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Research on the Correlation Mechanism between the Spatial Morphology of Traditional Villages and Resilience to Flood Disasters in Jiangsu Province

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Abstract: Jiangsu Province, in the lower reaches of the Yangtze and Huaihe River basins, has a dense river network, low-lying terrain, and frequent rainstorm and flood disasters, severely threatening traditional villages. Integrating the Pressure-State-Response (PSR) model with the Village Form Calculation (CVF) method, this study builds a morphological indicator database of 80 traditional villages in Jiangsu and analyzes the spatiotemporal characteristics of rainfall and flood disasters, village spatial forms (distance to water, water level, aspect ratio, density), and their correlation with flood resilience. Results show that: (1) since 2000, overall flood risk in Jiangsu has shown a "low in the north, high in the south" pattern; (2) village flood resilience is generally high, with 26% and 25% of villages having high and medium-high resilience, mainly in southern Jiangsu; (3) building density correlates significantly positively with flood resilience (ρ=0.250), while water system level correlates significantly negatively (ρ=-0.229). High-density villages (Type I, high-density elongated, 6.14; Type II, high-density square, 5.75) are significantly more resilient than low-density villages (Types III and IV, both 4.60), with high-density elongated villages being the most resilient. Accordingly, strategies are proposed from three dimensions: optimizing spatial form, hierarchical classification control, and activating traditional wisdom.

Keywords: Traditional villages; Spatial morphology; Flood disasters; PSR model; Resilience; Jiangsu Province

1. Introduction

Jiangsu Province is located in the core area of the Yangtze River Delta, downstream of the Yangtze and Huaihe River basins. With low-lying terrain and a dense network of rivers, it is one of China's regions most prone to heavy rainfall and flooding disasters. Frequent meiyu (plum rain) and typhoon-induced intense precipitation, enhanced tidal backwater effects, and intensive human activities such as high-intensity development have gradually led to a complex urban flood risk pattern characterized by multiple disaster drivers, high exposure of vulnerable assets, and fragile flood defense systems. Over the past 30 years (1981–2014), while the frequency of extreme precipitation events has declined in Jiangsu, the intensity of such events has significantly increased (Shen et al., 2015;Wang et al., 2026). Since 2010, extreme precipitation in the Yangtze River basin has become more frequent, starting earlier, ending later, and lasting longer. On this natural foundation, rapid urbanization has caused extensive surface hardening and encroachment on ecological spaces, further accelerating runoff accumulation and increasing peak flow rates during storms, thereby creating a compounded "natural-human" flood risk pattern. Therefore, assessing flood resilience forms the core and foundation of resilient urban planning for flood management, making it particularly important for high-quality development and rural governance in China (Zhai et al., 2024;Wang et al., 2024;Chen et al., 2024). As of August 2025, Jiangsu has officially recognized 79 traditional Chinese villages and 624 provincial-level traditional villages. At the macro scale, these villages are distributed with a general pattern of higher density in the south and lower in the north. At the micro scale, traditional villages are closely associated with rivers—their characteristic of "living near water"—which increases their vulnerability and exposure to flood hazards(Wang et al., 2023).

Currently, research on flood resilience in traditional villages primarily focuses on three aspects: In terms of theoretical understanding, the concept of disaster risk has evolved from a singular emphasis on the hazard posed by disaster-causing factors to a holistic grasp of complex systems characterized by dual "natural-societal" attributes. The PSR (Pressure-State-Response) model links environmental change drivers, system conditions, and system responses, providing an analytical framework for uncovering the internal mechanisms through which traditional villages respond to external disturbances(Shou et al., 2024;Tian et al., 2025;Zhou et al., 2025;Shi et al., 2022; Izgi et al., 2022). Regarding methodologies and techniques, the integrated application of GIS spatial analysis, remote sensing interpretation, and geographic detectors has significantly improved the accuracy (Wang et al., 2026;Zhang et al., 2025; Muzammul et al., 2025) of identifying relationships between village spatial patterns and disaster risks. In terms of influencing mechanisms, scholars generally agree that flood resilience in villages results(Chen et al., 2021;Zhou et al., 2024;Shi et al., 2026;Shi et al., 2023) from the combined effects of natural geographical foundations and village attributes such as spatial form, population density, and infrastructure levels.

However, although research on the resilience of traditional villages to flood disasters has become increasingly abundant, several weaknesses remain: (1) Most existing studies rely on the conventional PSR assessment framework, with insufficient attention paid to its applicability in rural areas. (2) Current assessments predominantly depend on city-level or coarser statistical units, neglecting micro-level spatial morphological characteristics, and thus lacking a bridge connecting macro-level data with micro-level forms. There is a lack of quantitative studies systematically linking macro-scale flood resilience features with micro-scale spatial morphology of large samples of traditional villages. (3) The driving factors behind flood risk in traditional villages are relatively complex, yet key drivers have either not been adequately identified or their explanatory power remains weak. Addressing these issues, this study focuses on Jiangsu Province, integrating the PSR model with CVF calculations to establish a flood resilience assessment framework. By combining morphological quantification and correlation analysis, and based on a morphological database of 80 traditional villages in Jiangsu, it primarily examines spatial morphological indicators such as proximity to water bodies, water adjacency level, aspect ratio, and density. The aim is to accurately identify the flood resilience characteristics of Jiangsu Province, the spatial morphological features of traditional villages (proximity to water, water adjacency level, aspect ratio, and density), and the underlying mechanisms linking them (Figure 1).

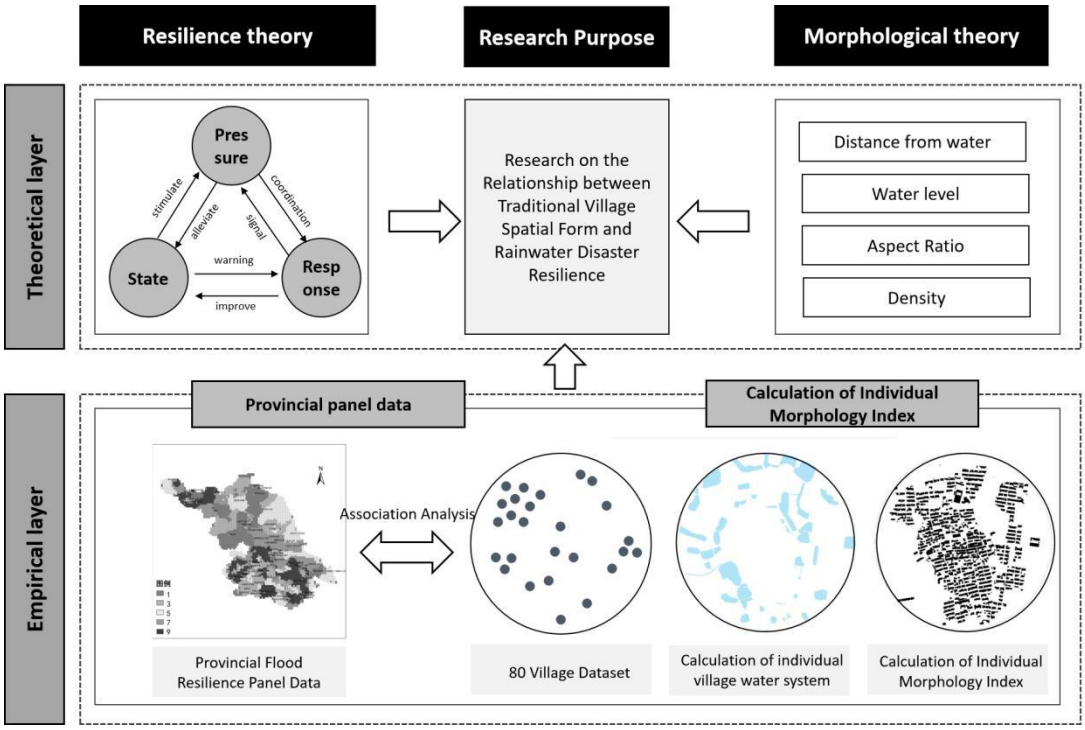


Figure. 1 Research Framework Analysis Diagram Image source: Author's own drawing.

2. methodology

2.1 Research Framework

This study establishes a five-step research framework: "feature identification—spatial form extraction—resilience assessment—correlation analysis—strategy formulation" (Figure

2):

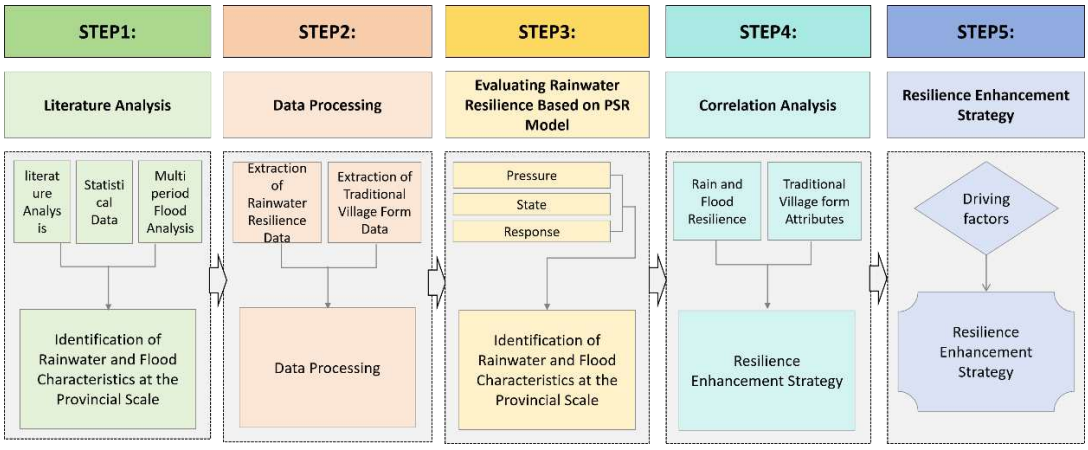


Figure. 2 Research Process Diagram

Step 1: Based on literature and statistical data, analyze the spatiotemporal evolution characteristics of heavy rainfall and flood disasters in Jiangsu Province; Step 2: Using GIS and remote sensing imagery, extract spatial morphological indicators for 80 traditional villages, including proximity to water bodies, water adjacency level, aspect ratio, and density; Step 3: Construct an evaluation index system for flood resilience of traditional villages based on the PSR model; Step 4: Employ correlation analysis, variance analysis, and regression analysis to reveal quantitative relationships between spatial morphological indicators and flood resilience; Step 5: Propose a graded and categorized strategy for enhancing resilience based on the analytical results.

2.2 Data Sources and Preprocessing

The sample village spatial morphology data were extracted using ALOS 12.5-meter resolution DEM data, Sentinel-2 satellite imagery, and OpenStreetMap hydrographic vector data, processed through the ArcGIS 10.2 platform. The list of traditional villages was obtained from the provincial-level and above traditional village directory published by the Jiangsu Provincial Department of Housing and Urban-Rural Development. Flood disaster data were sourced from the "China Flood and Drought Disaster Prevention Bulletin" (1984–2023) and Jiangsu Province's annual reports on flood control and drought relief. Socioeconomic data were derived from statistical yearbooks of Jiangsu Province and its cities and counties.

2.3 Indicator Selection

2.3.1 PSR Model and Flood Resilience Evaluation Indicators

The PSR (Pressure-State-Response) model, developed by the Organisation for Economic Co-operation and Development (OECD) in 1980, consists of three dimensions: pressure (P), state (S), and response (R). Pressure refers to environmental damage and disturbances caused by natural and human-induced factors; state represents a system's internal capacity to resist and adapt to external disturbances; and response denotes the ability of human societies to respond to and recover from environmental problems and crises(Meerow et al., 2016;Wang et al., 2026) .

Table 1 Flood Disaster Resilience Evaluation Indicator System

Target Layer	Criteria Layer	Indicator Layer	Direction	Weight
Flood Resilience	Pressure (P)	X1 Elevation (m)	Positive	0.065
		X2 Forest Coverage	Positive	0.058
		X3 Water System Density	Positive	0.074
		X4 Average annual rainfall (mm)	Negative	0.082
	Status (S)	X5 Primary Industry Value Added (in ten thousand yuan)	Positive	0.087
		X6 Secondary Industry Value Added (10,000 yuan)	Negative	0.069
		X7 NDVI	Positive	0.096
	Response (R)	X8 Local Government Revenue	Positive	0.112
		X9 Resident Population	Positive	0.105
		X10 Facility Agriculture Zone	Positive	0.091
		X11 Number of healthcare institutions	Positive	0.083
		X12 Local Knowledge Density	Positive	0.078

This study employs the PSR model to assess the flood resilience of traditional villages, applies the Delphi method and the entropy weight method to determine indicator weights, and uses the composite index method to calculate the comprehensive resilience index of each village. (Table 1).

2.3.2 Spatial Form Indicators

There is a profound theoretical relationship between the spatial characteristics of traditional villages—such as proximity to water, water system hierarchy, aspect ratio, and density—and their flood resilience: ① Proximity to water reflects how close a village is to water systems. Being too close exposes it directly to flood inundation, while being too far removes access to water resources. ② Water system hierarchy indicates the level of the water body on which the village depends. Different hierarchical water systems provide varying endowments of water resources and development opportunities, as well as differing levels of flood risk. ③ Aspect ratio reflects the compactness of a village's form. Villages with higher aspect ratios (elongated shapes) have larger exposed surfaces along waterways and longer boundaries vulnerable to stormwater impacts. ④ Density reflects construction intensity and

population concentration. Higher density means greater population per unit area, and also typically implies more developed infrastructure and stronger community organization capacity.

2.4 Research Methodology

2.4.1 Flood Disaster Resilience Index

Based on determining the weights of each indicator using the combined weighting method, the flood disaster risk index (FR) for Jiangsu Province is calculated as follows:

$$F_R = \sum_{j=1}^{n} X_{ij}^{'} \cdot W_j$$

where FR is the flood resilience index; X'ij is the standardized value of the j-th indicator for the i-th region; and Wj is the combined weight of the j-th indicator.

2.4.2 Calculation of Village Morphology Index

This paper employs the shape index calculation method, using aspect ratio (λ) and building density (M) to compute the shape index for individual village cases (Figure 3) (Wang et al, 2024).

(1) Aspect ratio (λ)

The aspect ratio refers to the ratio of the major axis (L1) to the minor axis (L2) in a settlement boundary map, and also serves as an index for the settlement area. It is typically determined by the aspect ratio of its bounding rectangle. The calculation formula is as follows:

$$\lambda = \frac{L1}{L2}$$

(2) Building and structure density (M)

The building density index is the ratio of the total floor area of buildings in a village to the area enclosed by the settlement boundary, directly reflecting the degree of architectural density within the village settlement. The calculation formula is as follows:

In the formula, M represents the settlement building density, S' is the total floor area of village buildings, and a' is the geometric area of the settlement boundary.

$$M = \frac{S'}{A'}$$

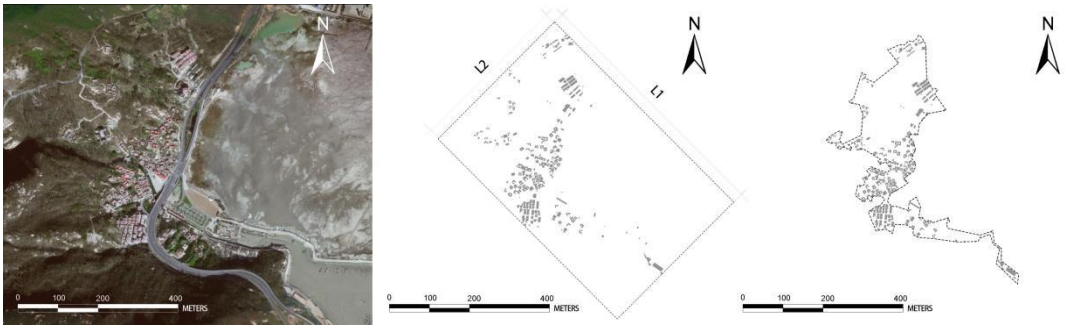


Figure 3 Calculation methods for aspect ratio (λ) and density (M).

2.4.3 Kriging Interpolation Method

The Kriging interpolation method is based on spatial autocorrelation and utilizes the structure of raw data and the semivariogram to interpolate unknown sample points of a

regionalized variable using an unbiased estimation approach; it is one of the main topics in geostatistics. Kriging interpolation can be simply expressed as:

$$Z(c) = \mu(c) + \varepsilon(c)$$

where c represents a point at a different location, which can be considered a spatial coordinate expressed in terms of latitude and longitude; Z(c) is the value of the variable at c, which can be decomposed into a deterministic trend component μ(c) and an autocorrelated random error component ε(c). By modifying this formula, different types of Kriging methods can be derived.

3 Study area and Flood disaster characteristics

3.1 Overview of the Study Area

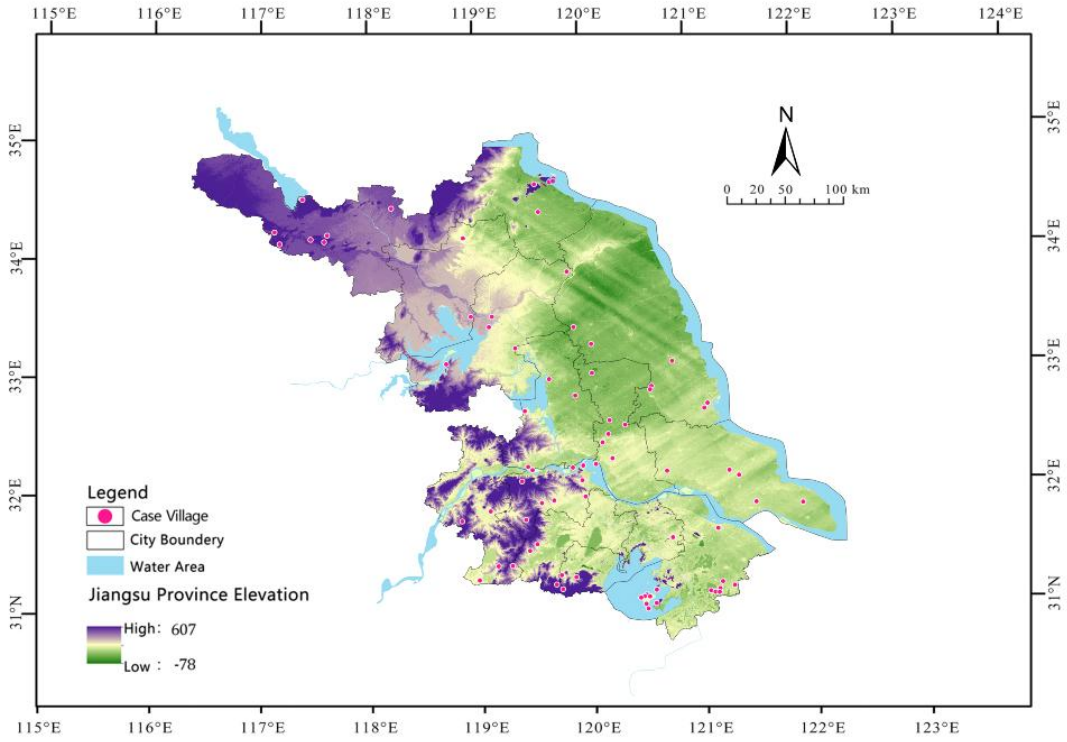


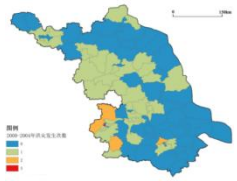
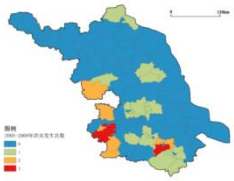
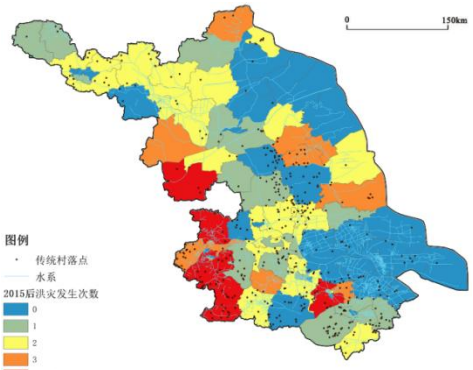
Figure 4 Study area map (based on the standard map No. GS(2019)3266, base map unmodified)

This study adopts a few-shot learning approach (Zhu et al, 2025), selecting 80 traditional villages from a total of 624 in Jiangsu Province as research samples to establish a micro-scale spatial morphology database. The sampled villages cover three major regions—southern, central, and northern Jiangsu—and span diverse watersheds, including the Taihu Lake basin, the Yangtze River basin, the Huaihe River basin, and the Lixiahe area. The regional distribution of the sampled villages is presented in Table 1 (Figure 4).

3.2 Spatiotemporal Evolution Characteristics of Heavy Rain and Flood Disasters in Jiangsu Province

Table 2 Spatiotemporal Evolution Characteristics of Heavy Rain and Flood Disasters in

Jiangsu Province

2000–2004	2005–2009	Cumulative from 2000 to present
		
2010–2014	**After 2015**	
		

Since 2000, high-risk areas for flooding in Jiangsu Province have mainly concentrated along the Yangtze River, around lakes, and in hilly regions. From 2000 to 2004, flood disasters were primarily distributed in the Ningzhen mountainous area and along the Grand Canal; from 2005 to 2009, they occurred mainly around urban areas of Nanjing and Suzhou; between 2010 and 2014, flooding was relatively infrequent and mostly occurred in the border region between Jiangsu and Anhui provinces; since 2015, flood events have been concentrated in Yancheng along the coast and in the Xuzhou region (Table 2).

3.3 Spatial Differentiation of Flood Exposure Induced by Heavy Rainfall

The exposure to heavy rainfall and flood disasters in Jiangsu Province exhibits distinct spatial distribution characteristics: generally higher in the south and east, and lower in the north and west. High-exposure areas are mainly concentrated in southwestern Jiangsu, particularly Huai'an and Nanjing; medium-exposure areas are distributed across Yangzhou, Suqian, Changzhou, and Yancheng; and low-exposure areas are mainly found in Nantong, Wuxi, and Suzhou. The table below presents the association between disaster conditions in typical years and the sampled villages (Table 3).

Table 3 Association between Disaster Conditions in Typical Years and Sample Villages

Year	Type of disaster	Associated sample village	Basis for association
2003	Floods in the Huai River Basin	Guishan Village (Huai'an)	Located along the waterway where the Huai River flows into Hongze Lake, Tuanjie Weir suffered damage from a breach.
2005	Typhoon Maesa	Lu Xiang Village, Tang Li Village, Dong Cun Village, Ya Lu Li Village, etc. (Suzhou)	Several old houses in Suzhou collapse as villages in the Taihu River basin suffer from typhoon and heavy rain.

Year	Type of disaster	Associated sample village	Basis for association
2006 — 2007	Heavy rain and flooding	Li Yuan Village, Wen Cun Village, Shou Xian Village, and Group 5 of Cao Yan Village (Yancheng)	In years of extreme rainfall, villages adjacent to water systems face the highest risk of flooding.
2015	Typhoon Soudelor	Qingzhen Village, Shaoyou Village, and Pihu Community's Taiping Street; Lanzi Village, Hengbei Village No. 2 Village, and Cao Yan Village Group 5 (Yangzhou, Yancheng)	Several cities and counties, including Nanjing, Yangzhou, and Yancheng, have been flooded, with multiple rivers exceeding their warning water levels.
2016	Heavy rains and flooding during the plum rain season	Xiemaqiao Village, Zhubang Village Zhujia Dian, Qibang Village Sanzhu浜 (Suzhou)	Kunshan and Zhouzhuang, among other water towns, experienced the heaviest rainfall, with a maximum precipitation of 178.3 mm.
2020	Heavy rainfall	Qiqiao Village, Qianyangliu Village, and Huanglongxian (Nanjing) in Piaofang Village	Water levels in the Shuiyang River and Qinhuai River basins have exceeded warning levels, prompting evacuations in areas such as Gaochun and Baguazhou.

4 Results

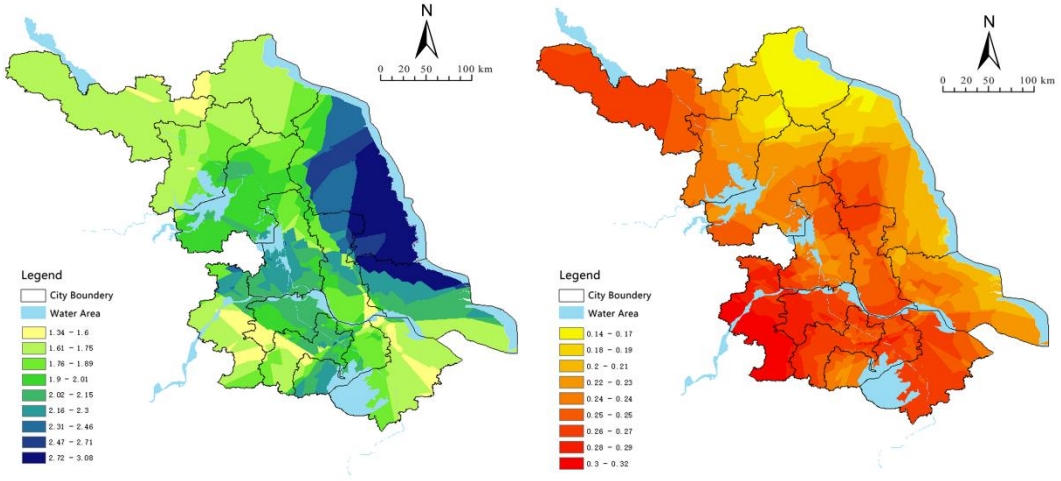
4.1 Descriptive Statistics of Spatial Forms

An analysis of spatial morphology indicators—such as proximity to water, water adjacency level, aspect ratio, and density—for 80 traditional villages reveals:

4.1.1 Overall Spatial Characteristics

Aspect ratio: the mean is 2.11, with a standard deviation of 1.37, ranging from 1.00 to 8.10. There are 28 cluster-type villages (35.0%) with an aspect ratio below 1.5, 38 strip-shaped villages (47.5%) with ratios between 1.5 and 3.0, and 14 elongated villages (17.5%) with ratios exceeding 3.0. Extreme cases such as Hengbei Village No. 2 (8.10), Gaoqiao Village Wujiawu (7.45), and Lanzi Village Groups 1–3 (6.40) exhibit highly elongated morphological characteristics.

Density: The average is 23.7%, ranging from 4% to 42%. There are 27 villages (33.8%) with a density below 20%, 36 villages (45.0%) with a density between 20% and 30%, and 17 villages (21.3%) with a density above 30%. Village density is generally higher in southern Jiangsu, while it is relatively lower in northern Jiangsu（Figure 5）.



(a)Aspect ratio (λ) (b)Building and structure density (M)

Figure 5 Kriging Interpolation Analysis Map of Traditional Village Morphological Indicators

Water proximity: The average distance from water for 80 villages is 98.2 meters. Of these, 61 villages (76.3%) are within 100 meters of water, 14 (17.5%) are between 100 and 200 meters away, and only 5 (6.3%) are more than 200 meters away. Ninety-three point eight percent of the villages are located within 200 meters of water, confirming the common spatial characteristic of traditional villages—residing close to water sources.

Water proximity level: 35.0% of villages are classified as first-level water-proximate, primarily relying on the Yangtze River, Grand Canal, and Huaihe River—the three major water systems; second-level water-proximate villages account for the highest proportion (43.8%); third-level water-proximate villages make up 17.5%; and only 3.8% are fourth-level non-water-proximate villages.

4.1.2 Correlation analysis of traditional village form indices

Divide the data into four quadrants based on the median values for aspect ratio and building density, and identify villages with extreme values, such as the highest/lowest building density and the greatest aspect ratio.The data reveals that:(1) The aspect ratios of the villages are primarily concentrated in the 1.0–2.5 range, exhibiting a distinct right-skewed distribution; a few villages (such as Wujiawei in Gaoqiao Village, with an aspect ratio of 7.45, and Hengbei Village, with an aspect ratio of 8.1) are extremely elongated; (2) Building density and aspect ratio exhibit a certain negative correlation—villages with larger aspect ratios (>3) generally have lower building densities, with most below 0.25; (3) Villages with high building density (>0.35) are primarily concentrated in the "square village" range with length-to-width ratios between 1.0 and 2.5, such as Zhonghe in Zhoucheng Village (0.42), Qianyangliu Village (0.41), and Qiqiao Village (0.39); (4) Villages classified as "large bubbles" (those far from water bodies) are predominantly distributed in areas of low to medium building density, suggesting that distance from water bodies may be negatively correlated with building density（Figure 6）.

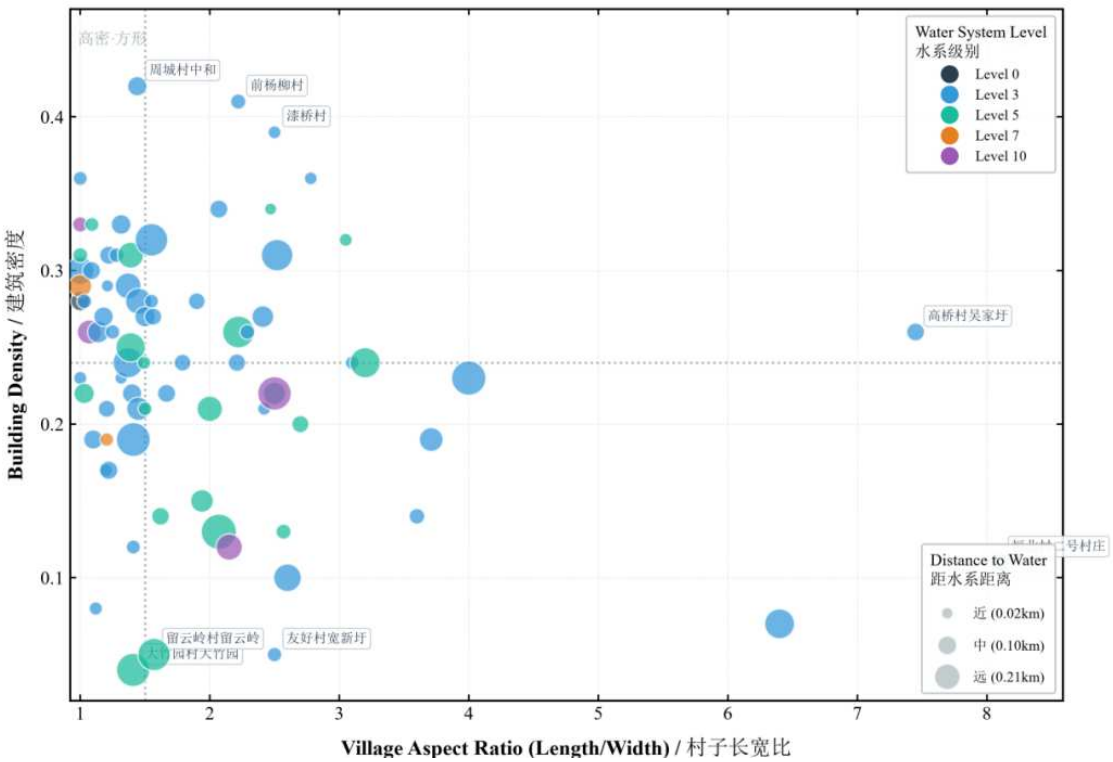


Figure 6 Correlation analysis of traditional village form indices

4.2 Flood Resilience Evaluation Results

4.2.1 Single-Factor Evaluation Results

This study calculated the scores of 80 traditional villages under three criteria layers—pressure (P), state (S), and response (R)—as well as for individual indicators, to reveal the contribution characteristics and differentiation patterns of each factor to village flood resilience (Figure 7).

4.2.2 Comprehensive Evaluation Results

The average comprehensive resilience index of the 80 traditional villages was 0.39, with a standard deviation of 0.08 and a range from 0.27 to 0.56. Using normalization, these values were assigned scores ranging from 1 to 9. Then, based on natural breaks classification, they were divided into five levels: 1 for low resilience, 3 for low-to-moderate resilience, 5 for moderate resilience, 7 for moderate-to-high resilience, and 9 for high resilience (Figure 8).

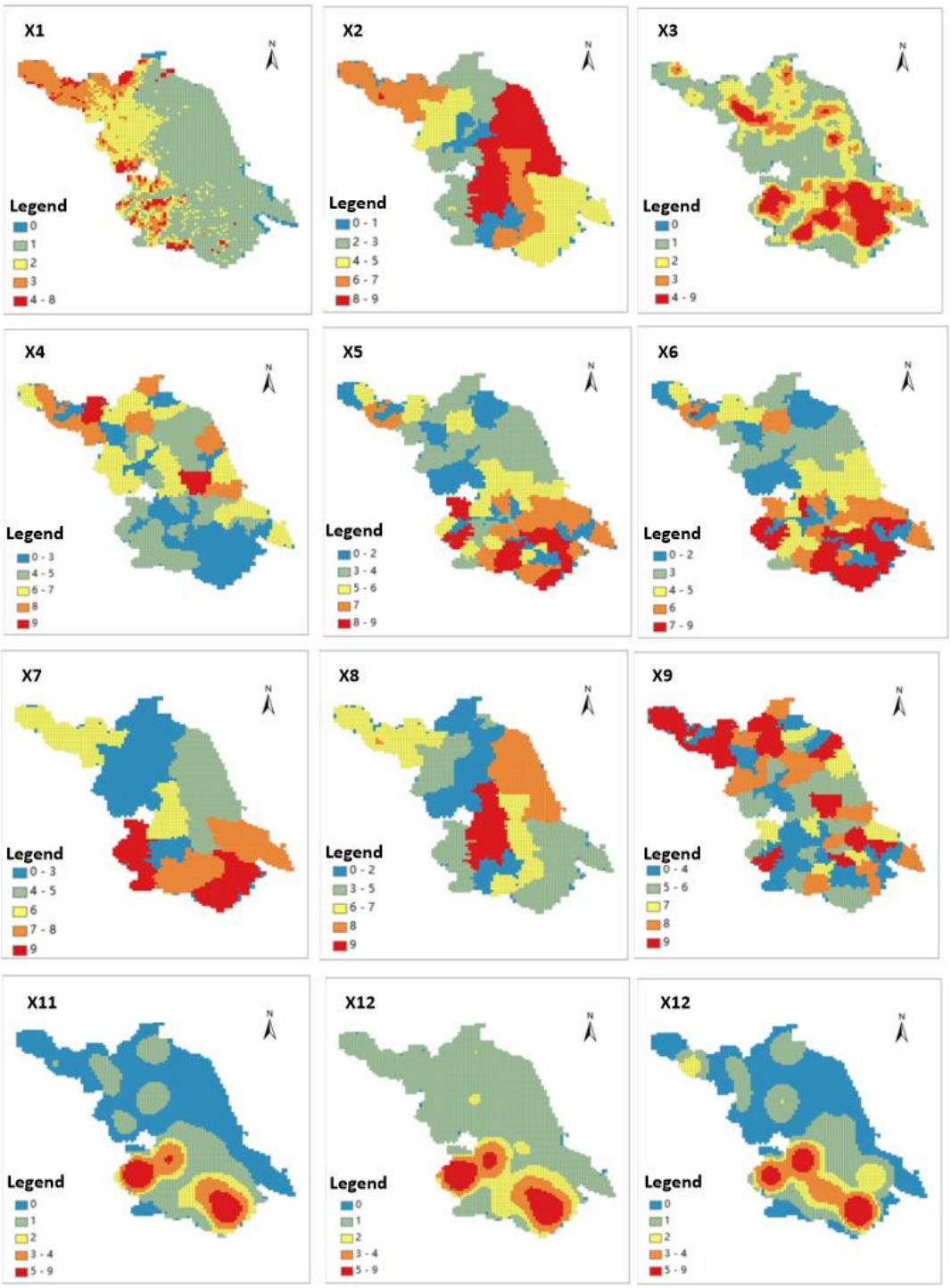


Figure 7 Flood Resilience Single-Factor Analysis Map

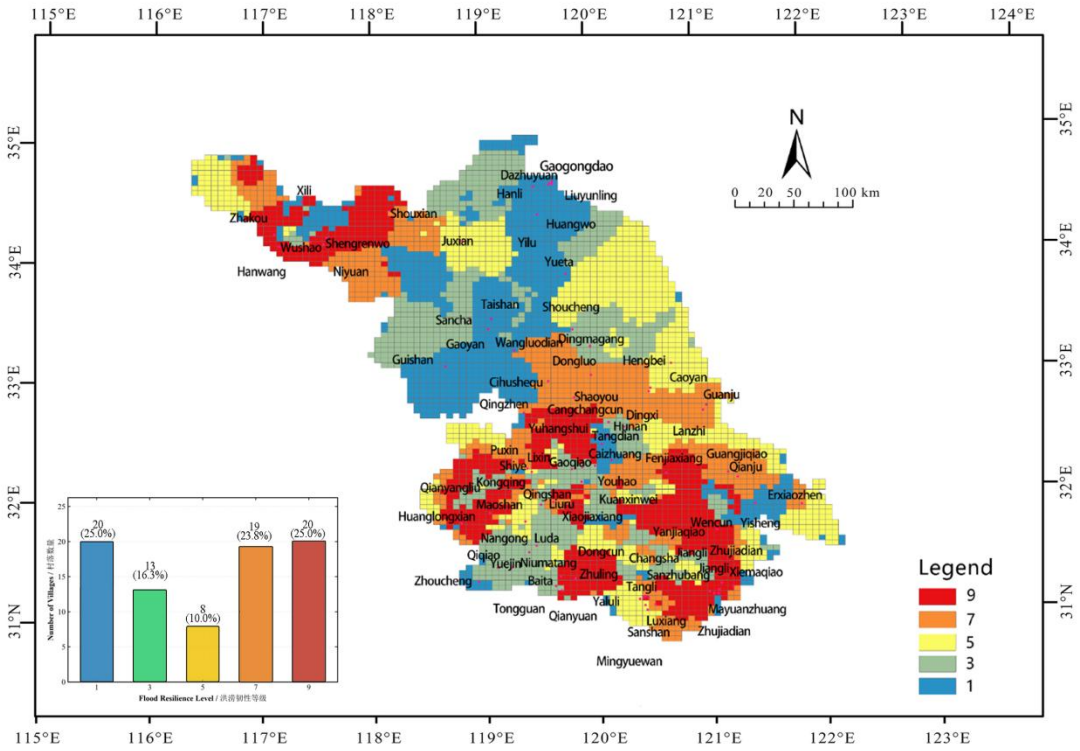


Figure 8 Overlay map of traditional villages and flood resilience

By overlaying the distribution map of traditional villages with the flood resilience distribution map, the following conclusions can be drawn: There are a total of 20 high-resilience villages (accounting for 25.0%), mainly concentrated in the southern part of Jiangsu Province, mostly distributed around the Taihu Lake or along the Grand Canal. These areas have a higher level of development, possess superior ecological conditions, and have well-established infrastructure; there are a total of 19 medium-high resilience villages (accounting for 23.8%), mainly distributed in the southern part of Suzhou and Yancheng, and the eastern part of Nantong; there are a total of 8 medium resilience villages (accounting for 10.0%), mainly located in Wujiang District of Suzhou and along the Chuanchang River in Yancheng - these villages are adjacent to water bodies but have relatively well-established flood control systems; there are a total of 8 low-medium resilience villages (accounting for 10.0%), mainly distributed in the low hilly areas or riverbank zones in the southern part of Jiangsu Province, such as Lishui District in Nanjing and Jintan District in Changzhou, which are often affected by mountain floods and floods; there are another 20 low resilience villages (accounting for 25.0%), mainly concentrated around Hongze Lake in the northern part of Jiangsu Province and in the Lixia River region in the central part (Figure 8, Figure 9).

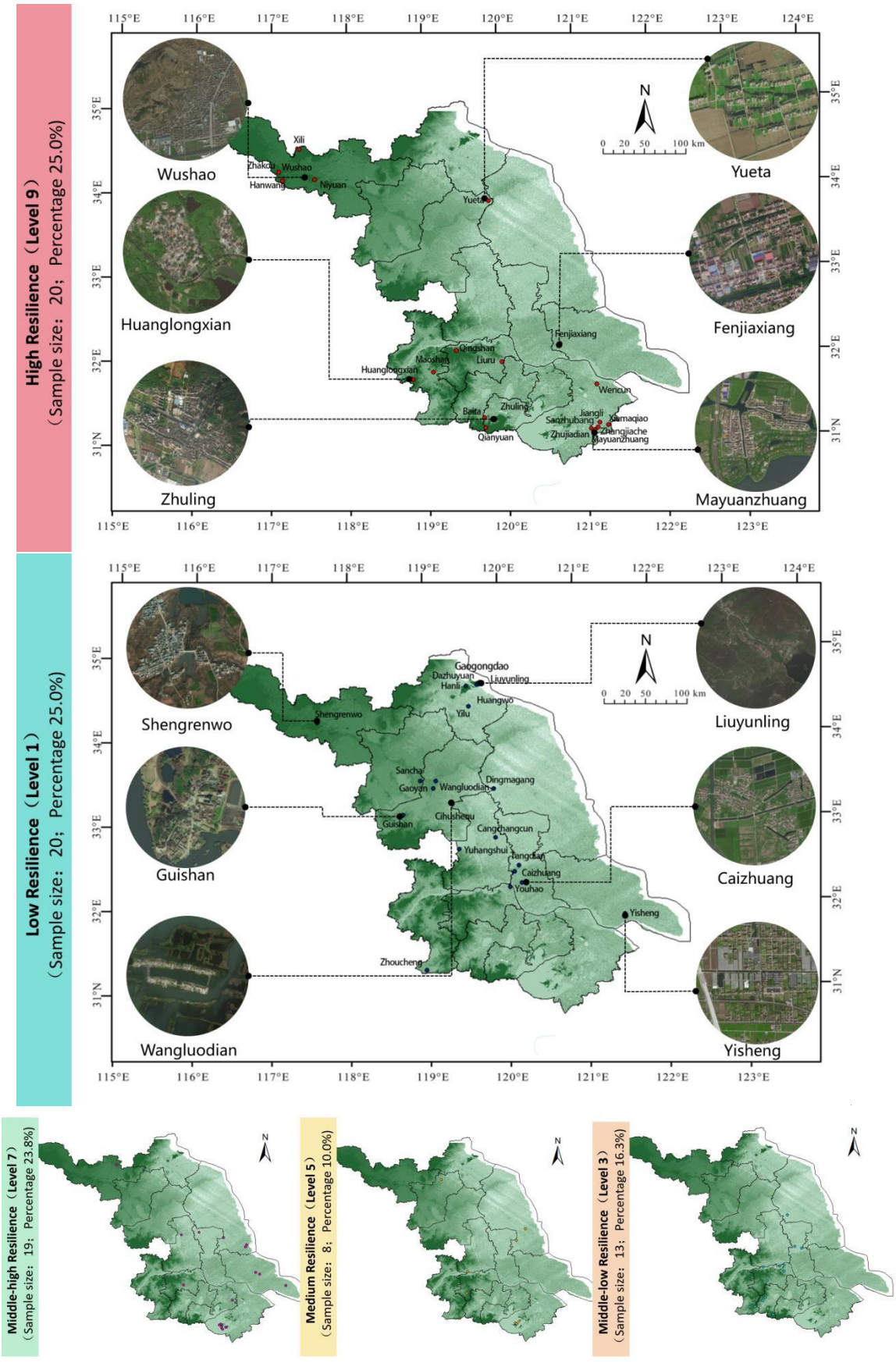


Figure 9 Distribution of Resilience Levels in Traditional Villages

4.3 Correlation Analysis between Spatial Form and Resilience

4.3.1 The Correlation between Flood Resilience and Building and Structure Density

Using violin plots overlaid with box plots and jittered scatter points, the distribution characteristics of village building density across five flood resilience levels are presented, with dashed lines connecting group means to reflect the trend of change (Figure 10).

The results show that: (1) building and structure density generally increases with higher flood resilience levels. The mean density is lowest for level 1 villages (0.196), followed by level 3 (0.241), level 5 (0.225), level 7 (0.255), and reaches the highest at level 9 (0.256). (2) Spearman rank correlation analysis reveals a significant positive correlation between flood resilience and building and structure density ($\rho = 0.250$, $p = 0.0251$, $p < 0.05$), indicating that villages with higher building density tend to have stronger flood resilience. (3) In terms of distribution patterns, the density distribution of level 1 villages exhibits the largest range (standard deviation of 0.090), with multiple low-density villages present; in contrast, the distributions for level 7 and level 9 villages are relatively concentrated (standard deviations around 0.06–0.08), with overall densities at medium to high levels. (4) The association between "high density and high resilience" contradicts previous assumptions that densely populated settlements are more vulnerable. However, this may reflect stronger building quality, better infrastructure, and enhanced collective disaster prevention capabilities in high-density villages, or suggest that density metrics indirectly indicate long-term development levels and governance capacity of villages.

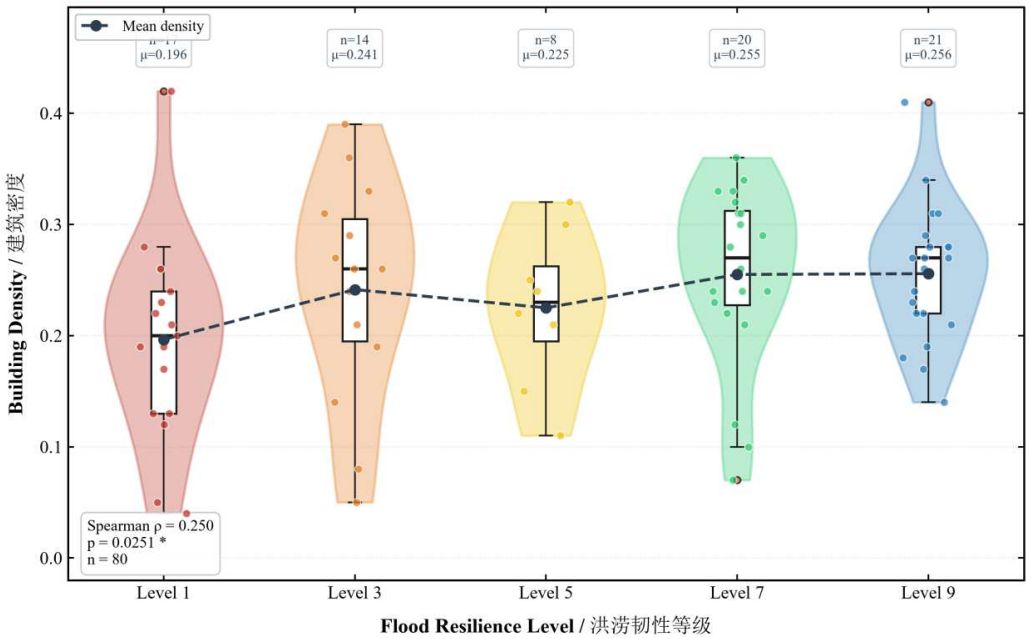


Figure 10 Correlation between Flood Resilience and Building and Structure Density

4.3.2 Correlation between Flood Resilience and Watershed Scale

A grouped scatter plot reveals the relationship between watershed level and flood resilience, with the horizontal axis representing five watershed levels and the vertical axis indicating resilience grades. Resilience values for each group are shown as scatter points in

different colors, while black horizontal lines mark the group means and gray dashed lines indicate the overall mean (Figure 11).

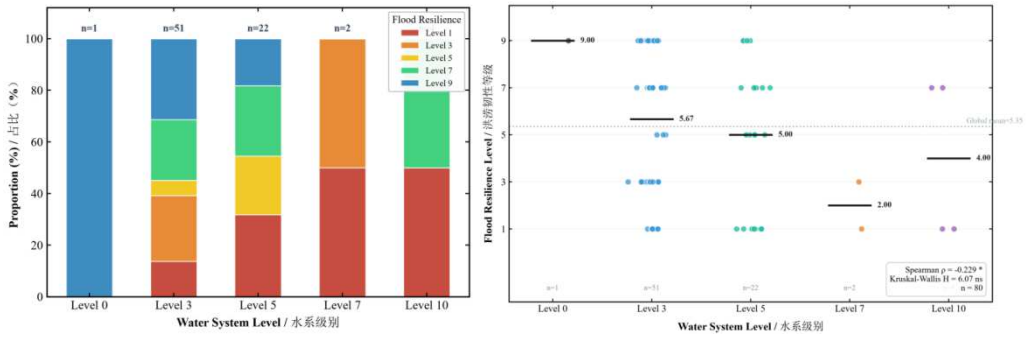


Figure 11 Correlation between Flood Resilience and Watershed Scale

The results show that: (1) the average resilience across different water system levels exhibits a clear decreasing trend: Level 0 is 9.00 (only one sample), Level 3 is 5.67 (n=51), Level 5 is 5.00 (n=22), Level 10 is 4.00 (n=4), and Level 7 is 2.00 (n=2). (2) The Spearman rank correlation test confirms a significant negative correlation between flood resilience and water system level ($\rho = -0.229$, $p = 0.041$, $p < 0.05$), indicating that villages located at higher water system levels (closer to major bodies of water such as large rivers and lakes) have lower flood resilience. (3) This finding aligns with the intuitive understanding that "the closer to major water bodies, the more vulnerable and less resilient": villages near high-level water systems face greater flood threats, yet their overall disaster resilience capacity lags relatively behind.

4.4 Cross-validation

A Spearman rank correlation matrix heatmap (Figure 10) was obtained through the correlation analysis between spatial form indicators and the integrated resilience index. The plot includes four variables: water system level, aspect ratio, building and structure density, and flood resilience. The matrix displays correlation coefficients and significance levels (*p<0.05, **p<0.01, ***p<0.001), with colors indicating the direction and strength of correlations (red for positive, blue for negative) (Figure 12).

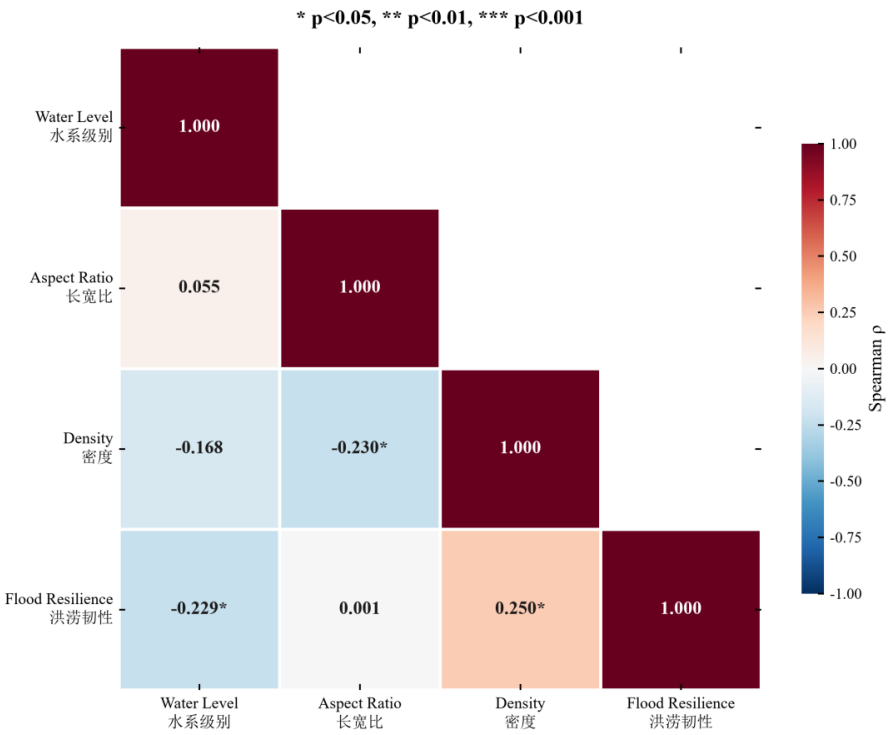


Figure 12 Multivariate Spearman correlation matrix plot

It can be observed that: (1) flood resilience is significantly positively correlated with building and structure density (ρ=0.250, p=0.025, *), representing the strongest relationship among all, indicating that higher building and structure density leads to greater flood resilience; (2) flood resilience is significantly negatively correlated with water system level (ρ=-0.229, p=0.041, *), suggesting that higher water system levels are associated with weaker flood resilience; (3) aspect ratio is significantly negatively correlated with building and structure density (ρ=-0.230, p=0.040, *), implying that villages with a more elongated shape tend to have lower building and structure density; (4) the correlation coefficients between water system level and aspect ratio (ρ=0.055) and between aspect ratio and flood resilience (ρ=0.001) are close to zero, indicating no significant association; (5) water system level and building and structure density show a weak negative correlation (ρ=-0.168), but it does not reach statistical significance (p=0.136). Overall, flood resilience is a key variable in the study area that exhibits significant associations with multiple morphological indicators, among which the positive "density–resilience" relationship and the negative "water system level–resilience" relationship are the two most important findings.

5 Discussion

Based on the quantitative analysis of factors influencing flood resilience in traditional villages of Jiangsu Province presented earlier, this study proposes targeted strategies for enhancing resilience across four dimensions: spatial form optimization, tiered and categorized management, provincial-scale risk adaptation, and revitalization of traditional wisdom. First, morphological classification is used to identify weaknesses and strengths in resilience; then,

optimization guidelines are developed for key morphological factors. These are subsequently calibrated differentially within the context of the province's overall risk landscape, with traditional wisdom activated throughout as a continuous source of resilience.

5.1 Graded and Categorized Management Based on Village Spatial Morphology

Based on the relationship between village spatial morphology characteristics and flood resilience levels, a four-quadrant classification and grading control framework is established using building density and aspect ratio as core classification indicators, providing spatial basis for differentiated policy implementation.

5.1.1 Quadrant-based Morphological Classification and Resilience Characteristics

Using the median values of aspect ratio (1.50) and building and structure density (0.240) from 80 sample villages as thresholds, the villages were classified into four morphological types: Type I (high-density elongated), Type II (high-density compact), Type III (low-density compact), and Type IV (low-density elongated). The mean flood resilience scores differed significantly among these four types: Type I high-density elongated villages showed the highest resilience (mean = 6.14, n = 21), followed by Type II high-density compact villages (mean = 5.75, n = 24), while Type III low-density compact (mean = 4.60, n = 15) and Type IV low-density elongated (mean = 4.60, n = 20) had the lowest resilience, with identical mean scores. Overall, high-density types (Types I + II, mean resilience ≈ 5.92) exhibited significantly higher resilience than low-density types (Types III + IV, mean resilience = 4.60), confirming the core finding of a positive correlation between density and resilience. In terms of resilience level distribution, bubbles representing high resilience levels (grades 7 and 9) were concentrated in medium-to-high density areas, whereas those indicating low resilience levels (grades 1 and 3) were more densely clustered in medium-to-low density regions (Figure 13).

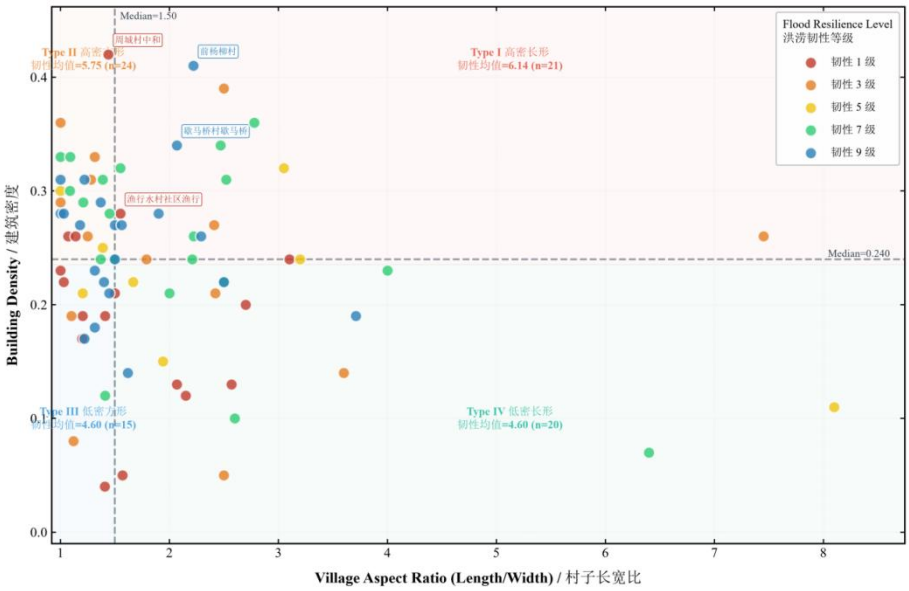


Figure 13 Quadrant classification of village morphology and flood resilience color-coded map

5.1.2 Key Points for Categorized and Differentiated Management

Based on the quadrants classification results, differentiated management guidelines are proposed for villages of different morphological types (Table 4):

Table 4 Resilience Characteristics and Management Key Points of Four Types of Morphological Villages

Type	Morphological Characteristics	Resilience mean	Control Key Points
Type I (High-density Long shape)	Density > 0.240, Aspect ratio > 1.50	6.14 (highest)	Maintain the compact advantage by focusing on strengthening the protection of waterfront embankments to prevent uncontrolled expansion from diluting the density benefit.
Type II (High-density Square)	Density > 0.240, Aspect ratio ≤ 1.50	5.75 (second highest)	Maintain the advantage of clustered form, control uncontrolled boundary spread, and strengthen the internal drainage system.
Type III (Low-density Square)	Density ≤ 0.240, Aspect ratio ≤ 1.50	4.60 (minimum)	Increasing the density of public service facilities and community organizations should not simply involve adding more buildings and structures.
Type IV (low-density, Elongated)	Density ≤ 0.240, Aspect ratio > 1.50	4.60 (minimum)	Focus on assessing flood risks and prioritize the construction of flood control facilities, guiding a moderately compact form.

Meanwhile, auxiliary management measures should be implemented according to the water proximity classification: Type I (high-density linear) villages exhibit the highest resilience (mean value of 6.14) and should be prioritized for protection, maintaining their current advantages while controlling excessive extension along waterways and guiding development toward more compact forms. Compact spatial organization can enhance resilience levels and strengthen the adaptive mechanisms of their spatial morphology. Type II (high-density square) villages should preserve their clustered form, control uncontrolled boundary expansion, and reinforce internal drainage systems. Type III (low-density square) villages should focus on enhancing vitality and resilience in built-up areas through functional

integration and improved infrastructure. Type IV (low-density linear) villages face the highest risk of flood inundation; therefore, water level and rainfall monitoring equipment should be installed at critical locations, a three-dimensional early-warning system covering the entire village should be established, and embankment construction should be strengthened as a priority.

5.2 Optimization Guidance Based on Key Morphological Factors

The regression model results indicate that building and structure density (ρ=0.250) and water system grade (ρ=-0.229) are key morphological factors influencing village flood resilience. Based on this, the following three optimization guidance measures are proposed.

Enhancing effective density improves the efficiency of spatial organization. Density is significantly positively correlated with resilience (ρ=0.250), but increasing "effective density" does not simply mean adding more buildings and structures; instead, it should focus on improving the density of public service facilities and community organizations. For low-density villages (density < 20%), organizational effectiveness and emergency response capacity can be strengthened—without altering traditional appearances—by optimizing the layout of public services, activating community networks, and refining the configuration of public space nodes.

Optimize proximity to water and strengthen risk management for areas near water bodies. The average distance from water for 80 sample villages is only 98.2 meters, with 93.8% of villages located within 200 meters of water, indicating that traditional villages in Jiangsu Province generally exhibit a characteristic distribution close to water sources. For villages with zero distance to water (i.e., built directly adjacent to the shoreline), priority should be given to reinforcing embankment protection and flood early warning systems, as well as installing water level markers and emergency evacuation guidance at critical river sections. It should be noted that greater distance from water is not necessarily better—moderate proximity facilitates drainage and water access, and regression model results suggest this factor should be considered in conjunction with other morphological indicators.

5.3 Differentiated Strategies Based on Provincial Risk Patterns

The overall comprehensive flood risk in Jiangsu Province shows a pattern of lower in the south and higher in the north.

Northern Jiangsu region (high-risk): Prioritize strengthening flood control infrastructure and improving village drainage capacity. Traditional villages in Huai'an, Suqian, Lianyungang, and northern Yancheng should be given priority for flood protection projects. In this study, the average resilience of villages in this area was only 0.34, significantly lower than the provincial average of 0.39.

Central Jiangsu region (medium risk): Strengthen the construction of early warning systems and enhance emergency response capabilities. Traditional villages in Zhenjiang, Taizhou, and northern Nantong should improve their emergency evacuation route networks.

Southern Jiangsu region (low risk): Focus on maintaining ecological advantages and leveraging the organizational strengths of densely populated villages. Traditional villages in Suzhou and Wuxi should enhance their resilience by building on a solid economic foundation.

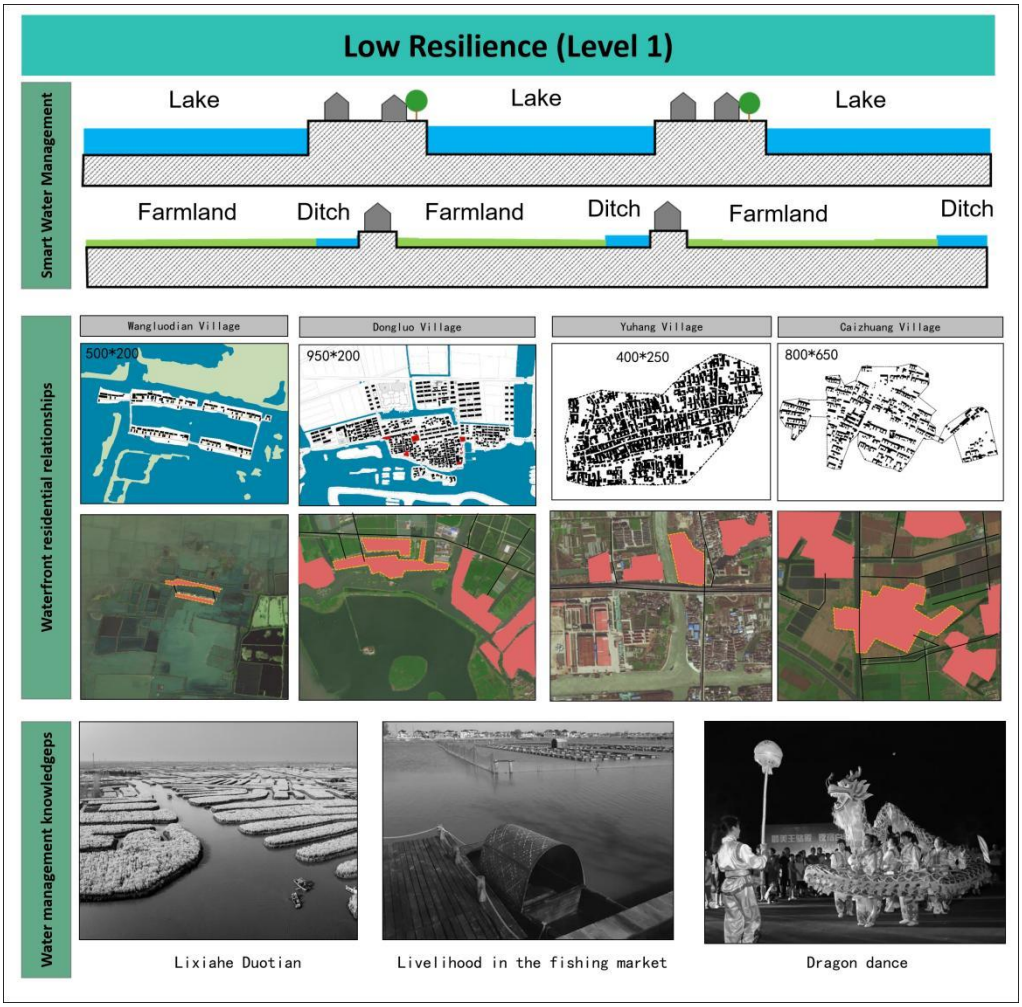


Figure 14 Analysis Map of Water Intelligence in Northern Jiangsu Region

Traditional villages are witnesses of human adaptation and transformation of the natural environment. The local knowledge contained in these villages is closely related to the local climate, ecological environment, folk customs, production methods, and cultural values (Chen et al., 2020, Jia et al., 2024, Geng et al., 2015).Jiangsu's traditional villages have accumulated rich adaptive wisdom in response to rainfall and flooding through long-term interaction with water systems: ① Site selection wisdom—villages such as Qi Bridge and Liu Ru chose elevated ground, while Tongli was situated on the inner bend of a river. These strategies reduced disaster exposure from the outset. ② Water management wisdom—Xinghua's Duo Tian developed a symbiotic system of "mounds, ditches, and embankments," while Mingyuewan established hydraulic structures including stone revetments and sluice gates for flood control. These water management features serve as spatial foundations for flood resilience. ③ Community wisdom—local residents in Jiuli Village developed traditional knowledge such as

"joint embankment maintenance" and "drum signals for flood warnings." Such community organizations form social capital that enhances adaptive capacity. In modern resilience building, it is essential to systematically document, preserve, and revitalize traditional wisdom, transforming it from "museum-like knowledge" into "living resilience resources." (Liu et al., 2022，Li et al., 2026)(Figure 14 and 15).

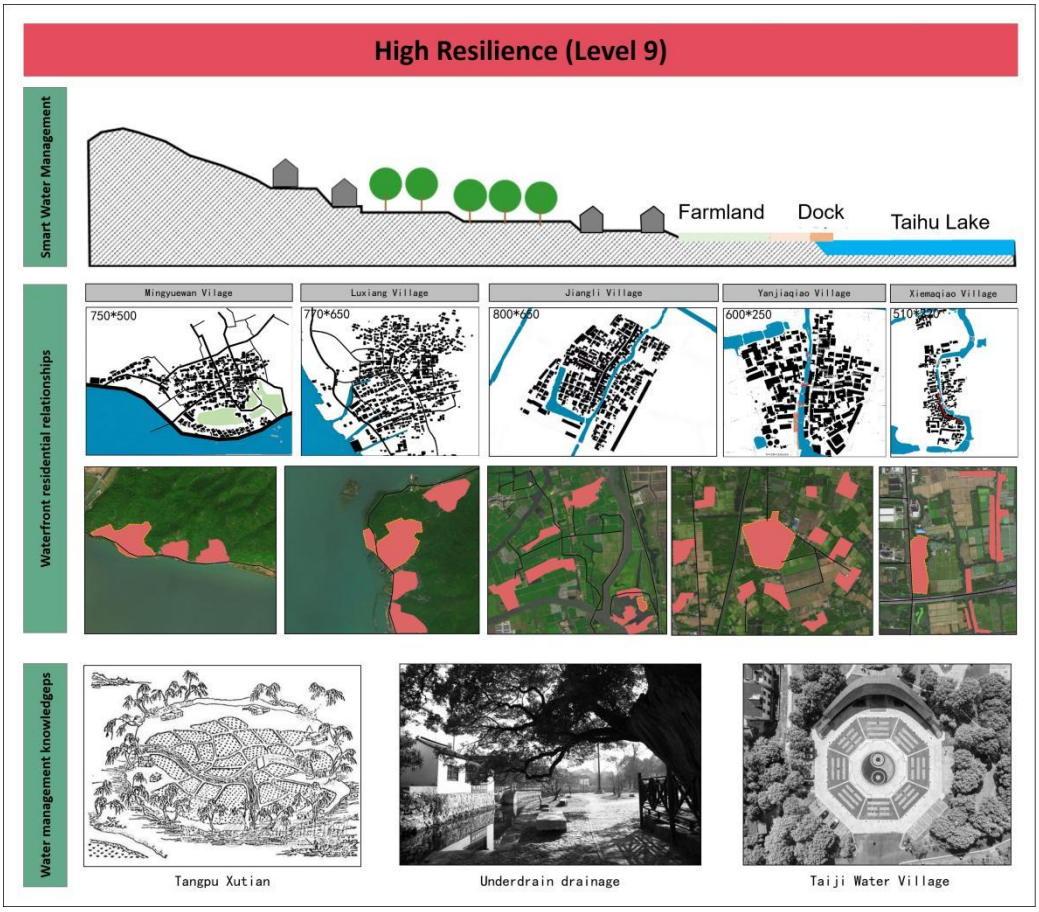


Figure 15 Analysis Map of Water Intelligence in Southern Jiangsu Region

6 Conclusion

This study established a village morphology database using 80 traditional villages in Jiangsu Province, and developed a resilience assessment framework for flood disasters based on the PSR model and CVF method. By systematically analyzing the spatiotemporal characteristics of flooding in the province, it examined the relationship between village spatial morphology and flood resilience. The research bridges the gap between the micro-level morphology of traditional villages and the macro-level distribution of flood resilience, leading to the following key conclusions:

(1) Flood exposure in Jiangsu Province exhibits significant spatiotemporal differentiation. From 2000 to 2026, the overall comprehensive flood exposure in Jiangsu Province was higher in the south and east, and lower in the north and west. High-exposure areas were mainly concentrated in southwestern Jiangsu, particularly Huai'an and Nanjing; medium-exposure

areas were distributed across Yangzhou, Suqian, Changzhou, and Yancheng; and low-exposure areas were mainly found in Nantong, Wuxi, and Suzhou.

(2) The overall flood resilience level of traditional villages in Jiangsu Province is relatively high, with more than half of the villages classified as highly resilient (26%) or moderately to highly resilient (25%), although these are mainly concentrated in southern Jiangsu. At the same time, the resilience levels of traditional villages show a polarized distribution: villages at level 9 (26%) and level 7 (25%) are the most numerous, followed by those at level 1 (21%), while those at the intermediate level 5 are the least (10%), forming a near-U-shaped pattern that reflects uneven development of village resilience across regions.

(3) The relationship between proximity to water bodies and village flood resilience follows an inverted U-shape. Water system level is significantly negatively correlated with flood resilience ($\rho = -0.229$, $p = 0.041$): villages located at higher water system levels (closer to major rivers and lakes) exhibit weaker flood resilience. Villages near high-level water systems face greater flood threats but have relatively insufficient resilience development.

(4) Building and structure density shows a significant positive correlation with flood resilience ($\rho=0.250$, $p=0.025$), making it an important morphological factor influencing resilience. Villages with higher building density exhibit stronger flood resilience. This counterintuitive finding suggests that densely populated villages may possess greater overall disaster prevention capacity, or that density indirectly reflects the level of village development and the completeness of infrastructure. Among them, high-density village types (Type I: elongated high-density, resilience 6.14; Type II: compact square high-density, resilience 5.75) demonstrate significantly higher resilience than low-density types (Types III and IV, both at 4.60), with the elongated high-density villages showing the highest resilience.

This study provides empirical evidence for the graded and categorized protection of traditional villages and their resilience enhancement, based on provincial-scale rainfall-flood analysis and large-sample quantitative analysis. Future research could further expand the sample scope to a national scale and deepen the investigation into the transformation mechanisms between "traditional wisdom" and "modern resilience."

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Author contributions H.W. conceived and designed the study, developed the research framework, and wrote the main manuscript text. P.L. contributed to methodology development and performed the spatial data analysis and statistical analysis. S.X. curated the morphological indicator database of the 80 traditional villages and prepared Figures 1 – 9. J.Z. contributed to data acquisition and processing, including DEM, remote sensing imagery, and hydrographic vector data extraction, and

prepared Figures 10 – 15. Y.S. supervised the project, secured funding, and critically revised the manuscript. All authors reviewed and approved the final manuscript.

Data availability Website sources for the list of traditional villages in Jiangsu: https://jsszfhcxjst.jiangsu.gov.cn/ and https://www.mohurd.gov.cn/. Spatial data sources for Jiangsu: https://www.resdc.cn/ and https://www.webmap.cn/. Flood data sources for Jiangsu: https://doi.org/10.5194/hess-29-767-2025. The list and morphological indicators of 80 traditional villages in Jiangsu are available in supplementary dataset S1.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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

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

References

Aman, J., & Matisziw, T. C. (2025). Urban sentiment mapping using language and vision models in spatial analysis. Frontiers in Computer Science, 7, 1504523. http://doi.org/10.3389/fcomp.2025.1504523

Shen, C., Sun, Y., Yin, D., & Bao, J. (2015). Analysis of characteristics of heavy rain and flood disasters in Jiangsu Province. Journal of Natural Disasters, 24(2), 203-212.http://doi.org/10.13577/j.jnd.2015.0226.

Chen, X., Xie, W., & Li, H. (2020). The spatial evolution process, characteristics, and driving factors of traditional villages from the perspective of the cultural ecosystem: A case study of Chengkan Village. Habitat International, 104, 102250. http://doi.org/10.1016/j.habitatint.2020.102250

Wang, C., Chen, H., & Zhang, X. (2026). Spatiotemporal differentiation characteristics and driving mechanisms of urban flood disaster risk in the Yangtze River Delta region. Urban Development Studies, 33(4), 151-156.

Zhai, G. (2024). Urban flood resilience from a planning perspective under climate change: Key concepts, fundamental approaches, and a general framework. Journal of Urban Planning, 1, 29-37.http://doi.org/10.16361/j.upf.202401004.

Wang, Y., Xia, J., & Zhou, M. (2024). Practice and adaptation of traditional village protection systems from an "institution-lifestyle" perspective: A case study of Suzhou. Urban Planning, 48(7), 90-97+122.

Chen, X., & Hu, J. (2024). Rural spatial governance practices in Jiangsu Province: Stages, pathways, and models. Urban Planning Journal, 1, 38-45.http://doi.org/10.16361/j.upf.202401005.

Wang, H. (2023). Study on the protection and inheritance of spatial pedigree of traditional villages in Jiangsu region [Doctoral dissertation, Southeast University].http://doi.org/10.27014/d.cnki.gdnau.2023.003899.

Shou, T. (2024). Elastic enclosure: Diagramming the construction logic of Huizhou vernacular architectural space. Journal of Architecture, 2, 1-8.http://doi.org/10.19819/j.cnki.ISSN0529-

1399.202402001.

Tian, J., Zeng, S., & Zeng, J. (2025). "Intelligent" disaster recognition and "resilient" disaster bearing: Reconstructing rain-flood safety patterns and planning methods based on ecological hydrological regulation. Urban Planning, 49(8), 118-130.

Zhou, M., Liu, Q., Wang, Y., & Lv, S. (2025). Resilience assessment and enhancement strategies for traditional villages from a governance network perspective: A case study of Wuzhong District, Suzhou. Southern Architecture, 3, 74-84.

Wang, B., Li, X., Xu, C., & Shi, Y. (2026). Resilience assessment of rainstorm and flood disasters in traditional villages of small hill watersheds based on the PSR model: A case study of Xindu, Hebei. Journal of Beijing University of Civil Engineering and Architecture, 42(1), 64-72.http://doi.org/10.19740/j.2096-9872.2026.01.07.

Zhang, F., Wang, Z., Liu, S., & Xu, D. (2025). A dual-scale study on household flood disaster resilience under different topographic conditions: A case of Sichuan Province. Progress in Geography, 44(10), 2188-2202.

Zhang, Y., Li, Z., Yang, M., Zhai, F., & Li, H. (2024). Assessment of flood disaster sensitivity in traditional villages of Central Henan Region. People's Yellow River, 46(3), 33-38.

Chen, Z., Hu, J., & Wang, H. (2021). Reflections on integrating resilient urban planning concepts into the territorial spatial planning system. Planner, 37(1), 72-76+92.

Zhou, M., Wang, Y., & Li, G. (2024). From self-governance to co-governance: The spatial governance logic of traditional villages in Suzhou from the perspective of institutional change. Human Geography, 39(5), 72-82.http://doi.org/10.13959/j.issn.1003-2398.2024.05.009.

Shi, Y., Jiao, M., & Liu, L. (2026). Research progress and framework construction on the social health effects of built environment in traditional settlements. Journal of Natural Resources, 41(10), 3210-3229.

Zu, X., Liu, P., Gao, C., Hou, R., Huang, Z., Ao, Y., & Wang, Y. (2026). Traditional village preservation status evaluation and optimization based on YOLOv10 and random forest model: Take the Tibetan-Qiang region in northwest Sichuan as an example. Frontiers of Architectural Research, 15, 353-369.http://doi.org/10.1016/j.foar.2025.05.007

Li, C., Li, X., Diao, J., Cao, F., Yang, Q., & Zhang, B. (2026). Research on local knowledge categories and formation mechanisms of traditional village landscapes: A case study of Jiangjin District, Chongqing, China. Frontiers of Architectural Research, 15(1), 24-40.http://doi.org/10.1016/j.foar.2025.03.011

Liu, S., Ge, J., Bai, M., Yao, M., He, L., & Chen, M. (2022). Toward classification-based sustainable revitalization: Assessing the vitality of traditional villages. Land Use Policy, 116, 106060. http://doi.org/10.1016/j.landusepol.2022.106060

Liu, C., Cao, Y., Yang, C., Zhou, Y., & Ai, M. (2020). Pattern identification and analysis for the traditional village using low altitude UAV-borne remote sensing: Multifeatured geospatial data to support rural landscape investigation, documentation and management. Journal of Cultural Heritage, 44, 185-195.

Shi, B., & Liu, H. (2022). Distribution pattern of and spatial correlation between traditional villages and geological disasters: A case study on Aba prefecture, Sichuan Province. China City Planning Review, 31(1), 74-83.

Wang, H., Shan, Y., Xia, S., & Cao, J. (2024). Traditional village morphological characteristics and driving mechanism from a rural sustainability perspective: Evidence from Jiangsu Province.

Buildings, 14, 1302. http://doi.org/10.3390/buildings14051302

Shi, B., Liu, H., Huang, L., Zhang, Y., & Xiang, Z. (2023). Increasing vulnerability of village heritage: Evidence from 123 villages in Aba Prefecture, Sichuan, China. Land, 12(11), 2048. http://doi.org/10.3390/land12112048

Sprague, D. S. (2013). Land-use configuration under traditional agriculture in the Kanto Plain, Japan: A historical GIS analysis. International Journal of Geographical Information Science, 27(1), 68-91.http://doi.org/10.1080/13658816.2012.665923

Elfadaly, A., Abutaleb, K., Naguib, D. M., & Lasaponara, R. (2022). Detecting the environmental risk on the archaeological sites using satellite imagery in Basilicata Region, Italy. Egyptian Journal of Remote Sensing and Space Sciences, 25(1), 181-193.http://doi.org/10.1016/j.ejrs.2022.01.007

Geng, H., & Zhou, Y. (2015). Concepts and methods of traditional village protection from the perspective of cultural heritage. Architecture & Culture, 5, 168-169.

Malarvizhi, K., Kumar, S. V., & Porchelvan, P. (2016). Use of high resolution Google Earth satellite imagery in landuse map preparation for urban related applications. Procedia Technology, 24, 1835-1842..http://doi.org/10.1007/s10115-025-02375-9

Muzammul, M., & Li, X. (2025). Comprehensive review of deep learning-based tiny object detection: Challenges, strategies, and future directions. Knowledge and Information Systems, 89, 3825-391.

Cai, C., Li, B., Zhang, Q., Wang, X., Biljecki, F., & Herthogs, P. (2025). Bi-directional mapping of morphology metrics and 3D city blocks for enhanced characterisation and generation of urban form. Sustainable Cities and Society, 129, 106441.http://doi.org/10.1016/j.scs.2025.106441

Wang, H., Liu, P., Shan, Y., Zhang, J., & Xia, S. (2025). Evolutionary characteristics, improvement strategies and driving mechanisms of the human settlement environment in Chinese traditional villages based on historical hydrological resilience assessment. Buildings, 15(23), 4264. http://doi.org/10.3390/buildings15234264

Izgi, B. D. (2022). Resilience of rural settlement morphology dynamics: The case of Kargalı district (village). Journal of Design Resilience Architectonics and Planning, 3(1), 112-126.

Jia, S., Bin Mohd Isa, M. H., & Binti Abdul Aziz, Z. (2023). Spatial characteristics of defensive traditional architecture in multiethnic village of Guangxi: Case studies of Mozhuang Village and Guxietun Village. Frontiers of Architectural Research, 12(4), 683-699.http://doi.org/10.1016/j.foar.2023.05.003

Jia, W., & Wang, L. (2024). Morphological typology pedigree of centripetal spatial schema in traditional Chinese settlements. Frontiers of Architectural Research, 13(6), 1198-1214.http://doi.org/10.1016/j.foar.2024.06.002

Sun, M., Zhang, F., Duarte, F., & Ratti, C. (2022). Understanding architecture age and style through deep learning. Cities, 128, 103787. http://doi.org/10.1016/j.cities.2022.103787

Zhu, X., Wang, X., & Tang, P. (2024). Research on classification of traditional village morphology based on few-shot learning: A case study of traditional villages in Jiangsu province. Urban Environment & Design, 150(4), 223-229.DOI:10.19974/j.cnki.CN21-1508/TU.2024.08.0223.

Meerow, S., Newell, J. P., & Stults, M. (2016). Defining urban resilience: A review. Landscape and Urban Planning, 147, 38-49.

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