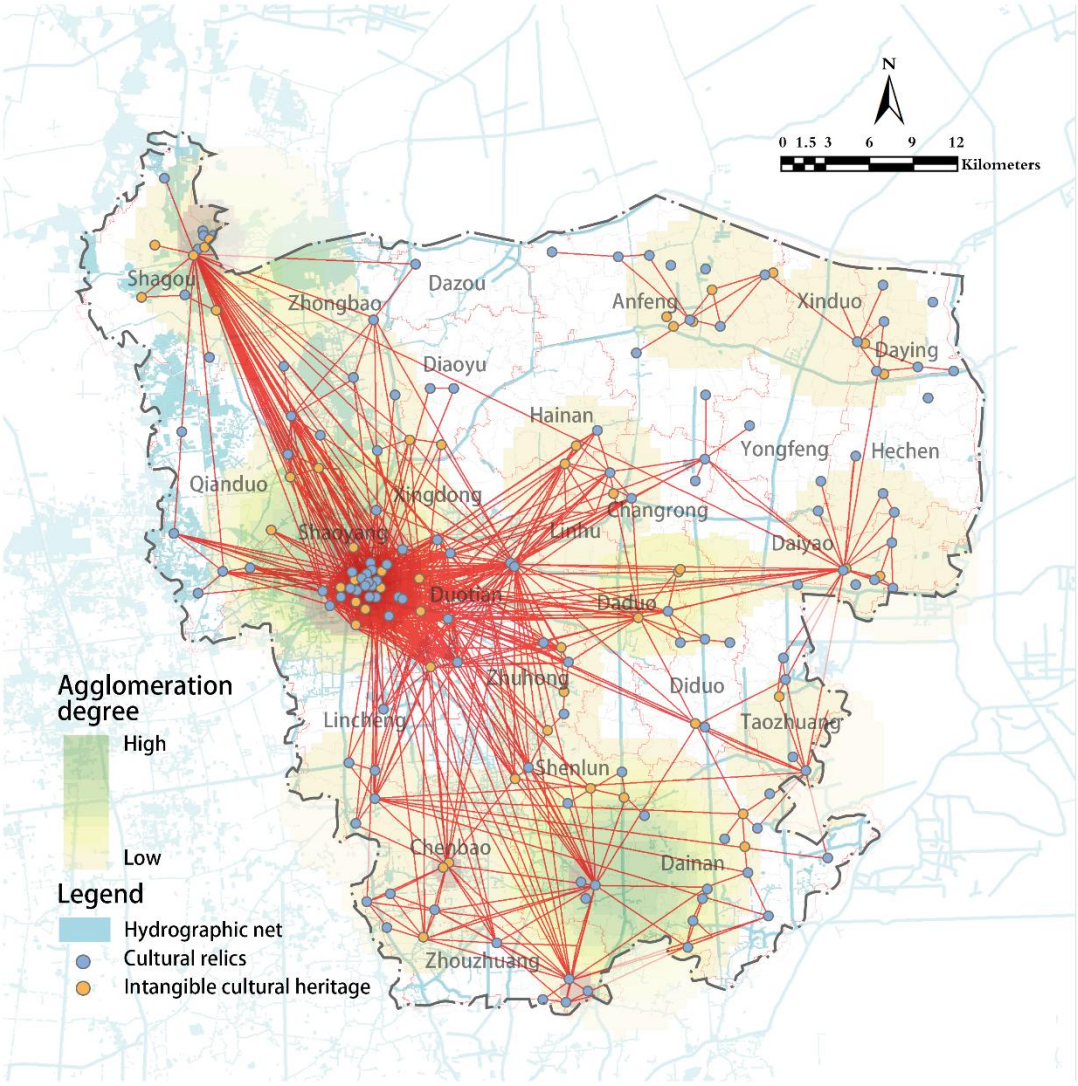


Figure 13. Analysis of gravity model and agglomeration degree based on historical and cultural values

4.2.2 Historical culture modular clustering

Based on the cultural gravity value, further clustering and modular analysis were conducted using Gephi. The results showed that the cultural spatial structure can be divided into 8 community categories (Fig. 14), and the modularization value is at a moderate level, indicating that historical and cultural resources are both interrelated within the region and exhibit certain regional grouping characteristics. From the clustering network diagram, it can be seen that historical and cultural nodes represented by villages including *Duotian* Aquatic Village, *Xinxuzhuang* Village and *Shiliang* Village, although limited in scale, have significant cultural influence, forming eight radiating settlement clusters. Although each category does not

form a highly independent cohesive structure in space, it still reflects the "*core-edge*" clustering characteristics of historical and cultural resource distribution similar to the geographic space. Of particular note is the clear visualization of the resources on the map. Villages with high historical and cultural value do not exist in isolation, but rather exhibit a trend of contiguous distribution in geographical space. For example, the areas surrounding Xinghua Ancient City and *Shagou* Town have formed dense areas of historical and cultural resources. This phenomenon indicates that the spatial distribution of historical and cultural resources not only has a networked correlation structure, but also echoes the organizational form of geographic space, further revealing the hierarchical and holistic characteristics of regional settlement systems from a cultural perspective.

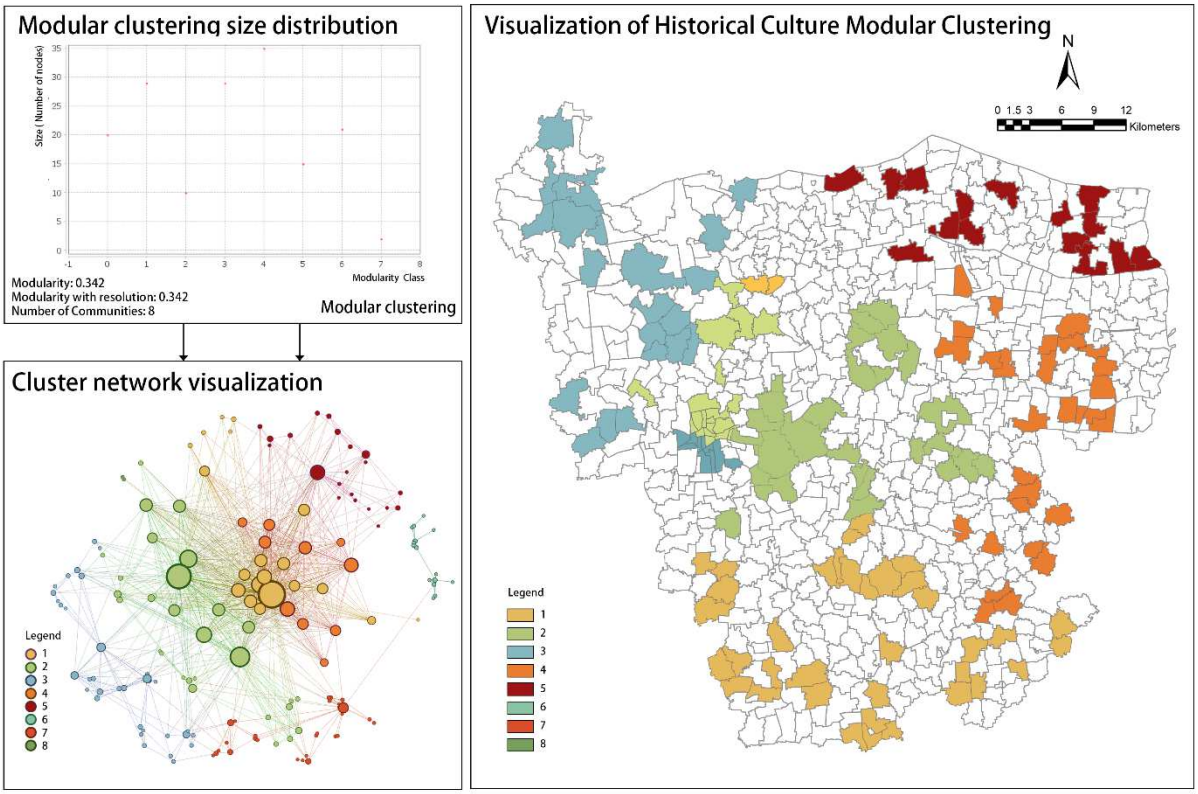


Figure 14. Eight historical and cultural modular clusters

5 Conclusion and discussion

On the basis of traditional geographic scale analysis, the study incorporates historical and cultural heritage as a key variable into the gravity model (Table 6), recalculates the comprehensive gravity value of villages, and conducts cluster analysis. The results indicate that the region can be divided into five highly integrated clusters (Fig. 15), which significantly enhance the overall correlation of villages in the area compared to the more numerous and fragmented community structures formed under a single geographical or cultural dimension. From the overlapping diagram of cluster space, it can be clearly seen that cultural heritage plays a key adhesive role in connecting isolated villages and strengthening regional cultural identity, effectively integrating dispersed villages into functional clusters with a common historical and cultural context. This discovery confirms that the structural connections between villages not only stem from geographical proximity, but also rely on common historical and cultural layers and spatial interactions.

Table 6. Weights of Gravity Model Indicators (Entropy Weight Method)

Element	Area Scale	Water System Scale	Cultivated Land Scale	Cultural Value
Weight	0.050339	0.237859	0.080254	0.631548

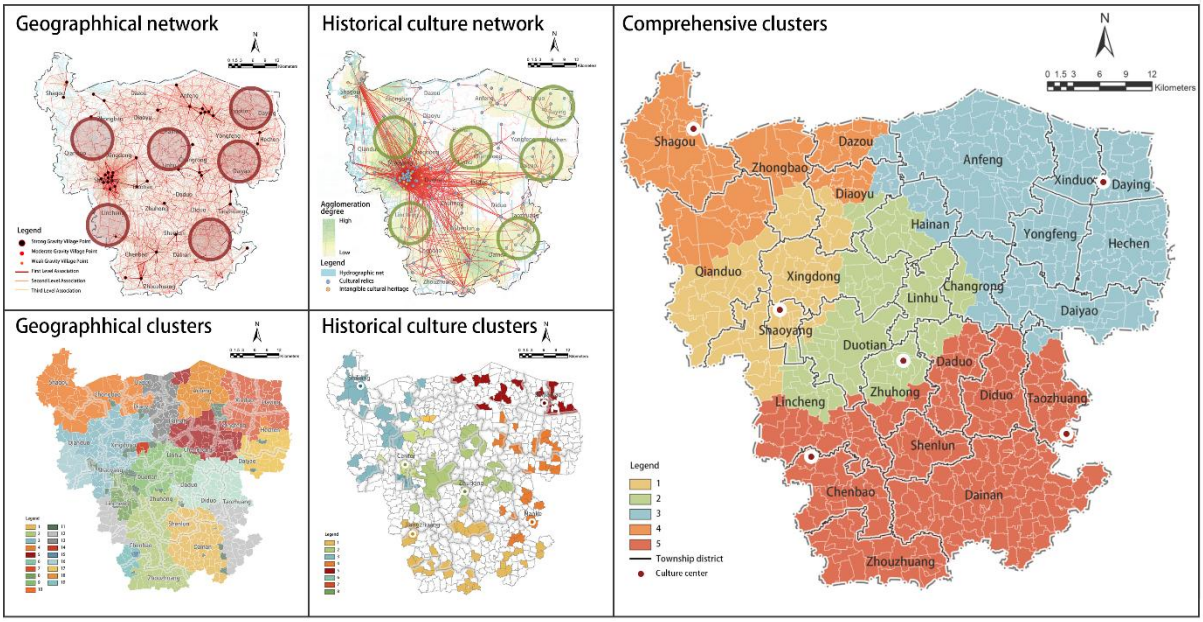


Figure 15. Comparative analysis of geographic and culture modular clusters

5.1 There is a significant spatial mismatch between geographical and cultural clusters

There are significant systematic differences in spatial distribution between the 19 communities formed by geographical clustering and the 8 communities formed by historical and cultural clustering. Geographical clusters are strictly constrained by the natural background, and the density of water systems and transportation factors directly determine the distribution pattern of "scattered in the northwest and connected in the southeast". Cultural clusters present a different spatial logic from geographical clusters. On the one hand, cultural influence can transcend geographical barriers. A wide and closely connected continuous cultural radiation belt has been formed in the area centered around Xinghua Ancient City and *Shagou* Town. On the other hand, historical and cultural clusters also exhibit multi-level characteristics, giving rise to cultural clusters of varying sizes in different regions. This systematic differentiation indicates that a single geographic determinism is difficult to fully explain the complexity of settlement spatial organization. Historical and cultural associations are not simply dependent on geographical proximity, but provide important supplementary explanatory dimensions for regional spatial structure through their unique historical continuity and spatial penetration.

5.2 Cultural deepens individual gravity differences in villages

In the geographical network diagram, strong gravity villages are mainly concentrated in the central region, with relatively scattered hierarchical relationships between nodes. Although there is a certain degree of regional concentration, the overall structure presents obvious problems. The network has not formed a continuous hierarchical structure of "*core-sub-core-edge*".

However, in the historical and cultural network diagram, the gravitational core is clearly concentrated towards the central western region. A large number of villages that do not have

advantages in scale and transportation demonstrate extraordinary attraction with their rich cultural resources. Traditional villages such as *Duotian* Aquatic Village and *Xinxuzhuang* Village are typical representatives. They are not central nodes in geographic networks, but they have become important cores in cultural networks due to their possession of traditional terraced systems, historical sites, and other cultural heritage.

This phenomenon highlights the structural role of culture as a differentiation mechanism. It does not smoothly increase the gravitational value of all villages, but selectively strengthens those villages with profound historical accumulation. Villages that have served as transportation hubs or cultural centers in history have gained a node status in the cultural network that far exceeds what their geographical conditions can support, thanks to their long-term accumulation of cultural capital. Therefore, the core influence of culture on the individual attraction of villages lies in the selective reinforcement. It breaks the relative balance of geographical patterns, activates the cultural value of historical heritage, reshapes the gravity hierarchy of individual villages, and thus shapes a more distinct and differentiated node hierarchy in the regional network.

5.3 Cultural reshapes the pattern of network connections in villages

The reshaping of village connectivity patterns by historical and cultural attraction lies in its effective repair of network structural faults caused by the widespread lack of moderate strength connections. In the gravity model dominated by geographical factors, nodes are mostly connected by either strong or weak connections, lacking a large number of intermediate gradient associations that connect the previous and the next. The dualization of this connection mode leads to a fragmented network structure, making it difficult to form smooth resource flow and functional transmission between core nodes and end nodes, resulting in regional development gaps.

The introduction of historical and cultural factors provides a critical path to compensate for this structural deficiency. Villages with profound historical and cultural heritage have naturally become the center of the internet due to their unique cultural resources. These centers not only exhibit extraordinary cultural attraction on their own, but also generate a series of moderately strong and stable cultural associations when interacting with surrounding villages. These associations formed based on common historical memory, similar intangible cultural heritage skills, or complementary cultural resources integrate geographically adjacent but functionally loose small villages into functional clusters centered around cultural centers. At the same time, different historical and cultural clusters are connected through cultural routes, such as historical transportation routes and folk activity flow lines. As a result, historical and cultural attraction forms a resilient secondary network composed of medium strength connections between originally isolated strong nodes and dispersed weak nodes, presenting a higher centripetal force and structural tightness in the overall network.

5.4 Discussion

This study systematically compared the roles of geographical and cultural factors in shaping village networks by constructing a parallel and comparable analytical framework. The research goes beyond the previous single dependence on geographical and economic scales, not only quantifying the impact of geographical scale and location, but also synchronously constructing a comprehensive cultural evaluation system that integrates material and intangible cultural heritage, statutory cultural protection areas, and cultural associations of place names.

This study demonstrates that culture is not a simple attachment to geographic space, but a core dimension that can play a critical role independently, providing an indispensable supplementary explanation for understanding the spatial organization of rural settlements.

5.4.1 Implications for rural planning

The phenomenon of spatial mismatch between geography and culture revealed in this study has important implications for the current promotion of centralized and contiguous protection and revitalization of traditional villages. It means that delineating collaborative development zones solely based on geographical proximity or transportation convenience may not be sufficient. Planning practice must attach great importance to and prioritize the identification of cultural connections based on a common historical context, using cultural networks as an important spatial basis for guiding resource allocation, designing tourism routes, and cultivating characteristic industrial clusters, in order to achieve deepening development from "geographical proximity" to "cultural synergy". Taking Xinghua area as an example, the ancient water transportation corridors could be used to connect dispersed cultural nodes, forming a cross-town cultural industry chain in the *Dainan–Shagou* area and encouraging surrounding villages to participate in collaborative operations such as co-branded tourism routes, shared artisan workshops, and joint cultural festivals, enhancing regional visibility and economic synergy. Additionally, cultural coding strategies can transform agricultural place names, such as "*duo*" and "*wei*". Thereby the villages can achieve cultural connectivity and potential tourism revenue growth through these unique IPs. By translating the layered value of historical and cultural heritage into an endogenous driver of rural development, these strategies help bridge the persistent gap between spatial planning initiatives and administrative boundaries.

For international academia and practice, this study provides empirical cases from China through rigorous comparative analysis for global cultural landscape protection and rural sustainable development. Our findings are highly consistent with the holistic protection concept of "cultural landscapes" emphasized by UNESCO, as well as the path of integrating cultural heritage in EU rural policies. The comparative framework of the "geography culture" dual perspective we provide challenges the hidden "geographical determinism" tendency in rural research and confirms the independent value and strong resilience of cultural capital in shaping rural spatial structure. This methodological framework can be used to examine rural settlement systems in other regions, promoting the international academic community to give more central weight to cultural factors in rural research, thereby enriching international dialogue on rural spatial planning and heritage led development.

5.4.2 Limitations and future works

Although the evaluation of historical and cultural value is multifaceted, it currently mainly remains at the quantitative and spatial levels. The simulated cultural gravity reflects the distribution and density of historical and cultural resource points, but fails to fully demonstrate the subtle narrative, significance, and historical connections behind them. Future work should combine spatial analysis with qualitative historical literature analysis. This will help reconstruct the historical formation mechanisms of cultural networks, such as family migration, ritual routes, and commodity flows, shifting from describing simple cultural associations to explaining how they were formed.

And the current analysis mainly focuses on the spatial structure of village networks. A more comprehensive understanding requires the integration of socio-economic and industrial dimensions. Future research should include data on population mobility, industry linkages, and

other factors. Analyzing the fit or differences between these functional networks and the spatial networks defined by culture will provide deeper insights into the operational mechanisms of rural regional systems.

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6 Figures legends

Figure 1. The technical route of the study
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7 Data availability

The datasets generated during and/or analysed during the current study are not publicly available due [The digital analysis processing involves land use data from Xinghua City, Jiangsu Province, China, obtained from the Chinese government for scientific research purposes only and not publicly available.] but are

available from the corresponding author on reasonable request.

8 Competing interests

The authors declare no competing interests.

9 Ethical statements

This article does not contain any studies with human participants performed by any of the authors.

Supplementary Files

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- Supplementarymaterials.zip