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DISTRIBUTION CHARACTERISTICS ANALYSES AND TREND PREDICTION OF GEO-HAZARDS IN EARTHQUAKE ZONES: THE CASE OF XIAOJIAGOU WATERSHED IN WENCHUAN EARTHQUAKE AREA

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Abstract: This paper uses Xiaojiagou in Yingxiu Town as the research object to study the evolution of the material sources in the debris flow basin in the strong earthquake area and predict the characteristics of its washout scale. It does this by using the four-phase high-definition remote sensing imagery and DEM data collected, combining them with ArcGIS technology, to carry out a detailed decipherment of the avalanches and sliders in the basin of Xiaojiagou, and using statistical analysis to derive the evolution law of the material sources and the characteristics of the material sources in the years following the earthquake. The next three to five years will continue to show a decaying trend and finally reach a stable state under the condition of no external force like strong rainfall. According to the field investigation, the ditch still has many channel sources and a small number of landslide sources. Additionally, the ditch's geomorphology makes it more likely that hydrodynamic conditions will form under the downcutting and erosion of earthquakes, flash floods, and debris flows, which in turn causes the initiation of sources and, to some extent, lowers the critical rainfall intensity of debris flow outbreaks. As a result, there is still a chance that debris flows may occur because of persistently heavy rainfall, and early warning, prevention, and control measures must be strengthened. Research on debris flow activity prediction, prevention, and early warning should be intensified. The debris flow in Xiaojiagou would partially silt the river but not completely block it under 5% and 2% rainfall frequency conditions, according to the results of a simulation of the outflow characteristics of the debris flow using the FLO-2D software. Under 1% rainfall frequency conditions, however, the debris flow would completely block the river.
Keywords: Xiaojiagou; Debris flow; Evolution of sources; FLO-2D; Outburst scale

1 INTRODUCTION

More than 30,000–40,000 geological hazards were caused by the Wenchuan earthquake[1]. The earthquake also caused a lot of loose accumulations to hang on slopes or in trenches, and the intense rainfall effect made it very easy for secondary hazards like avalanches and landslides to develop[2, 3], after which researchers projected that debris flows in the Wenchuan earthquake region would continue for 10 – 20 years during their active phase[4]. Although the Wenchuan earthquake occurred more than ten years ago and landslides and other geological hazards have altered in the affected area to varying degrees, there is still a risk of geological hazards[5].

This is the reason that many academics have studied the features of the evolution of the material sources of the debris flows following the earthquake and the estimation of the outflow's magnitude in detail. Tang Chuan[6] and colleagues employed remote sensing and GIS technology to analyze the area change characteristics of avalanches and slides in the debris flow basins in Yingxiu and Longchi areas successively. Tang Desheng chose 12 debris flow gullies in Longchi Township. Based on the results of the field investigation, he used FLO-2D to simulate the process of the gullies' movement and accumulation[7]. Liu Jinfeng computed the developmental characteristics of the debris flow ditch of the "8.14" debris flow by analyzing the Xiaojiagou's developmental characteristics and the conditions of its formation through field research and experiments[8]. The possibility of debris flow blockage under various rainfall frequencies was predicted using "8.14" debris flow dynamics parameters and theoretical calculations.

To improve the study of the long-term evolution characteristics of the geological hazards in the strong earthquake area, this paper uses Xiaojiagou, which is close to the epicenter of the Wenchuan earthquake, as its study area. It does this by analyzing the volume of material sources in Xiaojiagou based on statistics of the volume of material sources in the debris flow watershed over time. Furthermore, this study simulates the flow velocity, flow depth, and other debris flow movement characteristics under various rainfall frequency conditions using FLO-2D software to determine the outflow scale of the corresponding debris flow and predict the activity trend and outflow scale of Xiaojiagou. In addition to providing scientific references for the long-term study of material source changes in the earthquake region, the research findings of this paper provide a specific reference value for the disaster prevention and mitigation measures in Xiaojiagou.

2 STUDY AREA

Xiaojiagou is situated on the left bank of Yuzixi CRiver, Yingxiu Town, Wenchuan County (Figure 1). The ditch mouth's geographic coordinates are 103°26′ 20’ East, 31°04′ 32’ North, which puts it just 4.5 km from the "5.12" earthquake's epicenter. The watershed is situated in a region with significant tectonic activity, between the Yingxiu and Maowen faults. The basin's terrain is high in the north and low in the south. Its highest point is 3483 m above sea level, its mouth is elevated at 940 m, and its relative elevation difference is 2543 m. The main ditch is 4.5 km long, its width is between 1.6 km – 2.4 km, its average width is 2.1 km, its average longitudinal slope is 240 ‰, and its slope is between 30° – 70°. The basin's total area is 719 km², all of which is shaped like a funnel. The basin's topography includes deep cuts, narrow valleys, steep slopes, and steep banks. With its funnel-shaped topography, steep slopes, narrow valleys, and deep topographic cuts, the entire region is ideal for water catchment. In the western Sichuan rainy center area, Xiaojiagou is in the subtropical humid monsoon climate zone, which is characterized by frequent heavy rainfall[9].

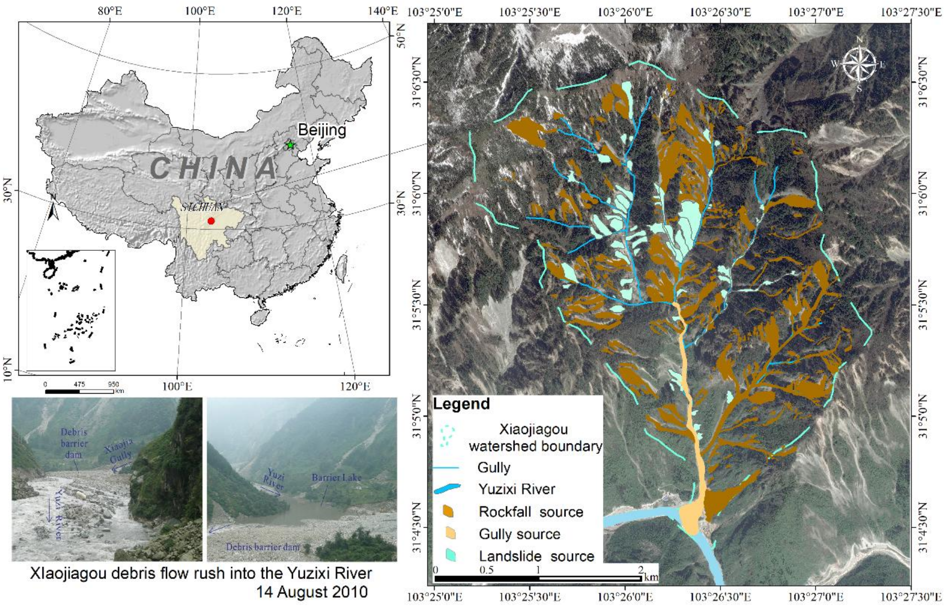


Figure 1 Location Map of the Xiaojia Gully
Source: The map boundaries are from the China Geographic Information Resources Catalog Service System: https://www.webmap.cn/main.do?method=index

According to the investigation data, there was only one large-scale debris flow eruption in Xiaojiagou in 50 years on April 26, 1991. The source of the debris flow material was discarded slag left in the trench by tunnel excavation, which ultimately caused the temporary blockage of Yuzixi River. Prior to the Wenchuan earthquake, the frequency of debris flow activity in Xiaojiagou was low and was primarily dominated by high sand content water flow or flash floods[9]. Following the Wenchuan earthquake, loose solids significantly increased, and debris flow activity in Xiaojiagou became active. One of them, an exceptionally large-scale debris flow in Xiaojiagou occurred in the early morning hours of August 13–14, 2010, due to a once-in-a-century rainstorm. The debris flow had a single outflow volume of 650,000 m³, a maximum width of 350 m, a maximum length of 150 m, and an average thickness of roughly 15 m. It buried the check dam (Figure 2), wiped out roughly 1,100 m of the roadbed of the highway (Figure 2), and subsequently, in September 2010 and July 2011, Xiaojiagou also encountered debris flows of a marginally lesser magnitude. This resulted in silting the original ditch entrance.

Figure 2 The Xiaojia Gully Debris Flow Outbreak in August 14, 2010 Flooded the Blocking Dam and the Highway

3 DATA AND METHODOLOGY

3.1 Data

In this paper, the amount of material sources in the debris flow basin in each period is obtained through interpretation based on multi-period remote sensing images collected after the earthquake. The material source evolution characteristics of the debris flow in Xiaojiagou are then analyzed. A year after the Wenchuan earthquake, the World View image of August 11, 2008, at a resolution of 2 m, was chosen to analyze the source characteristics. The World View image from December 10, 2010, the World View image from June 26, 2011, and the Google Earth image from April 15, 2015, all had a resolution of 1 m. These remote sensing data were utilized to analyze the source characteristics of the debris flow in Xiaojiagou following the eruption of the "8.14" debris flow (Table 1). (Table 1), as well as cloud-free Google Earth images taken on April 16, 2018, and March 3, 2023, with a resolution of 0.5 m, which allow for the clear identification of landmarks and the location of source features like avalanche-slip geohazards.

Table 1 Data Summary Table

Tybe	Time	Classify	Accurate
World View	2008-8-11	One year after the earthquake	2m
	2010-12-10	Four months after debris flow	
	2011-06-26	One year after debris flow	1m
Google Earth	2015-04-15	Two years after debris flow	
	2018-04-16	One year after debris flow	0.5m
	2023-03-03	Three years after debris flow	0.5m

Based on data collected over 25 years by Yuzixi River Hydrological Station, the average annual rainfall in the region of Xiaojiagou is 1253.1mm for many years. The average number of precipitation days per year is 202.7 days, with the highest annual rainfall occurring in 1964 at 1688 mm and the lowest in 1974 at 836.7l mm. The maximum precipitation for four consecutive months (June – September) is 853.2 mm, which makes up 68.2 ％ of the annual precipitation. The maximum daily precipitation is 269.8 mm. The total amount of precipitation for the day was 269.8 mm, of which 17 mm/h of real-time rainfall and 160 mm of cumulative rainfall at 2:30 pm[10], heavy rainfall in Xiaojiagou, Yingxiu on August 14, 2010, caused a debris flow disaster; the rainfall accumulation curve is displayed in Figure 3.

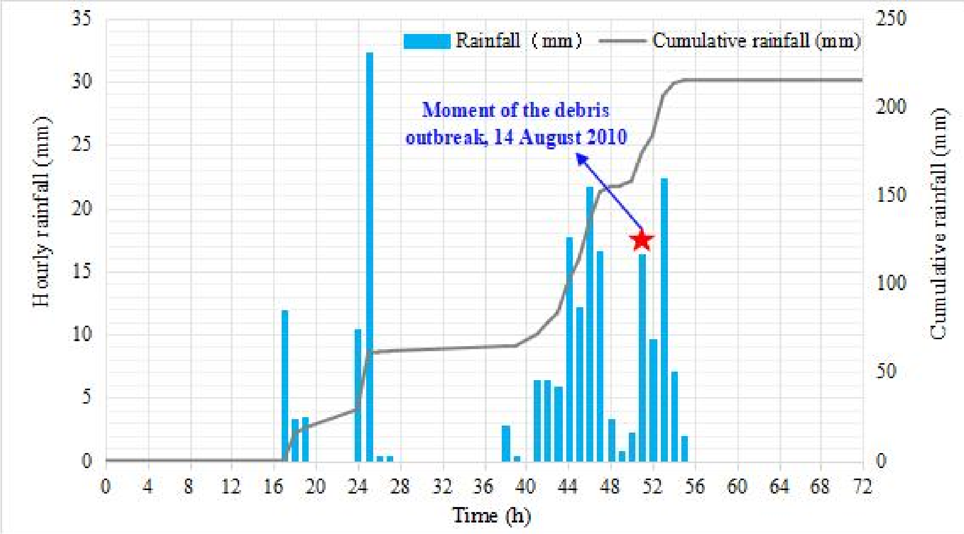


Figure 3 Rainfall Accumulation before and after "8.14" Debris Flow in Xiaojia Gully

3.2 Multi-Temporal Source Materials Inventories

To complete the interpretation of the source objects, pre-processing techniques like mosaic fusion, geographic alignment, image color enhancement, and multispectral transformation are applied to the images. These techniques help to identify the differences in color, morphology, and grey scale between the surrounding features and the avalanches and trench accumulations.[10]. The deciphering process is primarily based on optical discrimination, whereby the source body is extracted from the chosen high-resolution images by first identifying the visual differentiation signs between the source body and the surrounding features. While optical identification alone can only reflect the status of the object sources in each time and the area changes between periods do not deeply reflect the specific activity status of each landslide body, multi-period remote sensing image interpretation has the advantage of being able to reflect the dynamic changes of the object sources. Because of this, we used ArcGIS to calculate each landslide's area change rate over time to reflect the activity characteristics of all landslides. We then graded each landslide's activity status according to various area change rates; the grading criteria are displayed in Table 2.

Table 2 Source Activity Assignment

Activity class	Criteria	Attribute assignment
Very high	Either recently formed landslides or older landslides where the area affected has changed by more than 40% from the prior time frame.	4
High	Older landslides with a change in landslide area from the previous period of more than 20% and less than 40%.	3
Medium	Older landslides with a change in landslide area from the previous period of more than 10% and less than 20%.	2
Low	older landslides where the landslide area changed by less than 10% from the prior time frame.	1

The landslide activity level was assessed using the grading criteria in Table 3 by comparing the rate of change of the source area in the two periods prior to and following the earthquake. The activity levels of very high, high, medium, and low were represented by the values of 4, 3, 2, and 1, respectively, based on the rate of change. The specific grading procedure is displayed in Figure 4. Since 2009 was the year closest to the earthquake, with the greatest activity and the greatest quantity of material sources, all its landslides were classified as having very high activity. The landslides in the subsequent years were then valued and calculated based on these factors, year by year.

The multi-period source is deciphered using the above deciphering method, and each period's deciphering is based on the previous period's deciphering result to achieve continuity and comparison in the deciphering. This allows for the acquisition and assignment of values to the various landslide data, including area, location, activity, number, and so forth. Figure 4 presents the final outcomes.

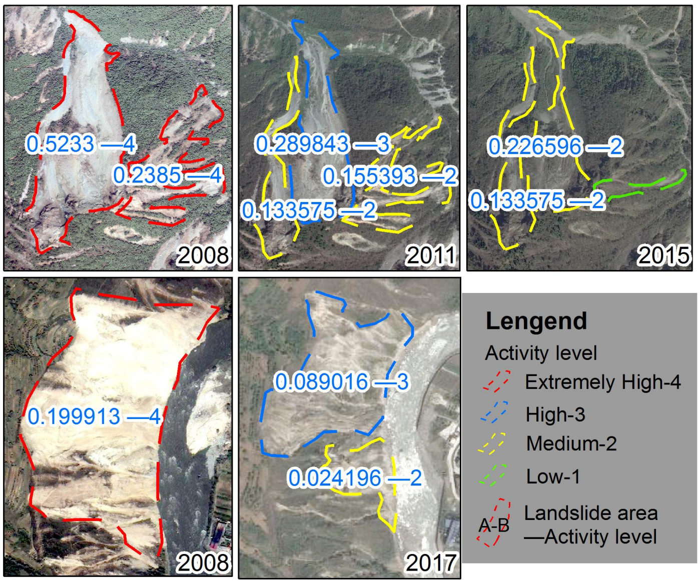


Figure 4 Landslide activity rate examples(The landslides in 2008 were all post-earthquake landslides, with the change rate of 100% and the value of 4. In the years after the earthquake, the part of the landslide area changed by more than 40% was 3, the part of the landslide that changed by 10% to 40% was assigned the value of 2, and the part of the landslide area changed by less than 10% was 1)

3.3 Debris Flow Prediction Using Numerical Modelling

The main gully's length is 9.19 km, the average longitudinal slope drop is 240 ‰, the basin area of Xiaojiagou is 7.19 km², and the density of the gully is approximately 1.3 km/km². Because of the steep terrain's ability to collect rainfall and the basin's abundant material resources, heavy precipitation events have the potential to cause debris flow. To provide a reference for the control and monitoring of Xiaojiagou, the FLO-2D software was used to simulate the activity characteristics and outflow scale of the debris flow under various rainfall frequencies using the contour data, based on the prior study on the evolution characteristics of the material sources.

O'Brien (1988) developed FLO-2D, a two-dimensional integration program primarily used to compute the washout process and debris flow associated with flood movement[11]. The FLO-2D model treats the debris flow body as a shallow water wave model, views the debris flow fluid pressure distribution as a hydrostatic pressure distribution, and uses Manning's roughness coefficient n and laminar flow resistance coefficient K to control the fluid. The Newton model and the finite difference method are used to solve the continuity equation and momentum equation of the two-dimensional model, which can simulate the fluid flow and the depth of the accumulation and can reasonably predict the range of the outflow[12]. To provide a scientific foundation for debris flow hazard zoning, monitoring, and prevention efforts, the FLO-2D model operates under these assumptions.

Acquisition of the DEM: After gathering the 1:5000 contour data from Xiaojiagou, the contour lines were transformed into irregular triangular network data (TIN) by using ArcGIS's Create TIN From Feature function. The TIN file is then transformed into DEM data using ArcGIS's Tin to Raster function. Next, the DEM data is transformed into an ASCII format elevation file using ArcGIS's Raster to AscII function. Finally, the elevation file is imported into FLO-2D to create a computational grid measuring 10 m × 10 m, set a computational range limit, and perform elevation interpolation processing on the grid.

The distribution of material sources in Xiaojiagou was then used to determine the debris flow initiation point, and several parameters were entered into the initiation point. The debris flow rate, volume concentration (CV), laminar flow retardation coefficient (K), Manning's coefficient (n), and so forth are the input parameters. Table 4 illustrates how the rainfall method is used to calculate the debris flow rate under various rainfall frequencies. The pentagonal law is then used to determine the clear water flow process line. Additional parameters can be chosen based on recommendations found in the FLO-2D manual[13] and combined with the actual conditions at Ginkgo Peak. Ultimately, the scale of flushing out is adjusted following multiple simulations. Table 3 displays the final values for the parameters.

Table 3 The Parameter Selection of Numerical Simulation in Xiaojia Gully

Laminar flow retardation coefficient K	α1	α2	β1	β2
2280	0.811	0.00462	13.72	11.24
Manning's coefficient n	volume concentration CV	Clearwater flow rate of debris flows at different rainfall flat rates Qp(m3/s)		
0.09	0.54	P=5% 19.8	P=2% 25.2	P=1% 29.4

4 RESULTS AND DISCUSSIONS

4.1 An Analysis of the Material Source Evolution in Xiaojiagou

4.1.1 Results of the 2009 post-earthquake interpretation

Xiaojiagou is situated near the epicenter of the earthquake, which has resulted in numerous avalanches, landslides, and other geological hazards. According to statistics derived from remote sensing interpretation, in August 2009, 183 avalanches and landslides with a total area of 127.49×104 m2 were developed in the Xiaojiagou watershed. The watershed of Xiaojiagou covers a total area of 7.19 km2, meaning that the area accounted for 17.73 ％ of the watershed area, and the length of gullies is approximately 9.36 km. Based on Table 4, the gully density is approximately 1.3 km/km². Xiaojiagou appears to have more material sources, a higher density of gullies, better confluence conditions, and a high likelihood of large-scale debris flows following the earthquake.

Table 4 Interpretation and Activity Rate Statistics of Landslide Based on a Series of Remote Sensing Images

Time	Gully length/km	Change rate/%	Source number	Change rate/%	Source area /104m^2	Change rate/%
2009	9.36	0	183	0	127.49	0
2010	9.84	5.17%	178	-2.73%	139.74	9.61%
2011	8.24	-16.28%	158	-11.24%	123.91	-11.33%
2015	7.45	-9.61%	99	-37.34%	65.77	-46.92%
2018	7.35	-1.33%	79	-20.20%	56.19	-14.57%
2023	7.30	-0.68%	73	-7.59%	51.42	-8.49%

4.2.2 Interpretation results after the "8.14" debris flow outbreak in 2010

Table 2 indicates that as of December 2010, the Xiaojiagou watershed had 178 landslides, which was 5 less than in 2009 and had a change rate of -2.73 ％. However, the area of the source had increased to 139.74 × 104m2, with an increase rate of 9.61 ％, and the trench's length had increased by 5.17 ％ to 9.84×104m2. The "8.14" debris flow had a major influence on the increase in the size of landslides in December 2010. It was primarily impacted by the 46-hour-long "8.14" debris flow, which was finally triggered by 160mm of accumulated rainfall. Additionally, 12.25 × 104m2 of landslides were added, mostly because of the earthquake, which significantly decreased the stability of the slopes themselves and consequently caused numerous unstable landslides. Heavy rainfall caused slopes, avalanches, and slides to enlarge even more. The sources in 2010 differed from those in 2009 in the following ways: (1) many of the neighboring landslides in 2009 were linked and combined into one, improving the integrity and coherence of the landslides in 2010; (2) the area increased by 9.61％ in 2010 despite a 2％ decrease in the number of landslides; (3) there were more gully sources. Rainfall transport played a major role in these phenomena. It not only created many potential landslides but also moved those that had already occurred downstream, where they eventually became channel sources and debris flow.

4.2.3 Results of source evolution for 2011

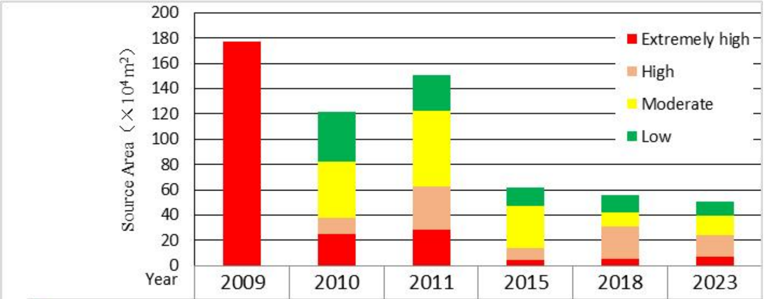
The amount of material sources in the Xiaojiagou watershed showed some attenuation due to the lack of external forces, such as heavy rainfall from December 2010 to June 2011. The area decreased by 11.33 ％ to 123.91 × 104m2, and the number of avalanches and landslides decreased by 11.24 ％ to 158. The gully channel was also attenuated by 6.13 ％ because of the runoff being reduced to 9.24 km. The material sources, such as avalanches and landslides brought on by earthquakes, are quickly returning to a stable state under the natural self-regulation without the intervention of outside forces like rainfall, according to the evolution characteristics of the material sources over the three years between 2009 and 2011.

4.2.4 Results of source interpretation for 2015

The amount of material sources within the Xiaojiagou watershed was further reduced in 2015, following seven years of post-earthquake recovery. The number of avalanches and slides decreased by 36.71 ％ from 2011 to 100, the area of material sources decreased by 65.72 ％ from 2011 to 42.47 × 104 m², and the trench's length decreased from 9.24 km in 2011 to 7.95 km, a reduction that reached 13.96 ％. A lot of avalanches and slides were stabilized or lessened in 2015 because of the vegetation's strong recovery, as evidenced by remote sensing photos.

4.2.5 Examination of evolutionary trends

The length of the channel and the quantity and area of landslides and avalanches over several periods were statistically analyzed to produce the multi-year material source evolution characteristics of Xiaojiagou, which are depicted in Figure 5, demonstrates that the amount of post-earthquake material source in Xiaojiagou demonstrated an increasing trend of landslides and avalanches in the 2008 – 2010 period, and that the material source during the 2010 – 2015 period demonstrated an annual attenuation trend. This is primarily because of the powerful earthquake that brought the avalanches and slides in the Xiaojiagou watershed to the limit state. During the 2008–2010 period, strong rainfall also generated new avalanches and slides, or the previously existing avalanches and slides were further expanded.



Year	2009	2010	2011	2015	2018	2023
Low		38.64	28.48	14.06	14.14	10.77
Moderate		44.65	59.76	33.89	10.63	15.11
High		13.03	34.81	8.87	25.6	17.65
Extremely high	176.82	24.94	28.08	4.95	5.82	6.79

Figure 5 Characteristics of Provenance Evolution in Xiao Gou for Many Years

Because of this, the Xiaojiagou watershed saw a significant number of landslides because of the continuous heavy rainfall that fell between August 12 and 14, 2010, during which time the amount of material sources was at its highest in the post-earthquake period. After that, the amount of material sources gradually returned to a stable state as the heavy rainfall gradually decreased, and the activity of the mountain body and the debris flows gradually stabilized. Based on the current trend of source evolution, it can be deduced that the source state of Xiaojiagou will continue to show a decreasing trend and eventually reach a stable state in the next three to five years, if there is no heavy rainfall or other external forces. Xiaojiagou's geomorphology is more favorable to the formation of hydrodynamic conditions under the down-cutting and erosive effects of earthquakes, flash floods, and debris flows. This induces the initiation of sources and, to some extent, reduces the critical rainfall intensity of debris flow outbreaks. Consequently, there is still a chance that debris flows will occur because of sustained heavy precipitation, and research on debris flow prevention, early warning, and activity prediction needs to be strengthened.

4.2 Outcomes of the Activity Trend Modeling

Figure 6 displays the simulation results of the debris flow depth and outflow extent under various rainfall frequencies based on the parameters used.

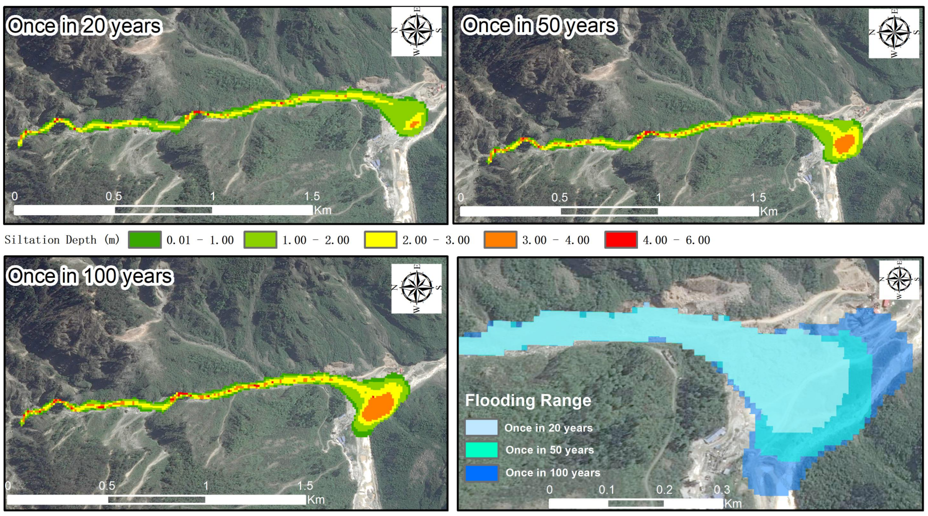


Figure 6 FLO-2D Simulation Results of Xiaojia Gully

From the simulation results:

(1) Rainfall frequency P = 5% (one in twenty years) results in an area of 276 × 104 m2 for the debris flow accumulation fan, with an average accumulation thickness of about 1.5 m. The distribution of the accumulation material in the ditch is relatively even, with the middle and lower reaches having a slightly thicker layer. A portion of the debris flow body washes out of the ditch and into the Yuzi Creek, but this will not cause the river to silt up or become blocked because of the limited amount and scope of the wash out.

(2) Rainfall frequency P = 2 ％ (one in 50 years) results in an area of 4.48 × 104 m2 for the debris flow accumulation fan, with an average accumulation thickness of about 3 m. Many gully accumulations occur in the middle and lower reaches of the gully, with the gully mouth having the thickest accumulation at around 2 m. The debris flow body washes out of the gully mouth into the Yuzi Creek, partially silting the river.
(3) The debris flow washed-out material essentially enters Yuzi Creek under the conditions of rainfall frequency P = 1% (one in 100 years), the debris flow accumulation fan area is 6.48 × 104m2, and the average accumulation thickness is 3 – 4 m. This will squeeze the river channel, forcing the water level to be elevated and possibly even block the river.

5 DISCUSSION AND SUMMARY

In order to improve the study of the long-term evolution characteristics of the geological hazards in strong earthquake, this paper uses Xiaojiagou, which is close to the epicenter of the Wenchuan earthquake, as its study area. It does this by analyzing the evolution characteristics of the material source volume in Xiaojiagou for many years after the earthquake based on the statistics of the material source volume in the watershed of the debris flows in multiple periods. Additionally, FLO-2D software is used to simulate the debris flow depth and other movement characteristics in Xiaojiagou under various rainfall frequencies. This allows for the determination of the corresponding debris flow's outflow scale, effectively reproducing the debris flow outbreak and serving as a point of reference for current mitigation and prevention efforts in Xiaojiagou. The study area's DEM data is used for this purpose. The following are the paper's primary conclusions.
(1) The amount of post-earthquake material sources in Xiaojiagou showed an increasing trend of avalanches and slides during the period of 2008 – 2010, and the material sources showed a yearly attenuation trend during the period of 2010 – 2015. These findings were obtained by statistically analyzing the number, area, and channel length of multi-period avalanches and slides. Therefore, the multi-year material source evolution characteristics of Xiaojiagou were determined. This is primarily because of the powerful earthquake that brought the landslides and avalanches in the Xiaojiagou watershed to the limit state. During the 2008 – 2010 period, strong rainfall caused the landslides and avalanches to expand further or to produce new ones. As a result, the Xiaojiagou watershed saw a significant number of landslides because of the continuous heavy rainfall that fell between August 12 and 14, 2010. During this time, the volume of material sources was at its highest in the post-earthquake period. After that, the heavy rainfall gradually decreased, and the activity of the mountain body and the debris flows also gradually stabilized. But as of right now, there are still a lot of channel sources and not a lot of avalanches and slides in Xiaojiagou, and there's still a chance that debris flow outbreaks could occur during periods of prolonged, intense rain. For these reasons, more research and early warning systems for debris flows as well as prevention and prediction are still needed.
(2) FLO-2D software was used to simulate the debris flow's outflow characteristics at various frequencies using DEM data. The findings indicate that, with a rainfall frequency of P = 5 % (one in every 20 years), the debris flow accumulation fan area is 2.76 × 104 m2, and the average accumulation thickness of the fan is approximately 1.5 m. A portion of the debris flow body washes into the Yuzi creek from the gully mouth, but its limited amount and range prevent it from causing siltation and river blockage. The area of the debris flow accumulation fan is 4.48 × 104 m2, the average accumulation thickness of the fan is approximately 3 m, and the average accumulation thickness of the gully is approximately 2 m. The debris flow body washes out of the gully and enters Yuzi Creek, causing a partial siltation of the river under the condition of rainfall frequency P = 2 ％ (one in 50 years). The area of the debris flow accumulation fan is 6.48 × 104m2, and the average accumulation thickness is 3 – 4 m, assuming a rainfall frequency of P = 1 % (one in 100 years). The debris flow essentially washed the material into Yuzi Creek, narrowing the river channel, raising the water level, and possibly blocking the river.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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