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Micro-Scale Analysis and Optimization of Rural Settlement Spatial Patterns: A Case Study of Huanglong Town, Dayu County

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Abstract: Optimizing the spatial patterns of rural settlements is crucial for rural development and revitalization. Enhancing the internal spatial configuration of these settlements necessitates a comprehensive understanding of their micro-scale spatial characteristics. This study develops evaluation indicators and methodologies to quantify rural settlement spatial patterns by analyzing their multidimensional aspects. The research utilizes Huanglong Town in Dayu County, Jiangxi Province, as a case study for exploring micro-scale spatial patterns and proposing corresponding optimization models. The research employs remote sensing image processing and GIS spatial analysis to collect data on the study area. The results indicate that rural settlements in Huanglong Town generally form clustered patterns with moderate spatial structure intensity and order. Notably, spatial heterogeneity is observed across the northern mountainous area, the central plain and low hilly region, and the southern hilly area. Based on these findings, the study categorizes rural settlements in Huanglong Town into four optimization models: stable improvement, internal potential exploitation, controlled expansion, and relocation and withdrawal. Each model is associated with differentiated optimization strategies. By integrating analyses of spatial form, structure, and order, this study reveals the intrinsic spatial characteristics of rural settlements, offering a systematic approach to guide their spatial optimization.

Keywords: spatial pattern; rural settlements; micro-scale analysis; optimization models; spatial characteristics

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1. Introduction

Rural settlements are the places where people in rural areas produce, live, and engage in various social activities, and are the basic framework for a functional and aesthetically pleasing countryside [1]. As a vital component of the human–land geographical system, rural settlements are an important focus of study in rural geography [2].

The study of rural settlement spatial patterns has a rich history dating back to the 19th century [3], evolving through four distinct stages that reflect the changing focus and methodologies in the field. The embryonic stage primarily focused on descriptive studies, defining rural settlements and their relationships with the geographical environment [4]. During the initial development phase, research concentrated on the formation, development, morphology, and function of rural settlements [5,6]. The expansion and transformation stage saw a shift towards quantification and modeling, emphasizing the impact of human behavior and decision making on settlement formation, development, and spatial patterns [7,8]. By the 1980s, the field entered a restructuring phase, with the

research paradigm shifting towards societal and humanistic perspectives. This evolution led to a diversification of research topics, including the relationship between population and spatial patterns, spatial pattern evolution, settlement morphology, type classification, rural settlement changes [8–12], and the influence of socio-economic and other factors on settlement spatial pattern evolution [13–15]. As the field matured, it transitioned from a predominantly qualitative, single-discipline approach to a multidisciplinary framework combining qualitative and quantitative methods, expanding its scope to encompass national and regional geographic units, such as Eastern Europe [16] and Southeastern Australia [17].

This global progression in rural settlement research has been mirrored and expanded upon in the Chinese context, with distinctive regional characteristics emerging. In China, the spatial pattern of rural settlements became a significant research focus after the 1990s [18,19], catalyzed by the advent of Remote Sensing (RS) and Geographic Information System (GIS) technologies. These technological advancements facilitated studies centering on morphology, spatial distribution differences, evolution and driving forces, hollowing out phenomena, and pattern optimization [20–22]. The diverse natural geographical conditions and socio-economic environments across China have given rise to region-specific studies, focusing on areas such as the Loess Plateau, the Central Plains Agricultural Region, and the Northwestern Alpine Tibetan Region [23–27]. This regional approach has provided valuable insights into the unique challenges and patterns of rural settlements across China's varied landscape. In terms of the research scale, studies on rural settlement spatial patterns have predominantly adopted a macro-scale approach, analyzing patterns at provincial, county, or trans-regional levels. These studies often conceptualize rural settlements as cohesive units, examining their spatial patterns and associated resource and environmental impacts [28,29]. This macro-level focus has allowed researchers to identify overarching trends and patterns, providing a foundation for more targeted, localized studies and interventions in rural settlement planning and optimization.

While macro-scale studies have provided valuable insights into broad patterns of rural settlements, recent developments in technology and research methodologies have enabled a shift towards more granular analyses. In recent years, with the support of data such as high-definition remote sensing images and the advancement of cross-disciplinary research, researchers have also emphasized the spatial pattern of village settlements at the micro-scale [30]. Despite this, the existing studies based on the micro-scale of the village area are mostly analyzed from the single element of the rural settlement space, such as the analysis of the settlement patch pattern based on the settlement boundary and the study on the form of architectural monoliths [28,31]. However, researchers still lack a comprehensive analysis covering multiple elements of points, lines, and surfaces of village settlement spaces, which makes it difficult to systematically and comprehensively explain the internal spatial characteristics of village settlements.

Given the current limitations in micro-scale analyses, several critical questions emerge for future research. How can we effectively describe the spatial pattern of rural settlements at a micro-scale from a multi-factor perspective? To what extent are the internal spatial characteristics of regional rural settlements differentiated? What strategies can be employed to optimize the internal space of rural settlements in a nuanced, context-specific manner? These questions represent urgent areas of inquiry in the field. To address these gaps, this study aims to analyze the fundamental aspects of rural settlement spatial patterns, develop quantitative indicators and methodologies for assessing these patterns, and apply them to a specific case study. Using Huanglong Town in Dayu County, Jiangxi Province, as the research area, we seek to uncover the characteristics of rural settlement spatial patterns at the micro-scale and propose corresponding spatial optimization models. This approach aims to provide valuable insights for the optimization of internal spaces in rural settlements, contributing to the growing body of micro-scale research in this field.

2. Research Framework

2.1. Research Concept

Rural settlements are the main places where farmers live and engage in agricultural production in rural areas. They are the products of the combined effects of historical and humanistic factors, economic and social factors, and geographic environment factors, and they are geographic complexes with multiple functions, such as production, living, and ecological and cultural functions. The spatial distribution and pattern of rural settlements are a concentrated manifestation of human adaptation to the natural environment, social conditions, and regional historical development. The essence of rural settlements is the gathering of various elements in a specific geographic location. These elements form an aggregate with moderate boundaries, including point-like architectural monoliths [32,33]. This aggregate contains point-like building monoliths, line-like internal space boundaries of the settlement, and surface-like land patches of the settlement. This aggregation interacts with the surrounding environment through the boundary, and the spatial form embodied in the land patches of the settlement is an important part of the spatial pattern of the settlement. The interior of the settlement land patches consists of building units and the settlement space enclosed by the building units. Within this space, there is a specific order relationship between the building units, and there are differences in the structural strength of the enclosed settlement space. Thus, the study of the structure and order of the settlement space is also of great significance in grasping the spatial pattern of the rural settlements as a whole. The spatial pattern of rural settlements at the micro-scale can be analyzed from three dimensions: spatial form, spatial structure, and spatial order (Figure 1).

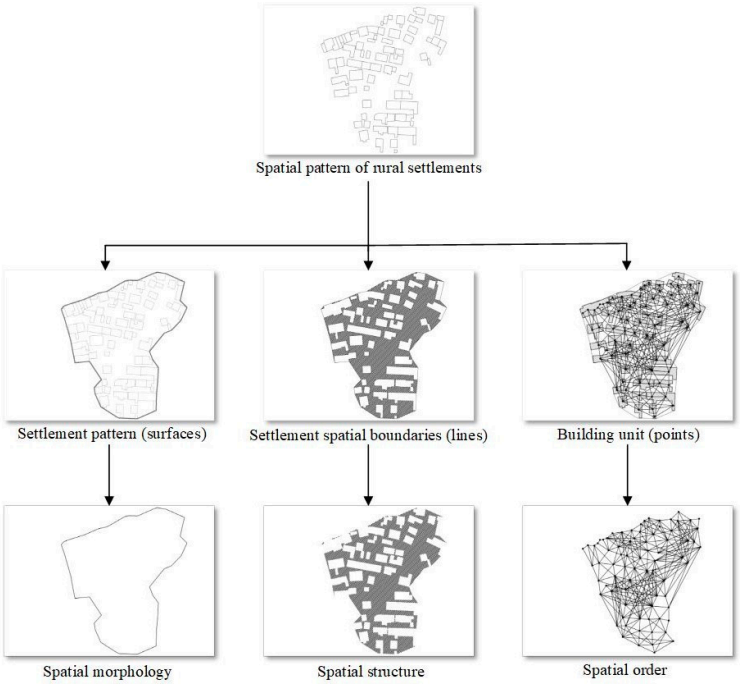


Figure 1. Multi-dimensional analysis of spatial patterns of rural settlements.

2.2. Indicator System

Rural settlements are spatial expressions rooted in the relationship between people and land, established for survival and development. These settlements are influenced by factors such as topography, water systems, and transportation, resulting in diverse land shapes and settlement patch forms. The spatial characteristics of rural settlements are primarily manifested in the geometric attributes of the settlement land (Table 1). To measure the spatial morphology of rural settlements, researchers often employ the aspect ratio (λ) and shape index (S). The aspect ratio, also known as the extension ratio, reflects

the cluster or belt-shaped characteristics of the settlement. Conversely, the shape index indicates the boundary's complexity; a higher value suggests a more convoluted settlement boundary, characterizing the settlement's tendency towards finger-like dispersion.

Table 1. Indicators for evaluating the spatial pattern of rural settlements.

Dimension	Indicator	Description of Indicator
Spatial pattern	Aspect ratio (λ), shape index (S)	λ reflects the cluster or band characteristics of the settlement, and S represents the finger-like discrete trend of the settlement. Settlements are categorized into clusters, bands, or finger-like patterns based on the combination of λ and S.
Spatial structure	Public space sub-dimension value (D)	The public space constructs the overall spatial structure of the settlement. The degree of density and structuring of the settlement spatial structure is indirectly reflected by D.
Spatial order	Comprehensive disorder of building units (C)	C combines distance, area, and angular disorder to characterize the spatial order of rural settlements

The rural settlement space encompasses all external areas of building units within the settlement. Its spatial structure refers to the organization of internal space within settlement patches, with the structural strength reflecting spatial compactness. Rural settlement spaces comprise public and courtyard areas. Public spaces, including roads, water bodies, green areas, and squares, serve functions related to production, daily life, transportation, and communication, forming the overall spatial structure of rural settlements. These public spaces often exhibit complex, fragmented geometrical forms with fractal characteristics. Consequently, the public space sub-dimension value (D) of settlements indirectly reflects the density and structuralization of the settlement's spatial arrangement.

The spatial order of village settlements refers to the arrangement of various elements within the village. As rural settlements originate from the clustering of building units, their spatial order is primarily manifested in the connections between these units. This order not only directly reflects the spatial texture characteristics of the village settlement, but also serves as a concrete expression of the village's internal social order. The area of building units, the distance between them, and their angular orientation are the most essential spatial order vectors in rural settlements. The spatial order of rural settlements is characterized by the comprehensive disorder of rural settlement building units (C), encompassing the distance disorder, area disorder, and angle disorder.

2.3. Quantitative Methods

(1) Aspect ratio and shape index

The aspect ratio is defined as the ratio between the long and short axes of the smallest area rectangle that encompasses the rural settlement boundary. The shape index (S) is calculated by comparing the settlement shape to an ellipse with an equivalent aspect ratio [34,35]. The mathematical formulas for these metrics are as follows:

$$S = \frac{P}{P_0} = \frac{P}{(1.5\lambda - \sqrt{\lambda} + 1.5)} \sqrt{\frac{\lambda}{A\pi}} \quad (1)$$

where P represents the perimeter of the settlement boundary, A denotes the area enclosed by the settlement boundary, and λ is the aspect ratio of the minimum area outer rectangle. The spatial form of rural settlements is categorized based on the quantitative results of λ and S. Settlements are classified as finger-like when $S \geq 2.5$, doughnut-like when $S < 2.5$ and $\lambda < 2$, and band-like when $S < 2.5$ and $\lambda \geq 2$.

Rural settlement boundaries comprise both the physical boundaries of building units and the imaginary boundaries between them. These imaginary boundaries can be delineated at scales of 100 m, 30 m, or 7 m [35]. Utilizing a moderate scale of 30 m, the corner vertices of building units at the settlement's edge are connected in a 'leap' style. This process creates a virtual boundary of the rural settlement, forming a planar closed figure that incorporates both the solid boundaries of building units and the imaginary connections between them.

(2) Public space sub-dimension value

In fractal theory, the fractal dimension value D is commonly used to indicate the complex fragmentation of a plot. Within a cluster's public space, a larger D value signifies greater complexity and fragmentation. Similarly, in settlement public spaces, a higher dimension value D indicates more complex and broken public spaces, while lower values suggest simpler and more regular configurations. The formula for calculating the dimension value D of the public space is as follows:

$$D = \frac{2lg\left(\frac{P}{4}\right)}{lg(A)} \tag{2}$$

where P represents the peripheral perimeter of the settlement's public space, while A denotes the total area of this public space. The sub-dimensional value D ranges between 1 and 2.

(3) Combined disorder of building units

The comprehensive disorder of rural settlement buildings is derived by weighting three components: the distance disorder, area disorder, and angle disorder of the buildings within the settlement.

$$d = \frac{\overline{D} - (\mu - 3\sigma)}{6\sigma},\ m = \frac{\overline{M} - (\mu - 3\sigma)}{6\sigma},\ \theta = \frac{(\mu + 3\sigma) - \overline{A}}{6\sigma} \tag{3}$$

$$C = \frac{d}{2} + \frac{\theta}{3} + \frac{m}{6} \tag{4}$$

where d, m, θ, C are the distance disorder, area disorder, degree disorder, and comprehensive disorder, respectively; $\overline{D}$ is the standard deviation of the minimum distance between building units; $\overline{M}$ is the mean value of the area difference between building units; and $\overline{A}$ is the standard deviation of the angle of building units. The comprehensive disorder C is calculated by assigning weights of 3:2:1 to distance disorder (d), angle disorder (m), and area disorder (θ).

3. Study Area and Data Processing

3.1. Study Area

Huanglong Town is located in Ganzhou City, Jiangxi Province, Dayu County, east of the central part of the county, 9 km from Dayu County. The town covers a total area of 91.96 square kilometers. Huanglong Township is now under the jurisdiction of 10 village committees, including Huanglong, Dalong, Daho, Dry Field, Xincun, Toutang, Trench Pond, Yedun, Lingtan, and Changsheng. The town has mainly mountainous and hilly terrain. The highest elevation is 1112 m at Yashan, while the lowest elevation is 145 m in the village of Daho. The town area consists of hilly mountains in the north and south, with plains, low hills, and granite in the middle. The Zhangjiang River crosses the middle and southern parts of the town. Huanglong Town belongs to the middle subtropical hilly mountain monsoon humid climate and has four distinct seasons.

To ensure that the quantitative data on the spatial pattern of rural settlements are meaningful and accurately express the characteristics of the spatial pattern of the settlements in the region, the selected rural settlements should satisfy the relative completeness and

diversity of the planar spatial patterns. Based on the administrative division information and remote sensing image data of Huanglong Town, Dayu County, 65 representative rural settlements were finally identified as the research objects by taking natural villages as the analyzing unit and eliminating the settlements with a defective morphology and too small of a scale (Figure 2).

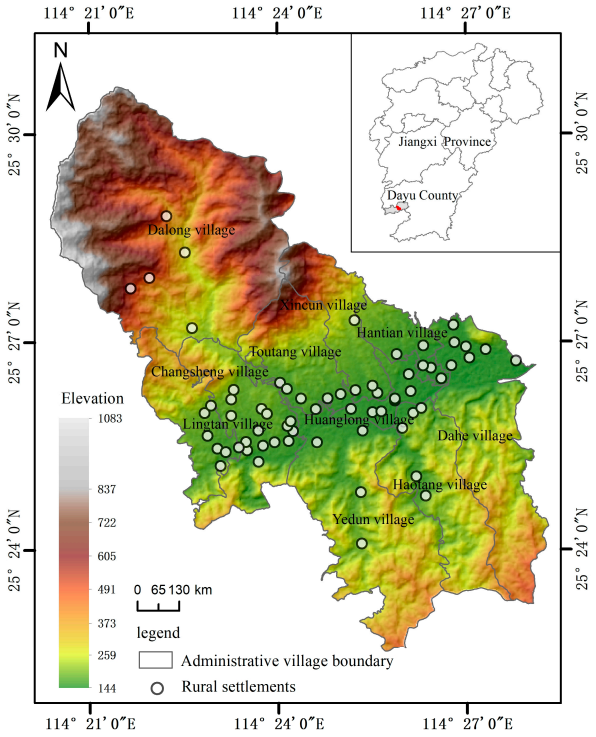


Figure 2. The location of the study area and the distribution of rural settlements.

3.2. Data Sources and Processing

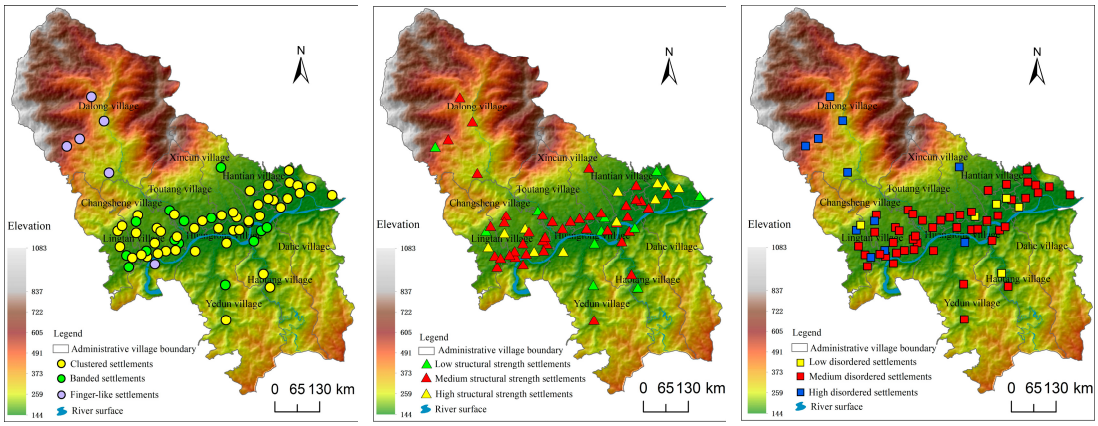
Based on the land use data of Huanglong Township obtained from the Dayu County Natural Resources Bureau, supplemented by high-definition Google Earth remote sensing images, we obtained the data of building units, roads, rivers, and other elements of rural settlements in Huanglong Township through geometric correction, coordinate alignment, visual interpretation, and vectorization. Using the spatial analysis module of ArcGIS10.5 and AutoCAD 2022 software, the 30 m scale boundary of rural settlements was drawn and quantitatively analyzed. With the 30 m rural settlement boundary as the boundary, the two-dimensional map base conversion was carried out on the rural settlement map spot to generate two parts of the space, namely, the building unit and the public space, and calculate the attribute values of the public space, such as the area and the perimeter; based on the general layout plan of each settlement, the distances, areas, and angles of the building groups of the rural settlement were measured via ArcGIS spatial analysis. The minimum distance standard deviation, building unit standard deviation, and angle between building units of the rural settlement were measured by the spatial analysis module of SPSS25. SPSS25 calculates the standard deviation of the minimum distance between buildings, the mean value of the difference in the areas of building units, and the standard deviation of the angle of building units.

4. Analysis of Results

4.1. Characteristics of Spatial Patterns of Rural Settlements in Huanglong Township

The spatial pattern of the rural settlements in Huanglong Township is diverse, covering three types: regimental, belt, and finger. Meanwhile, the spatial pattern of rural settlements in the region is generally more regular, with the proportion of regimented settlements

amounting to 69.2%. Finger-like settlements account for the smallest proportion, accounting for 9.3%, and are located in the northern mountainous area of Huanglong Town. Most of the regimental settlements and band-like settlements are located in the plains and low hills in the central part of Huanglong Town, distributed along the Zhangjiang River basin, and a small number of them are located in the southern hilly area (Figure 3).



(**a**) (**b**) (**c**)

Figure 3. Spatial pattern of rural settlements in Huanglong Town: (**a**) type of spatial form; (**b**) strength of spatial structure; and (**c**) disorder of spatial order.

Based on the results of the calculation of the sub-dimensional value D of the public space of the rural settlement, the natural breakpoint method was used to divide the low, medium, and high structural intensities according to $D < 1.3865$, $1.3865 \leq D \leq 1.4461$, and $D > 1.4461$. Overall, the spatial structural intensity of rural settlements in Huanglong Township was not high, and the proportion of low, medium, and high structural intensities was 16.9%, 66.2%, and 16.9%, respectively. The rural settlements in the northern mountainous areas and the southern hilly areas are of low or medium structural intensity, while the high structural intensity rural settlements are located in the central plains and the low hills.

The comprehensive disorder value C of the rural settlements in Huanglong Township conforms to normal distribution, and based on its mean and standard deviation, $C < 0.3695$, $0.3695 \leq C \leq 0.6305$, and $C > 0.6305$ are defined as low, medium, and high disorder, respectively. The percentages of low, medium, and high disorder in the spatial order of rural settlements in Huanglong Township were 10.8%, 72.3%, and 16.9%, respectively. The spatial order of rural settlements in the northern mountainous areas is high disorder, while in the southern hilly areas, there are rural settlements with low and medium disorder. In the central plains and low hills, low disorder settlements dominate, and there are also settlements with medium and high disorder.

4.2. Spatial Optimization Model of Rural Settlements in Huanglong Township

Based on the spatial form, structure, order characteristics, and combinations of each rural settlement, the rural settlements in Huanglong Town are categorized into four spatial pattern optimization models: stable improvement, internal potential tapping, expansion control, and relocation or mergence (Figure 4). The stable improvement type comprises 11 villages, all situated in the central plains (Table 2). The internal potential tapping type includes 34 villages, distributed across the central plains, low hills, and southern hilly areas. The expansion control type consists of 12 villages, located in the central plains, low hills, and southern hilly areas. Finally, the relocation or mergence type encompasses eight settlements, primarily situated in the northern mountainous regions or the central low-hill areas.

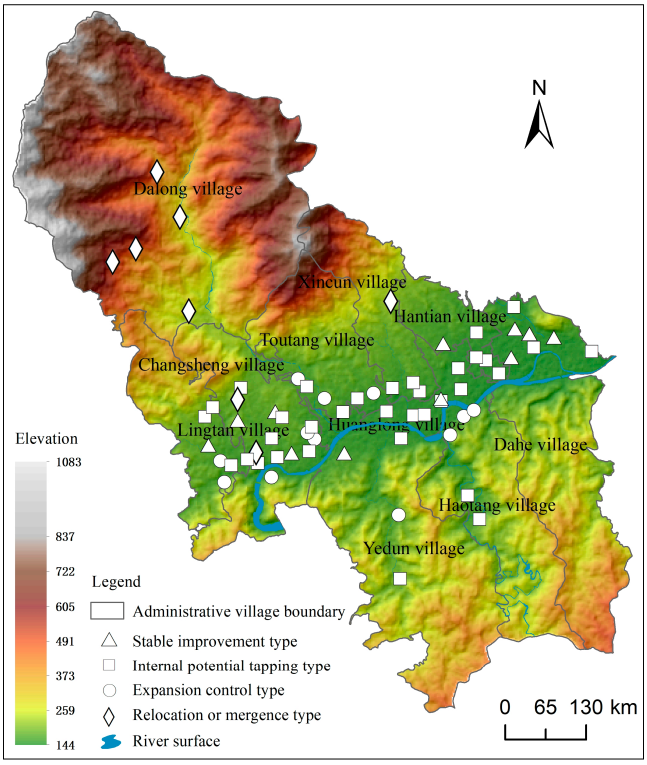


Figure 4. Spatial optimization model of rural settlements in Huanglong Town.

Table 2. Optimization strategy of spatial pattern of rural settlements in Huanglong Town.

Optimization Model	Number of Settlements	Characteristics of Spatial Pattern	Optimization Strategy
Stable improvement type	11	The settlement with the spatial form of regimental, medium, or low spatial disorder, and high spatial structural strength	Maintain the stability of the settlement space pattern and improve the level of public services and infrastructure
Internal potential tapping type	34	The settlement with the spatial form of mass, and medium or low spatial structural strength	Fully tap the potential of vacant land within the settlement and rationally guide the residential construction style
Expansion control type	12	The settlement with a band-like or finger-like spatial pattern, and medium or low spatial order disorder	Strengthen the control of settlement expansion and appropriately tap the potential of internal vacant land
Relocation or mergence type	8	The settlement with a band-like or finger-like spatial pattern, a high degree of spatial disorder, and a medium or low spatial structural intensity	Carry out village relocation or merger, guide centralized living, and implement land reclamation after relocation

Rural settlements in the stable improvement category are characterized by their regimented structure, large scale, compact layout, and good order, demonstrating solid foundations and development potential. Future plans for these settlements should focus on maintaining their spatial patterns, designating centralized housing construction areas, revitalizing inefficient or unused residential bases within villages, and enhancing public services and infrastructure. Settlements in the internal potential tapping category, while of considerable scale, lack strong spatial compactness. These areas should be thoroughly

examined to identify vacant land within settlements, strictly adhere to new residential base area standards, and reasonably guide residential construction styles to promote spatial order and structural strength. Expansion control type settlements, generally small in scale with limited development potential, should still be considered integral to the rural settlement system planning. Efforts should concentrate on controlling outward spatial expansion, particularly prohibiting the use of arable land for housing, while improving spatial structure through the utilization of internal free land.

Relocation or mergence type settlements, typically located in hilly and mountainous areas with steep slopes and high elevations, are characterized by small scales, dispersed buildings, inconvenient transportation, and underdeveloped infrastructure. These settlements should undergo orderly relocation or merger processes. Villagers should be guided towards living in concentrated settlements, with land reclamation carried out post-relocation to optimize the overall spatial pattern of rural settlements in the region.

5. Discussion

Given the ambiguity surrounding the concept and research scope of land use spatial patterns [36], this study proposes a novel approach to analyzing rural settlement spatial patterns. The method examines three key dimensions: spatial morphology, structure, and order, corresponding to the point-shaped building units, linear internal space boundaries, and surface land patches that constitute rural settlements. A quantitative framework is developed, employing aspect ratio and shape index to measure spatial morphology, public space dimension value to assess spatial structure, and comprehensive building disorder to characterize spatial order. This multifaceted approach establishes a robust foundation for uncovering the intricate spatial characteristics of rural settlements, addressing the current limitations in portraying land use spatial patterns.

Through the empirical analysis of Huanglong Town, Dayu County, Jiangxi Province, it is found that most of the plains and low-hill settlements in the central part of Huanglong Town are regimented or banded, with generally high structural intensity and good spatial order, while all the settlements in the northern mountainous areas are finger-shaped, with low structural intensity and high disorder, and the settlements in the hilly areas in the south are regimented or banded, with low structural intensity but good spatial order. The above results reflect that the rural settlements in the study area have obvious differences in spatial patterns, meaning that the spatial heterogeneity of rural settlements can be better characterized in three dimensions: spatial morphology, spatial structure, and spatial order. In particular, compared with the existing studies that only focus on single-factor analyses, this study constructs a spatial pattern of rural settlements [23,25]. The spatial pattern of rural settlements constructed in this study comprehensively considers multiple elements of points, lines, and surfaces, which can provide a reference for the depiction of spatial patterns of land use.

Optimizing rural settlement spatial patterns offers an effective approach to addressing structural issues in rural land use and integrating diverse elements of rural development. While current optimization strategies typically focus on macro-scale factors such as settlement location, natural geographic environment, and socio-economic development levels, they often overlook the intrinsic spatial characteristics of the settlements [37–39]. This study addresses this gap by examining internal spatial patterns at the micro-scale, classifying rural settlements in Huanglong Town into four optimization modes based on their spatial morphology, structure, and order: stable improvement, internal potential tapping, expansion control, and relocation or mergence. By applying multidisciplinary methods from landscape ecology, fractal geometry, and architecture, this study quantitatively reveals spatial pattern characteristics and heterogeneity among rural settlements. However, while these findings provide valuable guidance for differentiated optimization of rural settlement internal spaces and offer a reference for planning and development, they do not capture the dynamic evolution processes and mechanisms of rural settlements. Given the ongoing rural revitalization efforts and improvements to national spatial planning systems, further

exploration of the spatial and temporal evolution of rural settlements at the microscopic scale is crucial for developing more effective optimization strategies and promoting orderly rural development.

6. Conclusions

Rural settlements are the products of the combined effects of historical and humanistic factors, economic and social factors, and geographic environment factors, and are geographical complexes with complicated spatial patterns. By analyzing rural settlements at the micro-scale, we can deeply reveal the internal spatial pattern of rural settlements, which will help us to explore the formation process and differentiation law of rural settlements under different regional environments. The material space of rural settlements covers points, lines, surfaces, and other spatial elements, and is a systematic combination of spatial elements. Due to their different spatial elements and combinations, rural settlements show different spatial forms, spatial structures, and spatial order characteristics, which can be quantitatively analyzed with the help of multidisciplinary methods such as landscape ecology, fractal geometry, and architecture. From the perspective of individual rural settlements, the spatial optimization of rural settlements is the adjustment of spatial structure and order under a certain spatial form. The combination of spatial morphology, structure, and order determines what kind of spatial optimization mode the rural settlement adopts. Integrating multiple dimensions of spatial morphology, spatial structure, and spatial order enables a more systematic and comprehensive analysis of the spatial characteristics of rural settlements under the combination of multiple elements, and provides a new analytical perspective and research framework for examining the spatial pattern of rural settlements at the micro-scale.

Author Contributions: X.Z., J.L. and J.X. designed the analysis, developed the software, wrote the original and revised manuscript, and conducted data analysis and details of the work. J.X. and X.Z. conceptualized and designed the research experiment, wrote the original/revised drafts, designed, re-designed, and verified image data analysis, and guided the direction of the work. All authors have read and agreed to the published version of the manuscript.

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