Impact Assessment of the Effects of Strong Earthquake-Induced Hazards on the Socioeconomic Development Level of Earthquake-Stricken Areas after the 2008 Wenchuan Earthquake

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A strong earthquake-induced hazard has obvious long-term and spatial heterogeneity, which will result in continuous social and economic losses. Measuring the socioeconomic development level of the disaster area is of great significance for long-term development reconstruction after an earthquake. First, the kernel density estimation (KDE) is used to analyze the spatial effects of 10 extremely earthquake-stricken areas of the Wenchuan earthquake in this paper. Second, the economic gravity centers from 2006 to 2016 are calculated, and the temporal and spatial variation characteristics of the socioeconomic development level of the study area are analyzed. Finally, the relationship between the effects of strong earthquake-induced hazards and the level of socioeconomic development in earthquake-stricken areas is discussed.

The results indicate that the effect of landslide hazards show an oscillatory attenuation trend with time from 2008 to 2016 and has significant spatial differentiation characteristics. The economic gravity centers move in the direction of "moving northeast first and moving southwest later" with time, and the movement trend is closely related to the effect of hazard and the industrial structure of the earthquake-stricken areas.

1. Introduction

More than 100 destructive earthquakes occur every year in the world. Among them, China is one of the extremely earthquake-stricken countries. According to statistics, more than two-thirds of provinces have been impacted by earthquakes, causing millions of casualties and hundreds of millions of people to be affected by the disasters [1]. In the mountainous regions of China, especially the western mountainous areas where earthquakes are frequent, the risk of earthquake-induced hazards is higher. The direct losses caused by landslides, collapses, debris flows, and other disasters exceed 50 billion CNY. Geological earthquake disasters have become one of the important factors restricting the stable socioeconomic development of the extremely earthquake-stricken areas. The losses caused by earthquake-induced hazards have far exceeded the earthquake alone [2]. Therefore, quantitative exploration of the impact of geological disasters on the economy and society of earthquake-stricken areas will have great significance for the realization of regional sustainable development.

In the process of short-term postearthquake reconstruction and long-term development reconstruction after the earthquake, earthquake geological disasters have become one of the important factors restricting the stable development of the economy and society in the stricken areas. This poses new challenges to restoration and reconstruction planning for engineering experts and even government decision-making departments in earthquake-stricken areas. Some scholars have evaluated the performance of post-earthquake reconstruction from the perspectives of social, economic, and ecological impact, and from the inherent...
resource characteristics. Abramson et al. [3] proposed a social ecological model for performance evaluation of postearthquake reconstruction based on the combination of housing stability, economic stability, physical health, mental health, and social adaptability; this framework can provide a robust means for measuring recovery and for testing those factors associated with the presence or absence of recovery. Fan et al. [4] studied the impact of the Wenchuan earthquake on the environment and evaluated the value of natural resources in hazard areas for sustainable development in the reconstruction areas. On the basis of previous scholars, Tang et al. [5] revealed that Wenchuan has a close relationship between fragile built-in systems, degraded ecosystems, and socially vulnerable groups, and that many of these systems exist in rural areas throughout inland China. This indicates that while it is urgent to improve resilience of built systems, fundamentally, approaches should be adopted for rural dwellers to enter virtuous circles of economic activities as well as benign ecological cycles. Chang et al. [6] constructed an integrated method to realize resource management of postearthquake reconstruction and provided evidence of inherent resource bottlenecks during postearthquake reconstruction. The results are drawn from in-field surveys that highlight the areas where stakeholders need to concentrate effort, including revising legislation and policy, transportation network, and incorporating environmental considerations into overall planning. At the same time, experts and scholars worldwide have used a variety of methods and technologies to analyze the ecological and economic recovery, and reconstruction of postdisaster areas, such as using remote sensing images to evaluate the postdisaster recovery [7, 8], analyzing the indirect economic losses caused by hazards through night light images [9, 10], evaluating the hazard recovery degree by mathematical statistics from the aspect of the natural environment [11], extracting the hazard impact parameters to measure the impact of hazards on the economic system [12], and reflecting disaster-related production capacity changes, economic system chain effects, and adaptive behaviors of economic actors by dynamic simulation [13].

However, previous research focuses more on the social and economic impact of the geological disaster itself on the region and does not fully consider the long-term nature of strong earthquake-induced hazards [12]. Strong earthquake-induced hazards appear to be random, but in fact, they have inherent regularity and obvious spatial heterogeneity [14, 15]. The spatial heterogeneity of these hazard effects has a longer duration, deeper degree, and are more difficult to estimate the regional socioeconomic impact [16, 17]. At the same time, Cavallo and Noy [18] defined a disaster duration of more than five years as long-term, while the duration of geological disasters associated with the Wenchuan earthquake was approximately 20–25 years [19]. Therefore, quantitative analysis of the differential impact of strong earthquake-induced hazards on the socioeconomic status under long-term series can provide a theoretical basis for an area’s natural disaster relief policy and economic recovery.

From the perspective of spatial heterogeneity and the long-term nature of landslide hazards, this paper studies the quantification method of hazard effects in earthquake-stricken areas and combines the theory of gravity centers [20] to analyze the relationship between landslide hazard effects and regional socioeconomic factors, which is of great significance for improving the capacities of disaster areas to withstand postearthquake geological disasters. The remainder of this paper is organized as follows: taking the 10 extremely earthquake-stricken areas of the Wenchuan earthquake as the study area and correlating it with geographical factors, the KDE method was used to quantitatively describe the effect of landslide hazards on the study area from 2008 to 2016, and at the same time, the aggregation degree and movement trend of economic gravity centers were analyzed. Using this model, we analyze the temporal and spatial variation characteristics of the socioeconomic development level under the effect of landslide hazards.

2. Research Design

Considering the long-term effort of strong earthquake-induced hazards, based on the landslide hazard data of ten extremely earthquake-stricken areas from 2008 to 2016, and combined with the GDP per capita data of the study area from 2006 to 2016, this paper analyzes the spatiotemporal variation rules of the socioeconomic development level under the effects of these hazards. The research framework of this paper is shown in Figure 1, including the following steps:

(i) Collect the relevant data of landslide hazards in ten extremely earthquake-stricken areas of Wenchuan earthquake, comprehensively consider the spatial location of landslide hazards and other factors, and calculate the spatial effects of landslide hazards from 2008 to 2016 by the KDE method

(ii) Calculate the economic gravity centers by the gravity centers method and analyze the spatiotemporal variation characteristics of the socioeconomic development level before and after the earthquake from three aspects: the geographical location, aggregation degree, and movement trend of the gravity centers

(iii) Analyze the relationship between the socioeconomic development level and the effects of landslide hazards.

2.1. Study Area. According to the assessment results of the “5.12” Wenchuan earthquake in 2008, Wenchuan, Dujiangyan, Pengzhou, Shifang, Mianzhu, Anxian, Maokian, Beichuan, Pingwu, and Qingchuan were designated as the ten extremely earthquake-stricken areas (10 counties (cities)) which are all located in the Sichuan province, as shown in Figure 2. The geographical location is between 102°51’E~105°38’E and 30°44’N~33°02’N, with a total area of about 26410 km². The spatial location is distributed in a strip from southwest to northeast, with a maximum distance of about 350 km at both ends. And the regional terrain is relatively complex [21].
2.2. Processing of Research Data. After approximately ten years of postearthquake long-term development reconstruction in extremely earthquake-stricken areas of the Wenchuan earthquake, the overall socioeconomic development level of the region has exceeded the pre-earthquake level. Studying the spatial distribution characteristics of the effect of landslide hazards from 2008 to 2016 to grasp the relationship between the socioeconomic development level of the Wenchuan earthquake and the effects of strong earthquake-induced hazards over approximately 10 years, it has a very good representative value and has a guiding role in policies and suggestions in the long-term development
reconstruction process of similar mountainous earthquake-stricken areas. The landslide hazard data of 10 extremely earthquake-stricken areas from 2008 to 2016 are mainly obtained by collecting the historical information of a single landslide event and combining with remote sensing interpretation (Landsat 8, 30 m resolution), the data mainly include the number and spatial location of landslide hazards. The results are shown in Figure 3. There is a certain relationship between the level of socioeconomic development and the effects of landslide hazards. There are many indicators reflecting socioeconomic development, among which GDP per capita is the most comprehensive indicator reflecting the socioeconomic level [22]. Based on this conclusion, this paper obtains the GDP per capita of the study area from 2006 to 2016 through the statistical yearbook.

2.3. Study Methods

2.3.1. KDE. In order to deeply reveal the spatial distribution characteristics of seismic landslide hazards, this paper analyzes the spatial continuous variation trend of landslides in ten extremely earthquake-stricken areas of the Wenchuan earthquake by the KDE method, so as to quantitatively grasp the effects of landslide hazards in the study area. KDE is mainly used to estimate the density of point or line elements around each output grid pixel. Its formula is expressed as follows:

$$ f(s) = \frac{1}{nh^2} \sum_{i=1}^{n} K_0 \left( \frac{|dis|}{h} \right), $$

where, $f(s)$ is the kernel density calculation function at the spatial position $s$; $h$ is the search radius centered on $s$; $n$ is the number of events whose distance from position $s$ is less than...
or equal to \( r \); \( d_{is} \) is the distance from \( i \) to \( s \); the function \( K \) represents the distance attenuation function (i.e., the weight function), while the density value decreases as \( d_{is} \) increases until \( d_{is} \) is equal to \( r \), and the density value is 0.

2.3.2. Method of Gravity Centers. Gravity center change is an effective means to study the evolution trend of massive spatiotemporal data [23, 24]. To study the correlation between the effects of landslide hazards and socioeconomic development levels, this paper calculated the economic gravity centers of the study area and analyzed the movement trend of the economic gravity center. This paper takes the county (city) as the scale and the GDP per capita as the weight, the calculation formula is as follows:

\[
G_P(x) = \frac{\sum_{i=1}^{m} P(i) \times F_i(x)}{m},
\]

\[
G_P(y) = \frac{\sum_{i=1}^{m} P(i) \times F_i(y)}{m},
\]

where, \( m \) is the total number of counties (cities) (ten extremely earthquake-stricken areas in this paper), \( P(i) \) is the GDP per capita of the \( i \) county (city), \( F_i(x) \) and \( (y) \) are the \( x \) and \( y \) coordinates of the centroid point of the \( i \) county (city).

3. Spatiotemporal Characteristics of the Socioeconomic Development Level under the Effects of Strong Earthquake-Induced Hazards

3.1. Analysis of Spatiotemporal Effects of Earthquake-Stricken Areas. To understand the spatiotemporal distribution characteristics of landslide hazards, this paper not only considered the number of landslide hazards, but also comprehensively considered the spatial location of landslide points. The spatial effects of ten extremely earthquake-stricken areas from 2008 to 2016 are calculated through the abovementioned KDE calculation formula, as shown in Figure 4.

As shown in Figure 4, overall, due to the serious impact of the Wenchuan earthquake, the effect of landslide hazards in 2008 was strong in the whole study area. Locally, the effect of hazards has certain regional aggregation characteristics, which are closely related to the local geographical environment. From the temporal trend (Figure 5) in 2008, it was mainly affected by the Wenchuan earthquake and its effect of landslide hazard was the highest. The highest KDE value among the ten extremely earthquake-stricken areas was 0.269. By 2016, the highest KDE value among the ten extremely earthquake-stricken areas decreased to 0.1079.

In ArcGIS, the natural segment point method is used to divide the KDE value of the study area in 2008 into three levels (high, moderate, and low). Referring to the KDE division value in 2008, the KDE values in 2010, 2012, and 2016 are divided into three levels on the same scale. The classification of the effect of landslide hazard is shown in Table 1.

Table 1 shows that the number of landslide hazards in 10 extremely earthquake-stricken areas show a trend of oscillation attenuation over time. Among the three calculated hazard effect levels, the levels of high hazard effects and moderate hazard effects account for the largest percentage of landslides. At the same time, the sum of the regional area is far less than the area with a low hazard effect. In 2008, nearly 90% of landslide sites occurred in the areas with high and moderate landslide hazard effects (the sum of regional areas is nearly 8000 km²). By 2016, the percentage of landslide data decreased to nearly 64% (the sum of regional areas decreased to 4000 km²); from 2008 to 2016, the percentage of landslide points under the low level of the hazard effect increased by nearly three times, and the regional area also increased by nearly 4000 km², which fully shows that the landslide hazard effect in the study area gradually decreases over time. At the same time, combined with Figure 4, the landslide hazard effect has the characteristics of spatial aggregation. As the epicenter of the earthquake in 2008, the Wenchuan County has higher landslide hazard effects than other regions from 2008 to 2016. After data statistics, the spatial effects of landslide hazards over four years are classified as shown in Figure 6. The area with a high landslide hazard effect in the Wenchuan County accounted for the largest area in 2008,
Figure 4: Calculation results of the spatial effect of landslide hazards: (a) 2008; (b) 2010; (c) 2012; (d) 2016.

Figure 5: Temporal variation trend of the highest KDE value in the study area.
while the effect of landslide hazards increased slightly in 2012 compared with that in 2010 and decreased significantly by 2016.

3.2. Analysis of Gravity Centers of Socioeconomic Development. To study the correlation between the effect of the geological hazard of landslides before and after the earthquake and the level of socioeconomic development, this paper collected the GDP per capita data of each county (city) in the study area from 2006 to 2016, and the results are shown in Table 2. In addition, this paper averaged the GDP per capita value.

Using the gravity center calculation formula in Section 2.3.2, the gravity centers of socioeconomic development level from 2006 to 2016 are calculated and the results are shown in Figure 7.

In terms of the gravity center position and aggregation degree, the gravity center positions from 2006 to 2016 are located south of the study area, but the gravity center positions in the six years do not overlap. The range of change of the economic gravity centers is limited to Shifang and Mianzhu counties with an area of no more than 30 km², and the movement range is relatively small; from 2006 to 2008, the gravity centers moved the most, with a moving range of more than 9 km, followed by 2008 to 2010. After 2010, the gravity centers moved less, only approximately 1.5 km, and the moving range decreased by nearly 6 times.

From the movement direction of the gravity centers, the gravity centers of the socioeconomic development level of the study area showed a movement trend of “moving northeast first and moving southwest later.” The counties (cities) in the southwestern part of the study area were the most affected by the Wenchuan earthquake in 2008, so the economic center of the study area moved to the northeast. After the earthquake in 2008, the counties (cities) in the south recovered relatively rapidly, because Dujiangyan is a tourist city and Mianzhu, Shifang, and Pengzhou are strong industrial cities in the Sichuan province. They have unique policy advantages and resource advantages, which shows that the industrial structure plays an important role in the socioeconomic recovery of the earthquake-stricken areas. At the same time, it also shows that such areas show a strong ability to cope with geological hazards [21].

3.3. Analysis of Spatiotemporal Characteristics of the Socioeconomic Development Level under the Effect of Landslide Hazards. According to the location of each county (city), the study area is divided into four directions: northeast, southeast, southwest, and northwest. The effect of the landslide hazard of counties (cities) in different directions varies greatly with the level of socioeconomic development (GDP per capita), and the results are shown in Figure 8.
Figure 7: Movement trend chart of gravity centers of the socioeconomic development level.

Figure 8: Variation trend of the GDP per capita and KDE mean.
As shown in Figure 9, the four directions have obvious spatial characteristics. Although the GDP per capita shows a growth trend, the growth range is significantly different. At the same time, the KDE value (regional KDE mean) in the four directions shows a synchronous change trend, which indicates that there may be an interregional correlation. Combined with the movement trend, this paper mainly analyzes the effect of landslide hazards and the growth and change in GDP per capita in 6 counties (cities) in the south of the study area (Figure 9).

As shown in Figure 9:

1. In terms of the time, except for the negative growth from 2007 to 2008, the GDP per capita increased positively in other years, and the growth rate was the largest from 2008 to 2012. The change in the effect of landslide hazard is “negative growth first- positive growth later- negative growth last.” From 2008 to 2010, the effect of landslide hazard decreased by more than 30%. It shows that the socioeconomic development level of the extremely earthquake-stricken areas will be affected for a long time due to the continuous impact of the effect of earthquake-induced hazards.

2. Spatially, the GDP per capita of Wenchuan increased rapidly after 2008 (an increase of approximately 150%). The growth rate of GDP per capita in Shifang and Pengzhou was basically the same; the growth rate of GDP per capita in Anxian and Mianzhu from 2008 to 2010 was higher than that in 2008–2010. This shows that the counties (cities) in the southwest and southeast are greatly affected by the effects of geological hazards, but the recovery capacity of the hazard area is strong. The main reason for this strong recovery is that Mianzhu, Shifang, and Pengzhou are industrial cities and Dujiangyan is a tourist city. In addition, with a large amount of investment from the government and society, the northern part of the study area has a relatively weak industrial foundation due to its geographical environment which is more complex than that in the south, and it is also more vulnerable to seismic and geological hazards.

4. Conclusion

Based on historical landslide hazard data and socioeconomic data from 2008 to 2016, this paper analyzes the spatio-temporal characteristics of socioeconomic development levels under the effect of landslide hazards in ten extremely earthquake-stricken areas of the Wenchuan earthquake by using the KDE method and gravity center method. The conclusions are as follows:

1. The effect of landslide hazard showed a downward trend in the time from 2008 to 2016 and had obvious spatial differentiation characteristics. From 2008 to 2016, the area under the low level of the hazard effect gradually increased and the landslide density decreased significantly. Meanwhile, Wenchuan county is the area with a high landslide hazard effect among
the ten extremely severe hazard areas, and the average landslide hazard effect of the two counties (cities) in 2012 is slightly higher than that in 2010, which is consistent with the result that the number of postearthquake geological hazards shows oscillatory attenuation over time proposed by previous scholars [19].

(2) From 2006 to 2016, the economic gravity centers were located in the Shifang and Mianzhu counties of the study area, and the movement direction of the gravity centers mainly used 2008 as the node, which shows a movement trend of “moving northeast first and southwest later,” and the moving range was relatively low after 2010, which indicates that the economy of industrial cities and tourist cities in the south of the study area is easier to recover. Mountainous areas are greatly affected by the geological environment, and the recovery capacity of hazard areas is poor.

(3) In terms of the time, the GDP per capita increased positively after the earthquake, and the growth rate was the largest from 2008 to 2012. The change in the effect of landslide hazard was “negative growth first-positive growth later- negative growth last.” The persistence of the effect of landslide hazards will greatly affect regional socioeconomic development over a long-time range. Spatially, the counties (cities) located in the south of the study area are greatly affected by the effect of geological hazards, but the economic recovery ability is also strong, which is mainly related to the regional conditions of each county (city).

5. Discussion

After a strong earthquake, the significant increase in geological disasters in earthquake-stricken areas is a common phenomenon, and these events can last for a long time, which will have a continuous and serious impact on the regional socioeconomic development [19]. At present, there are many related studies on the socioeconomic impact of geological disasters on disaster areas, but most of the studies focus on the short-term impacts factors, and the conclusions are different [25, 26]. It is understood that geological disasters have obvious spatial heterogeneity, and quantitative research on the effect of landslide hazards can more accurately describe the spatial distribution characteristics of geological disasters. This paper analyzes the differential impact of strong earthquake-induced hazards on socioeconomic development under long-term series, and the results show that the movement trend of socioeconomic development levels in earthquake-stricken areas is closely related to the regional effect of landslide hazards and the industrial structure. Based on the conclusions, it is suggested that the government should not only consider reducing initial disaster losses, but also reduce long-term economic losses caused by the effect of landslide hazards when formulating postearthquake rescue policies. At the same time, in the long-term development reconstruction stage, the regional industrial structure, and realization of the strategic transformation of enterprises, industrial optimization and upgrading needs to be considered [27].

However, there are still many shortcomings in the research process. (1) When quantitatively describing the effect of landslide hazards, only a number and spatial location of landslide hazards are considered, and the scale data of landslide hazards should be further considered to quantify the spatial effects of landslide hazards more accurately. (2) The collection methods of landslide hazard data, and economic and social data may cause differences in time accuracy and the spatial scale. Effective data collection and matching will significantly improve the accuracy of the results. (3) Due to the availability of data, this paper takes the city (county) as the research scale, and a smaller research scale can more effectively reflect the differences in the impact of the effect of landslide hazards on regional socioeconomic development. In conclusion, it is of great significance to understand the complexity of regional disaster systems by studying the relationship between the effect of landslide hazards and socioeconomic development levels.

Data Availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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