

## Article

# Water-Facing Distribution and Suitability Space for Rural Mountain Settlements Based on Fractal Theory, South-Western China

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**Abstract:** The establishment of rural settlements in the topographically complex mountainous area of South-Western China is restricted by various geographical features. The fractal characteristics and water-facing distribution of rural mountain settlements and the suitability of spaces for rural mountain settlements were analyzed for a greater scientific understanding of what factors would facilitate a more appropriate selection of residential sites. The results showed that: (1) Rural mountain settlements have significant fractal characteristics—the fractal dimension values of rural mountain settlements in terms of elevation, slope, disaster risk, and water-facing level ranged from 0.853 to 1.071, 0.716 to 0.997, 0.134 to 0.243, and 0.940 to 1.110, respectively. (2) The fractal dimension value of rural mountain settlements initially increased and subsequently decreased with increasing elevation, and gradually decreased with increases in slope and disaster risk, but with wave-curve increases in water-facing levels. (3) The suitable spaces for rural mountain settlements were those with a low disaster risk and with slopes less of than 5° under a water-facing level of 0 ~ 500 m in the elevation range of 1500–2000 m. Currently, 8.77% of rural mountain settlements are situated in high-risk and sub-high-risk areas. The spatial planning of national land in China may enhance the land consolidation of rural mountain settlements and plan for the placement of settlements in suitable spaces while avoiding high-risk areas and sub-high-risk areas to ensure the safety of lives and property. The results from this study could be used as a reference for future revitalization activities and the site selection of rural mountain settlements.

**Keywords:** fractal characteristics; natural geographical features; water-facing distribution; suitable space; rural mountain settlements



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## 1. Introduction

Fractal theory was put forward by MANDEL-BROTBB, an American mathematician in 1975. It is used to refer to a kind of body composed of parts which are similar to the whole in some way, and then to analyze the self-organization evolution law of fractal form from the perspective of form, structure, and order [1]. The spatial characteristics of rural residential areas are irregular, unstable, and highly complex and are therefore difficult to study using traditional geometric theory [2]. However, fractal theory can provide a framework for understanding the spatial characteristics of irregular, unstable, and highly complex structures [3], and fractal characteristics are therefore very important for studying the spatial characteristics of rural settlements, especially in rural mountain settlements.

Fractal theory has been developed from the concept of “fractals”, the invariant laws, levels, and scales hidden within complex natural and social phenomena [4]. Fractal models are used to study urban growth [5], urban boundaries [6], urban road networks [7,8], and have achieved reliable results. Cheng (2016) [9] analyzed the urban primacy index, the scale-grade fractal characteristics and the equilibrium and relevance of the urban systems in the mountainous Qinba area of Sichuan province. Based on the geographical features of rural settlements, Che (2010) [10] and Song et al. (2013) [11] concluded that the spatial distribution of rural settlements was self-similar, and the fractal dimension reflected the spatial occupying ability and clustering ability of rural settlements. However, most of these studies focused on urban areas, with less attention given to rural mountain settlements with a complex and varied topography.

Whether urban or rural, the development of the distribution of a settlement depends on a reliable water source. The influence of a river on settlement distributions in urban areas has been thoroughly studied. Cronon (1991) [12] and Berziant (2000) [13] purported that riverine and estuarine areas were the first and naturally advantageous areas to be considered for urban settlements. Che (2010) [10] found that the fractal dimension of the residential area was higher than that of the traffic and water system. Liu (2012) [14] studied the relationship between the distribution of 655 organized cities and the natural environment and found that a city’s dependence on water is high, and the higher the city grade, the stronger the dependence. However, the effects and spatial correlation of natural geographical factors, especially the water-facing level (also known as distance to water), on the characteristics of rural mountain settlements are poorly known.

Mountainous areas are constrained by landform and physiognomy and characterized by closure. Rural mountain settlements are more constrained by geographical environments. A significant problem for rural mountain settlements is the lack of understanding on the selection of appropriate building sites. The fractal theory could help us judge the space occupying capacity of mountain rural settlements, and then identify the suitability space for mountain rural settlements. The fractal characteristics of rural settlements take on distinct spatial characteristics, with, for example, changes in the elevation, slope, and distribution of geological hazards [15]. Therefore, natural geographical factors, such as elevation, slope, water-facing level, and disaster risk, are used to analyze the fractal characteristics and distribution of rural mountain settlements. Studies of factors that influence the characteristics of residential areas have mostly examined factors separately [16]. In our study, we addressed the effect of interactions between the water-facing level and other natural geographical factors on the distribution of rural mountain settlements. The specific aims of this study were to: (1) Analyze whether the rural settlements and natural geographical factors have fractal characteristics, (2) determine the water-facing distribution of rural mountain settlements, and (3) identify the suitability of space for rural mountain settlements. We believe that the research results would provide reliable suggestions for policy-making in spatial planning for the future revitalization and site selection of rural mountain settlements in the mountainous area of South-Western China.

## 2. Study Region and Data Sources

The Panxi area, located in the south-western area of Sichuan province in China, is the transition zone between the Qinghai–Tibet Plateau and the Yunnan–Guizhou Plateau to the Sichuan Basin and mainly includes Panzhihua City and the Liangshan Yi autonomous prefecture [17]. The terrain of this area inclines from the northwest to the southeast with a large height difference [18]. The mountainous characteristics of the river are distinctive, with most being deep canyons. The proportion of the passing run-off water is relatively high, accounting for 73.5% of water resources in the region [19]. Four river basins (Figure 1), including the Anning, Yalong, Yantang, and Jinsha River Basins, containing more than 90% of rural settlements in Panxi area, were selected as the research areas. Data include a Landsat Thematic Mapper remote sensing image of the Panxi area (2010) using a 1:50,000 digital elevation model (DEM) of Panxi.

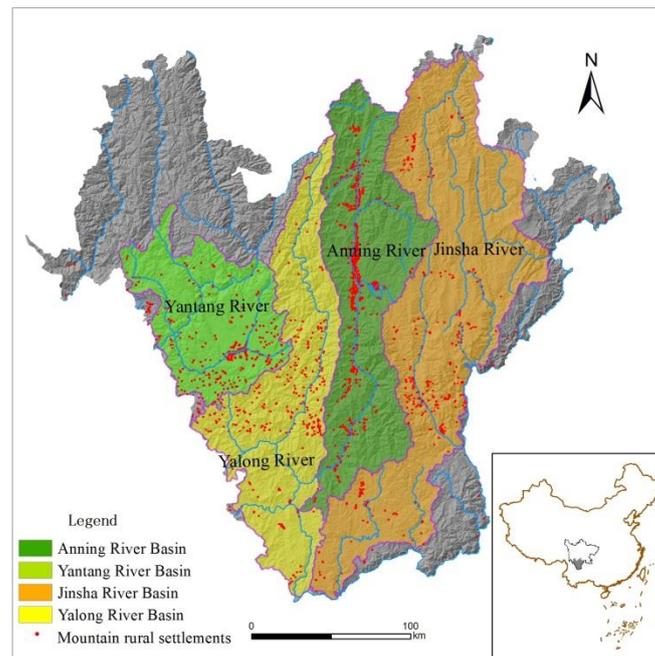


Figure 1. Sketch map of the study area.

### 3. Methods

In order to identify the suitability space of rural mountain settlements and judge the impact of the water systems on rural mountain settlements distribution, the rural settlements’ spatial distribution characteristics on different natural geographical factors and the water-facing distribution of rural mountain settlements should be determined firstly. Then, the fractal dimension values of rural mountain settlements were analyzed to identify the most important factors affecting the fractal characteristics of settlements in the mountainous region and therefore identify the importance of suitable space for rural mountain settlements. The main applied methodology methods and research process (Figure 2) are as follows:

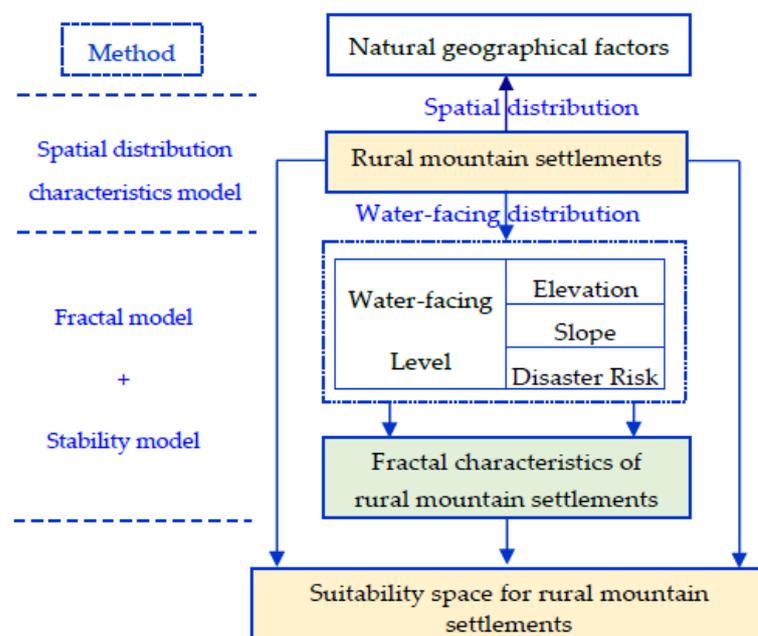


Figure 2. The process diagram.

### 3.1. Fractal Model

The fractal body of rural residential settlements in the south-western mountainous area is imbalanced. Therefore, we used the information-counting method [4] to calculate the information dimension of rural settlements in mountainous areas to identify the development of an orderly state, identify the spatial distribution's equilibrium degree of rural settlements, and characterize the ability of rural residential settlements to occupy space. The information dimension of the fractal model is a generalization of the box dimension (Figure 3); that is, this covers the fractal body with a small box with a side length  $r$  or  $r/2$ , numbers each small box, and records the probability that the part of the fractal falls into the  $i$  small box as  $P_i$ . The average amount of information measured using the small box of scale  $r$  is:

$$I = - \sum_{i=1}^{N(r)} P_i \ln P_i, \quad (1)$$

$$D = - \lim_{r \rightarrow 0} \frac{\ln \left( - \sum_{i=1}^{N(r)} P_i \ln P_i \right)}{\ln(r)}. \quad (2)$$

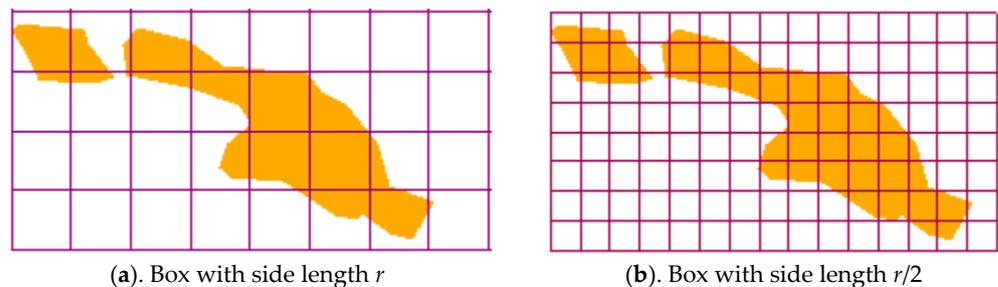


Figure 3. Diagram of the information dimension.

If  $I$  is substituted for small box number  $N(r)$  in Equation (1), the information dimension  $D_i$  can be obtained [4].

### 3.2. Spatial Distribution Characteristics Model

Using ArcGIS 10.3, the spatially aggregated curves of the rural mountain settlements were established with the Variable Clumping Method (VCM) [20,21]. A GIS spatial analysis was undertaken to quantitatively analyze the spatial clustering characteristics of the rural settlements in the study area based on elevation, slope, water-facing level, and disaster risk. The clustering of rural settlements in mountainous areas was quantified by the buffer analysis, and statistical analyses of the related attributes data were carried out by SPSS:

$$VCM_i = N_i / S_i \quad (i = 1, 2, 3, \dots, n), \quad (3)$$

where  $VCM_i$  is the degree of spatial aggregation,  $N_i$  is the number of rural settlements in buffer  $i$ , and  $S_i$  is the area of buffer  $i$ .

### 3.3. Stability Model

Mandelbrot held that the fractal dimension ( $D$ ) of the Brownian motion was 1.50, and the  $D$  value drew closer to 1.50 the more unstable this was. According to this principle, Xu et al. (2001) [22] defined the patch morphology stability index,  $S_i$ , as the following:

$$S_i = |D - 1.5|. \quad (4)$$

$S_i$  is the stability index that characterizes the difference between the fractal dimension of rural residential areas and that of the Brownian motion, and is an indicator of the stability

of rural residential areas. The higher the  $S_i$  value, the more stable the plaque pattern in rural settlements and vice versa.

### 3.4. Grading Standards

The natural geographical factors affecting the spatial distribution of rural mountain settlements mainly include elevation, slope, river, and disaster in South-Western China. Therefore, the fractal dimensions of residential points at the natural geological factors were analyzed. The grading standards for the natural geological factors are listed in Table 1—e.g., the distance grades of elevation ( $\leq 500$  m, 500–1000 m, 1000–1500 m, 1500–2000 m, 2000–2500 m, and 2500–3000 m) were respectively labelled as elevation zone 1, elevation zone 2, . . . , elevation zone 6.

**Table 1.** Grade standards for the natural geographical factors.

Influencing Factors	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Elevation (m)	$\leq 500$	500–1000	1000–1500	1500–2000	2000–2500	2500–3000
Slope ( $^{\circ}$ )	$\leq 5^{\circ}$	5–10 $^{\circ}$	10–15 $^{\circ}$	15–20 $^{\circ}$	20–25 $^{\circ}$	25–30 $^{\circ}$
Disaster Risk	Low risk	Medium risk	Sub-high risk	High risk	/	/
Water-facing Level (m)	$\leq 500$	500–1000	1000–1500	1500–2000	2000–2500	2500–3000

## 4. Results

### 4.1. Spatial Distribution Characteristics of Rural Settlements on Natural Geographical Factors

Rural settlements in the Anning, Yalong, Yantang, and Jinsha River Basins account for 41.63%, 16.37%, 22.58%, and 19.42% of the total rural settlements (Figure 1).

The spatial distribution characteristics of rural settlements in terms of elevation, slope, disaster risk, and water-facing level were analyzed. A total of 81.45% of the rural mountain settlements were distributed at 1500–2500 m. As the elevation increases, the numbers of rural settlements initially increase and subsequently decrease. The number of rural settlements is the maximum at the slope of 0–5 $^{\circ}$ , which accounts for 41.38% of the total rural settlements. When the buffer radius of the slope exceeds 15 $^{\circ}$ , the overlapping areas between the rural settlements and the buffers decrease sharply. A total of 88.03% of the rural mountain settlements are distributed within 1 km of the river. When the water-facing level exceeds 1 km, the overlapping areas between the rural settlements and the buffers decrease. A total of 91.23% of the rural settlements are distributed in low- and medium-risk areas. As the disaster risk increases, the numbers of rural settlements decrease significantly.

### 4.2. Water-Facing Distribution of Rural Mountain Settlements

#### 4.2.1. Water-Facing Distribution of Rural Mountain Settlements in Terms of Elevation

The VCM curve reflects the spatial correlation and distribution characteristics of rural mountain settlements in terms of the water-facing level and terrain (Figure 4). The overall change trend of rural settlements is the same in water-facing levels 1–6. As the elevation increases, the number of rural settlements initially increases and subsequently decreases. However, local variations in the water-facing levels are significantly different, with two major trends. At water-facing levels 1–3, the number of rural settlements is the highest at 2000 m, while at water-facing levels 4–6 the number of rural settlements is highest at 3000 m.

#### 4.2.2. Water-Facing Distribution of Rural Mountain Settlements in Terms of Slope

According to the VCM curve of rural settlements and slopes in terms of water-facing levels (Figure 5), the spatial correlation characteristics of rural settlements and slopes undergo similar changes. There are two major trends. At water-facing levels 1–3, the number of rural settlements decreases with increasing slope, with the highest number at the slope of 5 $^{\circ}$ . At water-facing levels 4–6, the number of rural settlements initially increases and subsequently decreases with increasing slope, and with the highest number at a slope of 15 $^{\circ}$ .

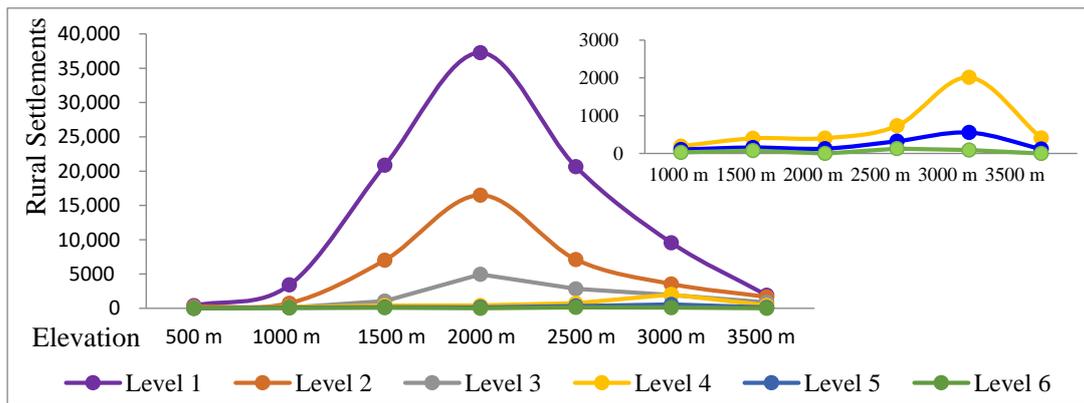


Figure 4. Variable Clumping Method (VCM) curves of rural settlements and elevation in terms of water-facing level.

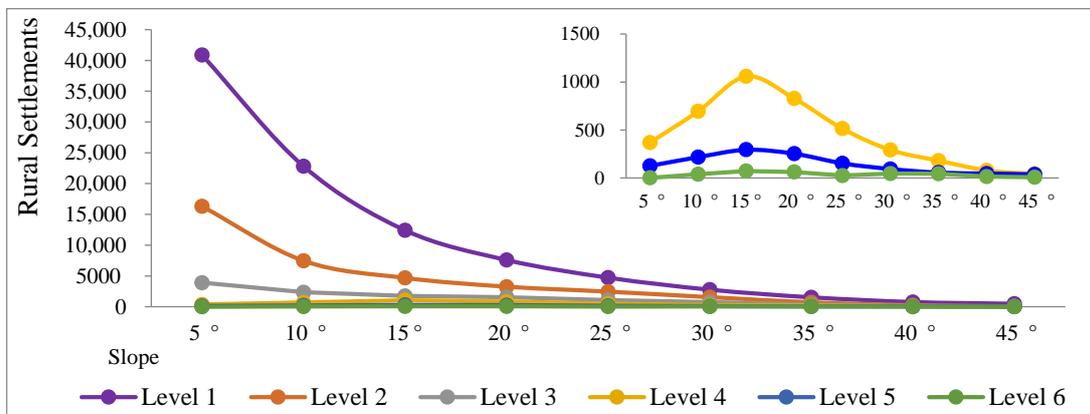


Figure 5. VCM curves of rural settlements and slopes in terms of water-facing levels.

#### 4.2.3. Water-Facing Distribution of Rural Mountain Settlements in Terms of Disaster Risk

According to the VCM curve of the rural mountain settlements and disaster risk in terms of water-facing levels (Figure 6), the spatial distribution characteristics of rural settlements and disaster risk undergo similar changes. The number of rural settlements decreases with increasing disaster risk, with the highest number in the area at a low disaster risk.

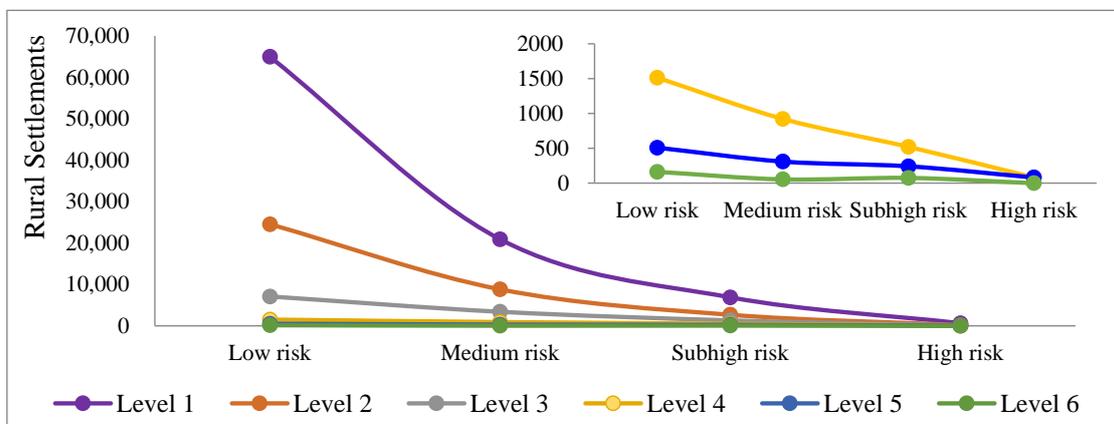


Figure 6. VCM curves of rural settlements and disaster risk in terms of water-facing levels.

### 4.3. Fractal Dimension Value of Rural Mountain Settlements

By creating a fishnet grid in ArcGIS 10.3 with side lengths of 100, 500, and 1000, the  $\ln r$  and  $\ln I$  values corresponding to different sizes of rural mountain settlements were obtained. The fractal dimension of rural settlements was subsequently obtained in the natural geographical factor zones. A double logarithmic regression analysis established that  $R^2$  was greater than 0.99, and the rural mountain settlements' fractal dimension value was 1.17. The fractal dimension curve of rural mountain settlements showed that the effect of fractal dimension values separately on elevation (Figure 7), slope (Figure 8), disaster risk (Figure 9), and water-facing level (Figure 10) ranged from 0.853 to 1.071, 0.716 to 0.997, 0.134 to 0.243, and 0.940 to 1.110, respectively. Through comparison, the fractal dimension value of water-facing level is the highest. The fractal dimension value of disaster risk is the lowest.

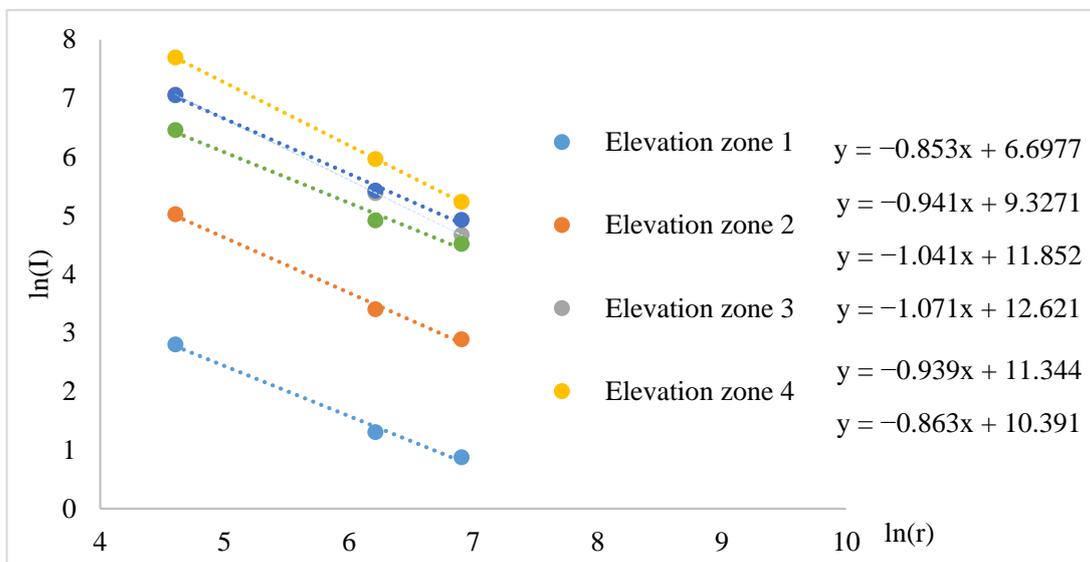


Figure 7. Fractal dimension curve of rural mountain settlements in terms of elevation.

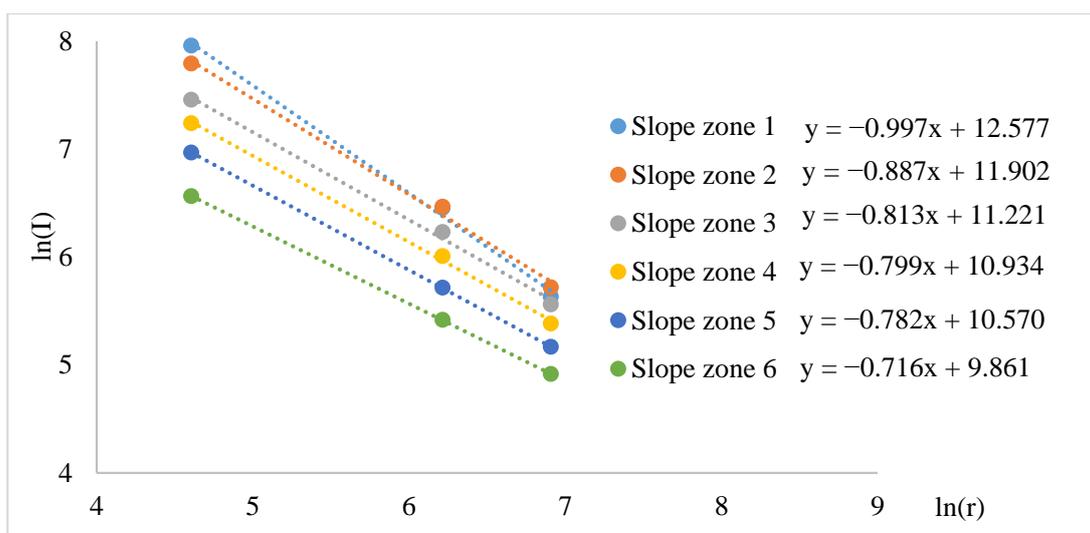


Figure 8. Fractal dimension curve of rural mountain settlements in terms of slope.

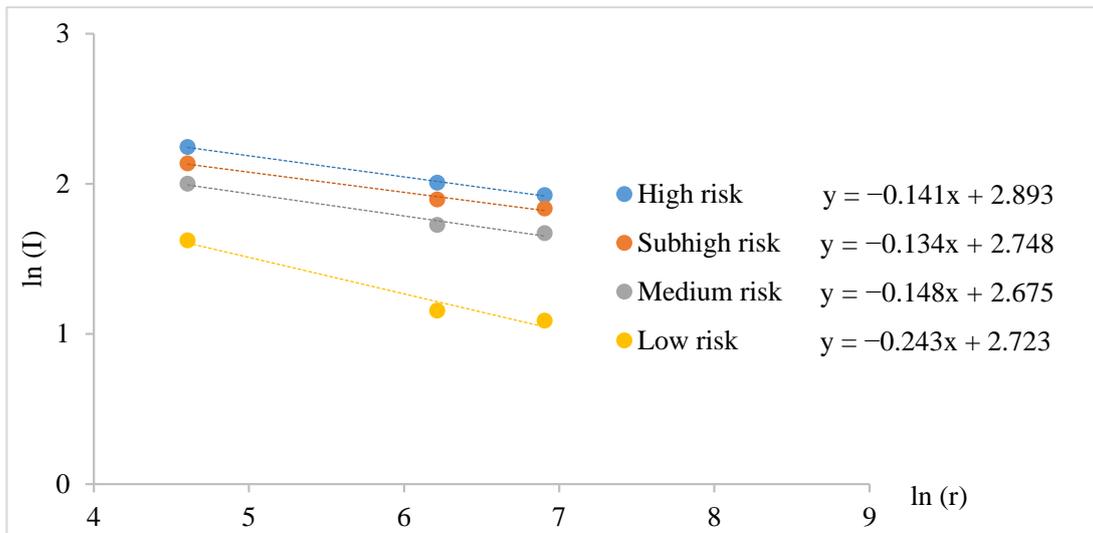


Figure 9. Fractal dimension curve of rural mountain settlements in terms of disaster risk.

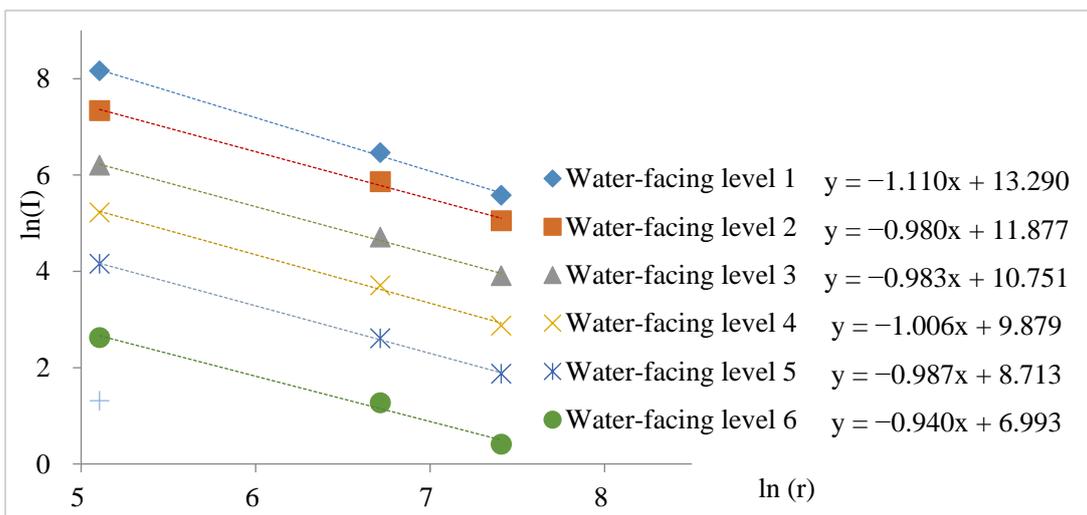


Figure 10. Fractal dimension curve of rural mountain settlements in terms of water-facing level.

#### 4.3.1. Fractal Characteristics of Rural Mountain Settlements in Terms of Elevation

The fractal dimension of residential points at elevation zones (Figure 11) showed that with increasing elevation, the fractal dimension value of residential areas initially increased and subsequently decreased, with the highest value at elevation zone 4. The fractal dimension values of distinct zones were lower than those of the whole area by 1.17. To a certain extent, the higher the number of settlements, the higher the fractal dimension. This finding indicates that elevation is an important factor that affects the fractal characteristics of settlements.

#### 4.3.2. Fractal Characteristics of Rural Mountain Settlements on Slope

The fractal dimension value gradually decreases with increasing slope (Figure 12). In the range of slope zone 1, the spatial structure of residential areas is the most complex and the space occupation capacity is the strongest. In addition, the variation in fractal dimension at zones 1–3 is higher than at zones 4–6, indicating that the space occupation capacity at zones 1–3 is higher than at zones 4–6, with different fractal characteristics.

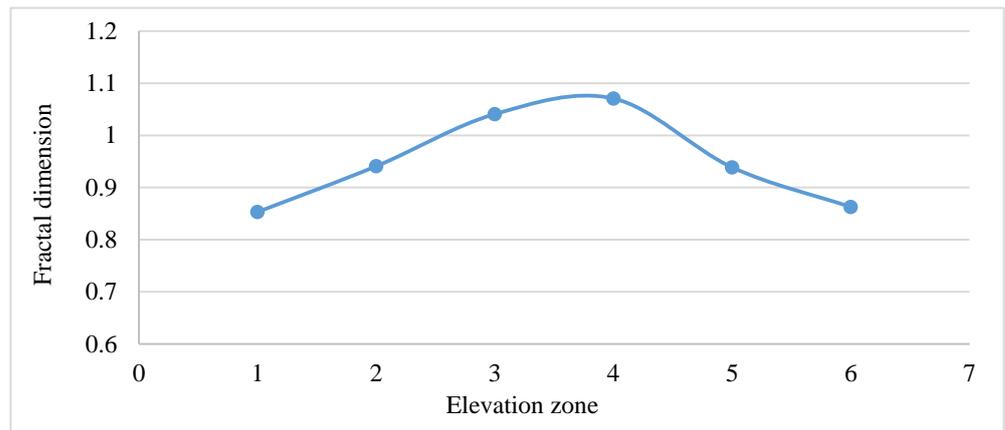


Figure 11. Fractal dimension of rural settlements in terms of elevation zones.

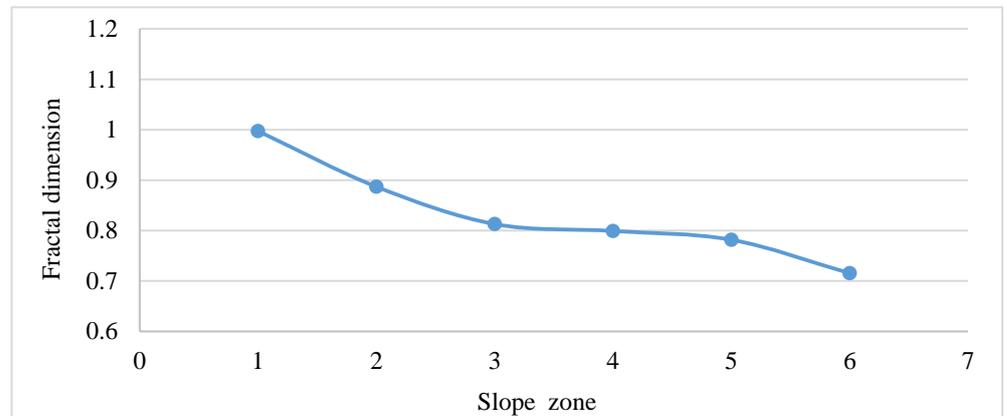


Figure 12. Fractal dimension of rural settlements in terms of slope zones.

#### 4.3.3. Fractal Characteristics of Rural Mountain Settlements on Disaster Risk Zone

As the risk level of disasters increases, the fractal dimension value of the settlements decreases (Figure 13) in disaster risk zones. The highest fractal dimension is in disaster risk zone 1, and the distribution of settlements becomes complicated.

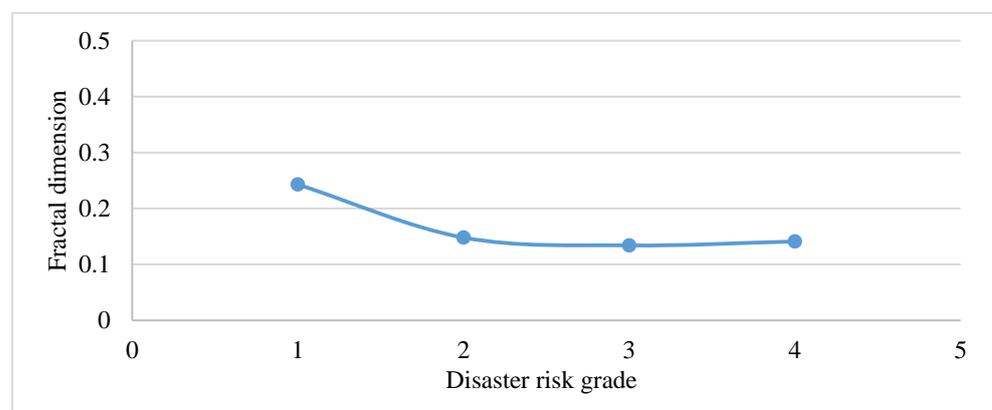


Figure 13. Dimension value of rural settlements in terms of disaster risk zone.

#### 4.3.4. Fractal Characteristics of Rural Mountain Settlements in Terms of Water-Facing Level

The maximum fractal dimension value of rural mountain settlements in the Panxi area appeared at the first water-facing level (Figure 14), indicating that rural settlements have the strongest space occupation capacity in those areas. The fractal dimension value decreases

with wave curves in water-facing levels. During spatial change in rural settlements, attention should be paid to coordinated development to avoid damage to the rivers' natural environment. Rivers play a direct or indirect role in the course of the evolution of these settlements.

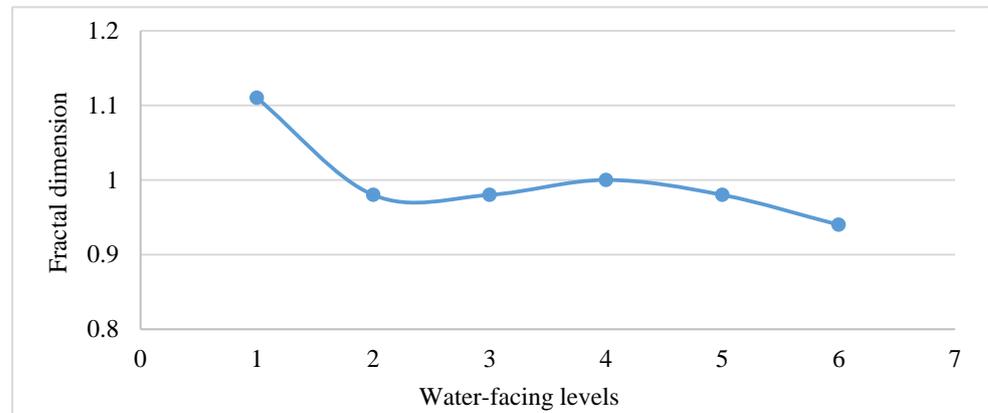


Figure 14. Fractal dimension of rural settlements in terms of water-facing levels.

## 5. Discussion

### 5.1. Water Systems Affect the Distribution of Rural Mountain Settlements

In mountainous areas, water systems play a significant role in controlling settlement distribution [17]. Restricted by the topography of mountainous areas, rural mountain settlements are situated along riversides to facilitate production and life. There is significant negative correlation ( $k = -1.00^{***}$ ) between water-facing level and rural mountain settlements, which means that water systems are the key factor affecting the distribution of rural settlements in mountainous areas. By comparison, most rural mountain settlements are established on the first water-facing level (Figure 15) at every elevation, slope, and disaster risk level. The first water-facing level is better than other water-facing levels for settlements, with approximately 88.03% of rural settlements being established within 1 km from the river. Therefore, we consider that the area within 1 km from the river is ideal for the site selection of rural mountain settlements because this is close to the water source and the terrain is relatively gentle, which makes it convenient for farmers to take water for irrigation. However, the mouth of the mountain gully is usually a flood passage or debris flow alluvial fan, where geological disasters are easily induced during rainstorms or extreme weather events. Therefore, to ensure the safety of life and property, areas at high risk of geological disasters within the range of 1 km from the river need to be avoided.

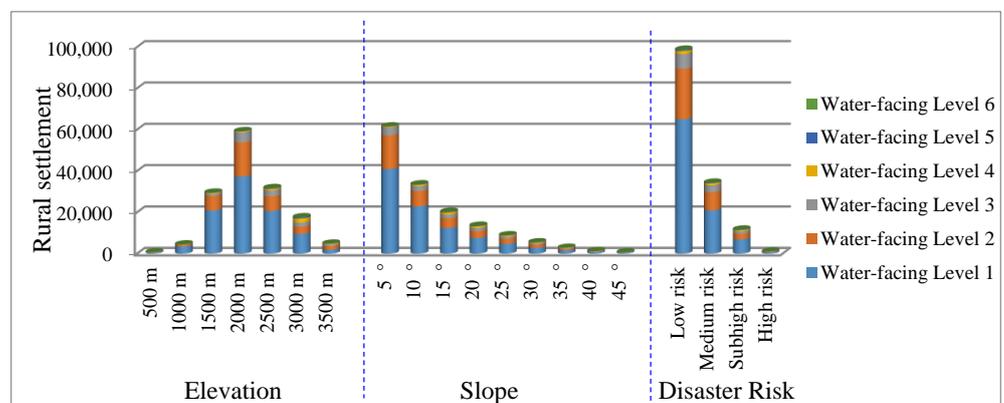


Figure 15. Water-facing distribution of rural mountain settlements in terms of natural geographical factors.

### 5.2. Suitability Space for Rural Mountain Settlements

There is a significant negative correlation ( $k = -1.00 *$ ) between disaster risk and rural mountain settlements. The  $S_i$  of disaster risk is higher than that of elevation, slope, and water-facing level (Figure 16). To a certain extent, this indicates that disasters are one of the most important factors affecting the fractal characteristics of settlements in mountainous regions. Rural mountain settlements are most numerous in the low-risk zone with a higher  $S_i$ , indicating a more stable plaque pattern in the low-risk zone. Li (2014b) [23] identified a lack of understanding relating to the appropriate selection of establishing residential areas and therefore identified the importance of locating suitable spaces for rural mountain settlements.

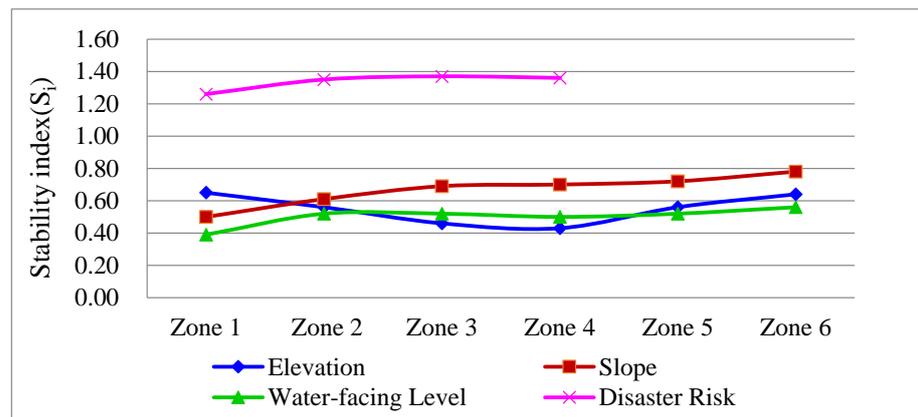


Figure 16. The stability of rural mountain settlements in terms of natural geographical factors.

According to fractal theory, the larger the fractal dimension value, the stronger the space occupying capacity and the more complex the settlement pattern [17]. On the contrary, the settlement pattern becomes simple and tends to shrink in space [2]. The results showed that the largest fractal dimension values of rural mountain settlements in terms of elevation, slope, disaster risk, and water-facing level were 0.85, 1.00, 0.24, and 1.11, respectively (Figure 17). Rural mountain settlements therefore have the strongest space-occupying capacity in disaster risk zone 1, slope zone 1, elevation zone 4, and water-facing level 1, meaning that the ideal suitability space for rural mountain settlements development (Figure 18) occurred where there was a low disaster risk and a slope of less than 5° in the elevation of 1500 m–2000 m under the water-facing level of 0–500 m.

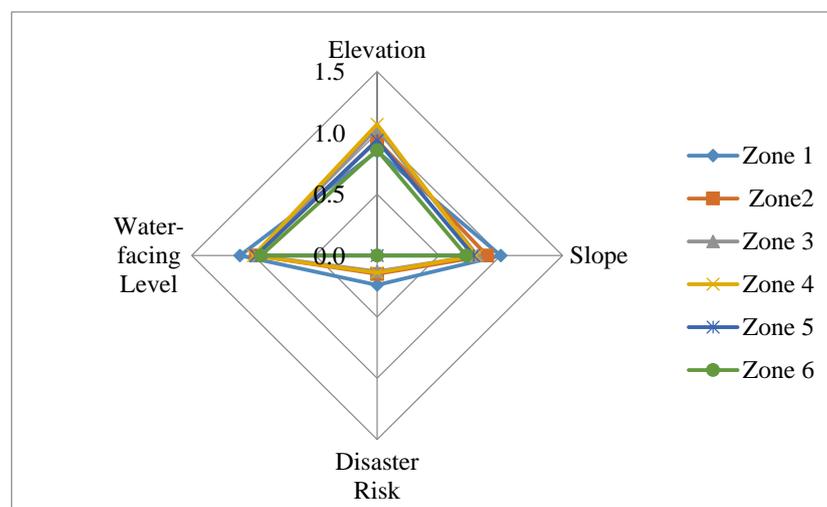
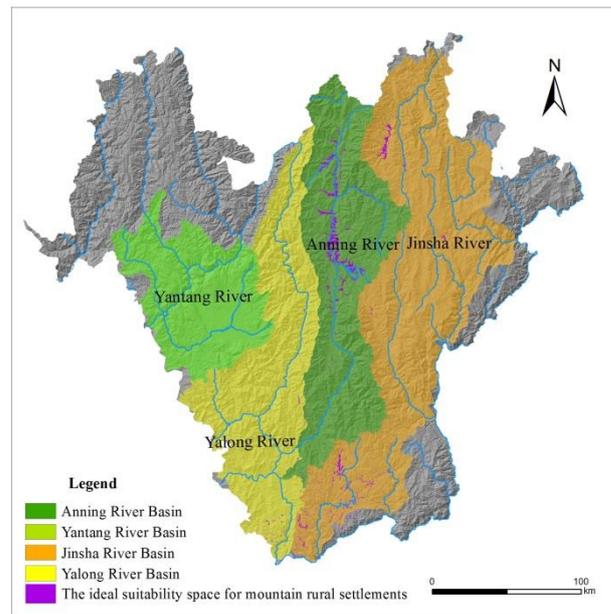
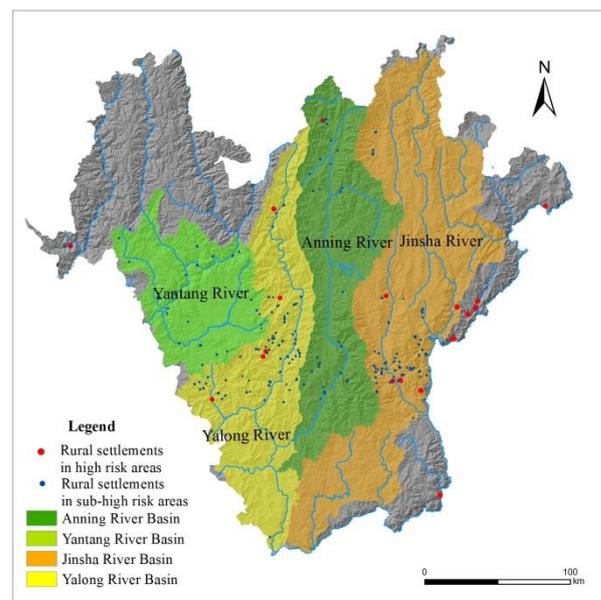


Figure 17. Fractal dimension value of rural mountain settlements in terms of natural geographical factors.



**Figure 18.** The ideal suitability space for rural mountain settlements.

Currently, 8.77% of rural mountain settlements occur within high-risk and sub-high-risk areas (Figures 13 and 15). These settlements have poor production and living conditions, and are in the high-risk and sub-high-risk areas (Figure 19) which are not suitable for settlement development, and need to be relocated to safer places. There is a need to formulate scientific and reasonable resettlement plans that will gradually guide population transfer to a central village that has a relatively complete infrastructure. The 3D maps (Figures 18 and 19) showing the suitable areas for the settlement development and the settlements which are in the unsuitable areas, would help us make the decision about the relocation planning where the settlement should be stopped or cleared if required.



**Figure 19.** The rural mountain settlements in high risk and sub-high risk areas need to be relocated to safer places.

## 6. Conclusions

Rural mountain settlements are constrained by the geographical environment. The fractal dimension value of rural mountain settlements showed that the fitted double logarithmic coordinates were in the scale-free area. Therefore, the rural settlements and natural geographical factors all had fractal features. Through a series of analyses from the perspective of elevation, slope, water-facing level, and disaster risk, we identified the suitability of spaces for rural mountain settlements.

Water systems and disasters are the key factors affecting the distribution of rural settlements in mountainous areas. In the mountainous areas of southwest China, construction land is scarce. Rural mountain settlements are scattered and their positioning lacks systematic planning. To carry out rural construction in China, the land consolidation of rural mountain settlements should be facilitated using the spatial planning of national land. For the scattered rural settlements, the relocation planning should be undertaken to avoid settling people in high-risk areas and sub-high-risk areas, and the settlements should be arranged in a suitable space to ensure the safety of people's lives and property. It is very important to improve the life safety index and happiness index of mountain residents. The fractal characteristics and water-facing distribution of rural mountain settlements in the study area can be used as a reference for the future revitalization and site selection of rural settlements. Suitability spaces for settlement should be found to avoid high-risk areas and to ensure the safety of lives and property. The results of the study could be used as a reference for future settlement planning and development.

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