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Characteristics, Dynamic Analyses and Hazard Assessment of Debris Flows in Niumiangou Valley of Wenchuan County

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Abstract: Niumiangou valley, the epicenter of the 12 May 2008 Wenchuan earthquake (MS 8.0), became an area with frequent and dense debris flow disasters post-earthquake. Based on the in situ investigations after the earthquake on 14 August 2010 and a series of gathered data, characteristics and dynamic analyses of post-earthquake debris flows in Niumiangou valley were conducted, and then their hazard degree was assessed. Some research conclusions are obtained: (1) these post-earthquake debris flows have some typical characteristics, such as rainstorm viscous-type debris flow, happening usually between 11 p.m. and 5 a.m., broken out in the main channel as well as six branch gullies at the same time and also induced in the branches with good vegetation; (2) the dynamic parameters of Niumiangou debris flow (including volumetric weight, velocity, peak discharge, impact force, total amount of debris flow, total amount of solid materials washed out by single debris flow, maximum height of the debris flow rises and super elevation in bend) are relatively significant, and due to which it can be indicated that these debris flow disasters have great destructive power and harmfulness; (3) the hazard degree of debris flow in Niumiangou valley is very high, compared with the debris flows that occurred in the years of 2008 and 2013 in Niumiangou valley post-Wenchuan earthquake, and the comparison result shows that the hazard degree of debris flow in Niumiangou valley is relatively higher, which is consistent with the current situation. Therefore, according to these results, debris flows in Niumiangou valley are in the development phase and large-scale rainfall-induced debris flow disasters, with greater damage and stronger wallop, will easily occur in the rainy seasons of the 20 years after the earthquake.

Keywords: Niumiangou valley; debris flow; dynamic analysis; hazard evaluation; formation characteristics

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1. Introduction

Niumiangou valley is the epicenter of the 12 May 2008 Wenchuan earthquake (MS 8.0). It is located in the town of Yingxiu in Wenchuan County, Sichuan Province, 78 kms away from Chengdu, and belongs to the tributary of the Minjiang River (Figure 1) [1–4]. After the Wenchuan earthquake, Niumiangou valley became an area with frequent and dense debris flow disasters; so far, more than 10 large-scale debris flows have occurred.

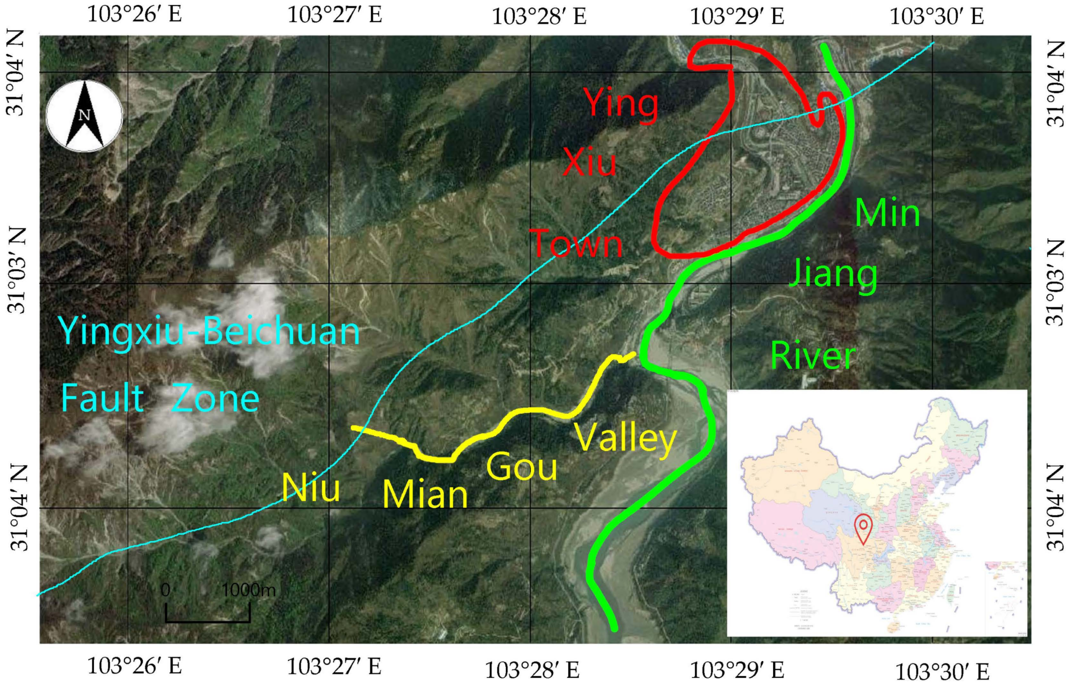

Figure 1. Geographical position of Niumiangou valley.

Debris flow disasters in post-earthquake mountainous regions inevitably have hysteretic characteristics. Secondary disasters in areas having suffered earthquakes, such as landslides, collapses, debris flows, etc., have generally relatively active periods from 10 to 20 years, even up to 30~40 years [5–7]. After the Wenchuan earthquake in 2008, many scholars analyzed the geological disasters caused by this very rare earthquake. For example, Huang et al. [2] conducted a numerical simulation analysis of the Niumiangou landslide after the Wenchuan earthquake in 2008 under the influence of pore pressure; Cui et al. [3] conducted field investigations and laboratory tests to prove the starting and movement mechanism of the Niumiangou landslide; Wang et al. [4] established a prediction model for the rainstorm debris flow in the source area of Niumiangou, and the accuracy was high after verification; Xie et al. [7] summarized the activity characteristics and post-disaster reconstruction of debris flow after the earthquake. However, little research has been conducted on the post-earthquake mudslides in Niumiangou on 14 August 2010. Therefore, characteristic and dynamic analyses of post-earthquake debris flows in Niumiangou valley are conducted, and then their hazard degrees are assessed in order to provide some theoretical supports for the warning and forecast as well as disaster prevention and mitigation of debris flow in this watershed.

2. Geographical Environment of Niumiangou Valley

2.1. Geology and Geomorphology

Niumiangou valley is seated in the Yingxiu–Beichuan fault zone, which belongs to one of the three Longmen mountain fault zones. The Yingxiu–Beichuan fault zone is the main geological structure in this area and plays a decisive role in the development of strata. Therefore, tectonic actions and seismic activity are very strong in the region of Niumiangou valley. Numerous shallow-focus earthquakes with a high intensity have broken out in the Longmen region since 1169, including 13 VI-degree earthquakes and 4 earthquakes greater than or equal to VII degrees.

The regional terrain of Niumiangou valley is typically alpine valley landform, with high mountains, deep valleys and steep slopes. It is located in the basin mountainous region of the transition zone between the eastern margin of the Tibetan plateau and Szechwan Basin, which belongs to the cutting strong alpine regions [3,8–11]. The highest elevation and maximum relative relief are 2677 m and 1812 m, respectively. Hillside slopes range from 30°~70°, with an average slope of 36.8°.

Niumiangou valley holds a main channel and six branch gullies [12]. Their characteristic parameters and distribution are shown in Table 1 and Figure 2, respectively.

Table 1. Characteristic parameters of gullies in Niumiangou valley.

Gully Name \ Characteristic Parameter		Drainage Basin Area/km^2	Gully Length/km	Highest Elevation/m	Maximum Relative Relief/m	Gully Bed Gradient/%
Niumiangou main channel		10.57	6.31	2677	1812	28.73
Branch gullies	Lianhua xin gully	2.07	2.76	2381	1343	48.62
	Bao gully	1.96	2.46	2521	1253	50.89
	Dao gully	0.60	1.61	2597	1001	62.32
	Niujing xiang gully	0.64	1.12	2621	773	68.77
	Piaochang gully	0.54	0.87	1852	396	45.57
	Qing shui gully	0.31	1.07	1754	464	43.65

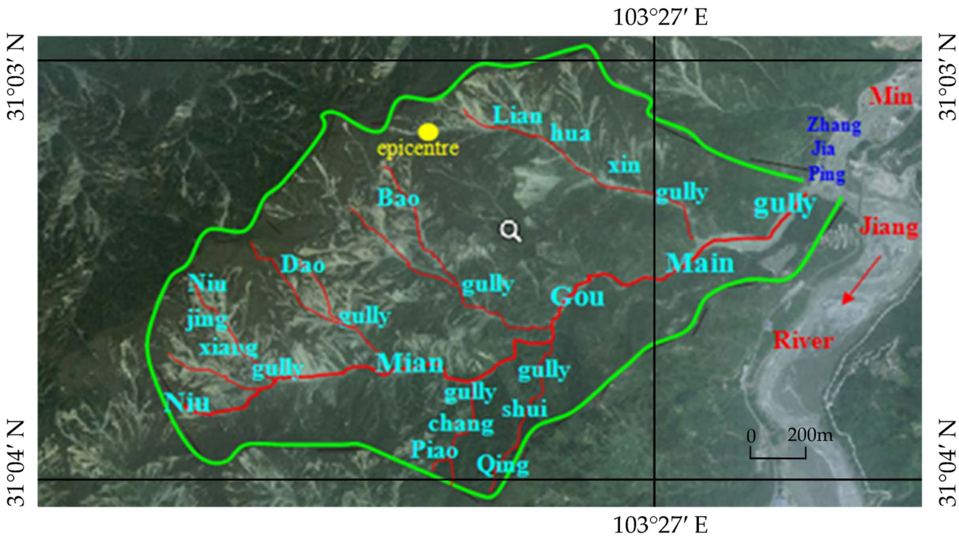

Figure 2. Gully distribution in Niumiangou valley.

2.2. Stratum Lithology

Stratum lithologies are relatively complete in Niumiangou valley and those from the Mesoproterozoic erathem to the Quaternary system are all exposed. In this area, the Upper Triassic (T_3) is widely too wide, developing many sets of detachment horizons, such as the middle Triassic of the Leikoupo Formation ($T_2$1), the lower Triassic of the Jialingjiang Formation (T_1j), the Silurian system of the Longmaxi group (S_1l) and Maoxian group (Smx), etc. [7,13–16]. Silurian system lithology mostly consists of epimetamorphic rocks, such as phyllite rocks and slates, while the Triassic system primarily includes clastic rocks, metamorphic fragmental rocks, etc. The weak rock strata such as phyllite rocks, slate, clastic rock and metamorphic fragmental clastic rock, which are widely distributed in the region, destroy the stability and integrity of the rock strata due to the lifting, squeezing and stretching of the fault zone, forming a large number of loose deposits. These are the main sources of landslides and debris flows. In addition, the undulating terrain is too large, which leads to the formation of rainstorm debris flow under the condition of heavy rainfall.

2.3. Climatic Characteristics

Niumiangou valley has a typical subtropical moist climate, mainly controlled by the southeast warm wet airflow. Through analysis of rainfall data during the period of 2010–2013 from a HOBO small-sized automatic weather station installed at this watershed, the average monthly rainfall characteristics of Niumiangou valley are obtained following the Wenchuan earthquake, (Figure 3).

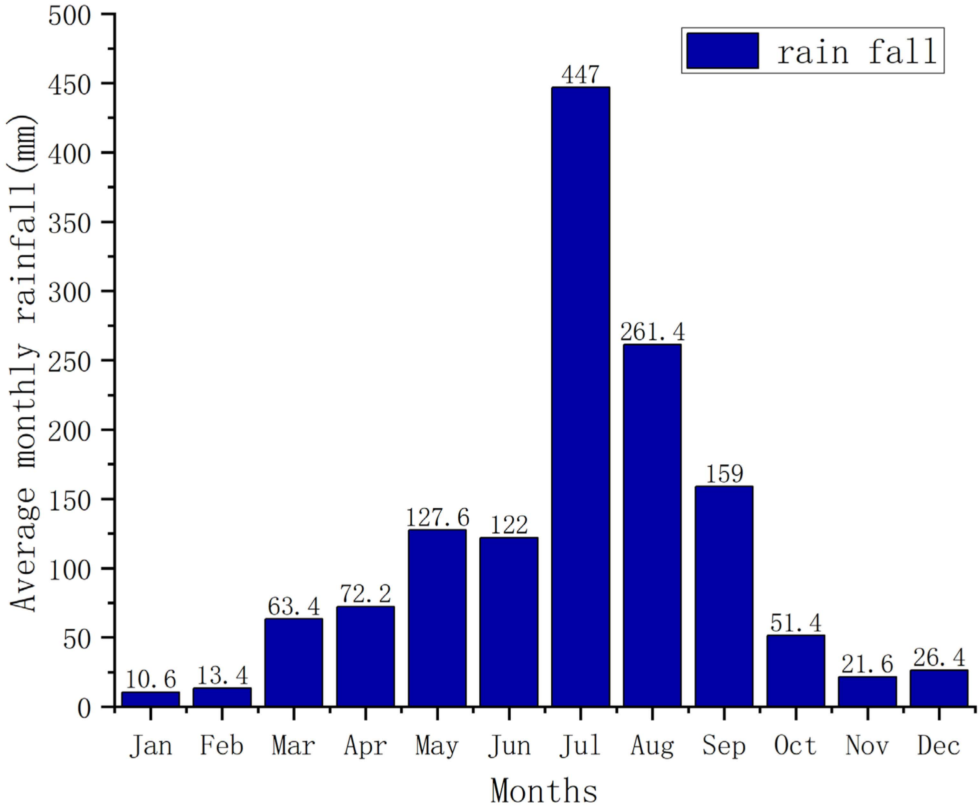

Figure 3. Average monthly rainfall characteristics of Niumiangou valley after earthquake (mm).

From Figure 3, it can be seen that the total annual rainfall in the Niumiangou watershed is 1376 mm and the rainfall after the earthquake has obvious wet and dry seasons. The rainy season occurs between May and September every year, with a precipitation accounting for 81.2% of annual precipitation. Rainstorms often occur in the region, while the drought season is distributed from October to April, with minimal precipitation. The daily and hourly maximum precipitation values during the monitoring period are 269.8 mm and 84.1 mm, respectively.

3. Characteristics of Post-Earthquake Debris Flows in Niumiangou

3.1. Summary of Post-Earthquake Debris Flows

Three basic conditions inducing rainfall-type debris flows have developed in Niumiangou valley. Rich and loose solid sources, which arise from collapses and landslides, supply the main solid sources for debris flows [17]. Mountainous landform with very high and steep slopes provides the movement condition for debris flow. Concentrative high strength precipitation in the rainy season per annum offers an abundant water condition for debris flow.

Numerous debris flow disasters have occurred in Niumiangou valley after the 12 May 2008 Wenchuan earthquake. Thus far, 12 large-scale debris flows (Figure 4) have occurred on 12 May 2008, 27 June 2008, 22 August 2008, 29 September 2008, 14 October 2008, 21 July 2009, 22 August 2009, 15 July 2010, 14 August 2010, 4 July 2011, 21 August 2011, 18 August 2012 and 10 January 2013, et al. These flows not only buried the old national road 213 line and blocked the Minjiang river at the mouth of the main gully, but also seriously endangered the post-earthquake relocation of houses and placed more than 1100 people's lives in danger in the Zhangjiaping village.

Figure 4. Debris flow that occurred on 14 August 2008.

3.2. Characteristics of Post-Earthquake Debris Flows

The debris flow disasters in Niumiangou valley exhibited several typical characteristics:

(1) They were rainstorm-type debris flows. More specifically, the flows all occurred in the rainy season every year, especially during July and August, when there were rainstorms.
(2) They were viscous debris flows. Field surveys have indicated the debris flows' densities ranged from 2.19 g/cm^3 to 2.35g/cm^3, revealing that the debris flow disasters in Niumiangou valley were viscous [18].
(3) The debris flows generally happened between 11 p.m. and 5 a.m.
(4) Debris flows simultaneously broke out in the main channel and the six branch gullies. The field investigation observations suggested that the mouths of the main channel and six branch gullies may have exhibited obvious fresh accumulations after large-scale debris flows.
(5) Debris flows were induced in branches with high vegetation cover. Fresh trees carried by debris flows could be caught by local residents in the mouth of Niumiangou valley and Minjiang river after large-scale debris flows.

4. Dynamic Analysis of Debris Flows in Niumiangou Valley

The debris flow disaster occurring on 14 August 2010 was the largest and most destructive debris flow disaster in the Niumiangou valley watershed outbreak after the Wenchuan '5 · 12' earthquake (hereinafter referred to as the Niumiangou valley 8 · 14 debris flow). Therefore, this study analyzed the dynamic parameters of the 8 · 14 debris flow disaster in Niumiangou valley.

4.1. Volumetric Weight of Debris Flow

Based on a previous study on the particle gradation characteristics of the Niumiangou valley source [19], we obtained the volumetric weight of Niumiangou valley debris flow using the method proposed by Peiji Li and the Gansu Provincial Institute of Transportation Science, respectively.

1. The debris flow volumetric weight calculation method proposed by Peiji Li is described in Equation (1) [20]:

$$\gamma_D = 1.887 d_{50}^{0.0779} \tag{1}$$

where γ_D is the debris flow volumetric weight, g/cm^3; and d_{50} is the median particle size of the induced debris flow source, mm.

According to the reference [19] which gives d_{50} = 6.83mm, according to Equation (1), the volumetric weight of the Niumiangou valley 8 · 14 debris flow γ_D as 2.19g/cm^3.

2. The debris flow volumetric weight calculation method proposed by Gansu Institute of Transportation Science is shown in Equation (2) [21]:

$$\gamma_D = 1.30 + \lg\frac{10d_{50}+2}{d_{50}+2} \tag{2}$$

Similarly, the volumetric weight of the Niumiangou valley 8 · 14 debris flow calculated according to Equation (2) is γ_D = 2.20 g/cm^3.

The volumetric weights of the debris flow calculated by the above two methods were averaged to determine the volumetric weight of the Niumiangou valley 8 · 14 debris flow. Therefore, the volumetric weight of the Niumiangou valley 8 · 14 debris flow is γ_D = 2.20 g/cm^3.

According to reference [22], the type of debris flow hazard of the debris flow outbreak in Niumiangou valley is typical viscous debris flow.

4.2. Debris Flow Velocity

As the debris flow disaster in Niumiangou valley is a typical viscous debris flow, this paper adopts the calculation method of viscous debris flow velocity proposed by the Ministry of Land and Resources of the People's Republic of China and Lanzhou Institute of Glacial Permafrost, Chinese Academy of Sciences, respectively, to determine the debris flow velocity of this watershed outbreak.

1. The calculation method of viscous debris flow velocity proposed by the Ministry of Land and Resources of the People's Republic of China is shown in Equation (3) [23]:

$$V_C = H_C^{2/3} I_C^{1/2} / n_C \tag{3}$$

where V_C is the debris flow cross-section average flow velocity, m/s; H_C is the average mud depth of the calculated cross-section, m; I_C is the hydraulic gradient of debris flow, ‰, determined by the weighted average gradient from the formation area to the circulation area of the induced watershed; and n_C is the roughness of gully bed inducing debris flow.

A field measurement of the Niumiangou valley 8 · 14 debris flow determined the average mud depth of the section to be H_C = 3.8 m and the weighted average slope from the formation area to the circulation area to be I_C = 427.9‰. The gully bed roughness can be selected as n_C = 0.067, according to reference [23]. Therefore, according to Equation (3), the average flow velocity of the Niumiangou valley 8 · 14 debris flow is calculated as V_C = 23.77 m/s.

2. The calculation method of viscous debris flow velocity proposed by the Lanzhou Glacier and Frozen Soil Research Institute of Chinese Academy of Sciences is shown in Equation (4) [24]:

$$V_C = M_C H_C^{2/3} I_C^{1/2} \tag{4}$$

where M_C is the roughness coefficient of the debris flow gully bed; the other symbols have the same meaning as above.

Combined with the field investigation of the Niumiangou valley 8 · 14 debris flow and the references [23,24], the roughness coefficient M_C = 14 was selected. Similarly, the average velocity of the Niumiangou valley 8 · 14 debris flow can be calculated as V_C = 22.30 m/s.

The average velocity of the debris flow obtained by the above two methods is averaged to determine the average velocity of the Niumiangou valley 8 · 14 debris flow. Therefore, the average velocity of the Niumiangou valley 8 · 14 debris flow is V_C = 23.04 m/s.

4.3. Debris Flow Peak Discharge

The rain-flood method is currently a widely used method to determine the peak debris flow as follows (5) [23]:

$$Q_C = Q_P(1+\varphi)D_C \tag{5}$$

where Q_C is the peak discharge of the debris flow with frequency P, m^3/s; Q_P is the design flow of the storm flood with frequency P, m^3/s, determined according to 'Calculation Manual of Storm Flood in Medium and Small Watershed of Sichuan Province' [25]; φ is the correction coefficient of debris flow sediment, calculated by $\varphi = (\gamma_D - \gamma_W)/(\gamma_S - \gamma_D)$; γ_W is the volume weight of clear water, g/cm^3; γ_S is the volume weight of the solid material inducing debris flow, g/cm^3; and D_C is the block-up coefficient, selected according to the actual situation of debris flow gullies.

By combining the previous literature [19,22] and the field investigation of the Niumiangou valley 8 · 14 debris flow disaster, the bulk density of the solid material inducing the debris flow source is set as γ_S = 2.69 g/cm^3 and the block-up coefficient is set as D_C = 5.0. Table 2 reports the peak flow of the Niumiangou valley 8 · 14 debris flow calculated by Equation (5).

Table 2. The results of dynamic parameters of the Niumiangou valley 8 · 14 debris flow.

Dynamic Parameters	Computation				
Volumetric weight of debris flow/(g/cm^3)	2.20				
Average velocity of debris flow/(m/s)	23.04				
Liquid dynamic pressure of debris flow/(Pa)	3.5×10^6				
Impact force of debris flow stone/(N)	1.77×10^8				
The maximum height of the debris flow rises/(m)	27.08				
The super elevation in bend of debris flow /(m)	28.07				
Different frequencies/%	10	5	2	1(8 · 14 actual outbreak frequency of debris flow)	0.5
Storm flood design flow/(m^3/s)	16.42	19.04	22.27	25.16	27.95
Debris flow peak discharge/(m^3/s)	283.2	328.3	384.0	433.9	482.0
Total amount of debris flow/($10^4 m^3$)	26.91	31.21	36.50	41.24	45.81
Total amount of solid materials washed out by a debris flow/($10^4 m^3$)	19.11	22.16	25.92	29.28	32.53

4.4. Debris Flow Impact Force

Debris flow impact force is an important parameter in the design of debris flow prevention projects, and can be mainly divided into the debris flow liquid dynamic pressure and rock impact force.

1. Liquid dynamic pressure of debris flow.

The liquid dynamic pressure of debris flow can be calculated by the following equation [26]:

$$\sigma = K_C \gamma_D V_C^2 \tag{6}$$

where σ is the debris flow liquid dynamic pressure, Pa; K_C is the non-uniform coefficient of debris flow fluid and the other symbols have the same meaning as above.

According to the reference [27,28], the non-uniform coefficient K_C = 3 of debris flow fluid is selected, and the liquid dynamic pressure σ = 3.50 × 10^6 Pa of the Niumiangou valley 8 · 14 debris flow is calculated according to Equation (6).

Impact force of debris flow boulders.

2. The impact force of debris flow boulders is calculated using Equation (7) [29–31]:

$$F = \rho_{\mathrm{d}} C V_{\mathrm{d}} A_{\mathrm{d}} \tag{7}$$

where F is the impact force of boulders in the debris flow, N; ρ_{d} is the boulder density in the debris flow, kg/m^3; C is the longitudinal wave velocity, m/s; A_{d} is the contact area between the boulder and debris flow, calculated according to 10 % of the plane area of the center and short diameter of the largest stone, m^2; V_{d} is the velocity of the boulder in debris flow, m/s, according to reference [23], which is calculated according to Equation (8); and the meaning of the other symbols is the same as above.

$$V_{\mathrm{d}} = \alpha \sqrt{d_{\max}} \tag{8}$$

where α is the friction coefficient, within $3.5 \leq \alpha \leq 4.5$ and $d_{\max}$ is the largest stone particle size in debris flow, m.

The field investigation of the Niumiangou valley 8 · 14 debris flow disaster reveals that the largest boulder in the debris flow was phyllite, the longest diameter was 4.9 m, the volume was 89 m^3 and, according to reference [32], its density and longitudinal wave velocity can be selected as ρ_{d} = 2.75 × 10^3 kg/m^3 and C = 4000 m/s; the friction coefficient α is the average value of α, that is, α = 4. According to Equation (8), the velocity of the stone is calculated as V_{d} = 8.85 m/s; according to the longest diameter and volume of the largest boulder, the contact area A_{d} = 1.82 m^2 was calculated. In summary, the maximum impact force of boulders in the Niumiangou valley 8 · 14 debris flow is calculated according to Equation (7) as F = 1.77 × 10^{8}N.

4.5. Total Amount of Debris Flow

The total amount of debris flow can be calculated based on the rapid fluctuation characteristics when the debris flow occurred, as follows [23]:

$$Q = 0.264 T Q_{\mathrm{c}} \tag{9}$$

where Q is the total debris flow amount, m^3 and T is the duration of debris flow, s; the other symbols have the same meaning as above.

According to Reference [33], the Niumiangou valley 8 · 14 debris flow lasted for about 1 h, that is, T = 3600 s. The results of the total amount of the Niumiangou valley 8 · 14 debris flow obtained according to Equation (9) are shown in Table 2.

4.6. The Total Amount of Solid Materials Washed out by a Debris Flow

The total amount of solid materials washed out by a debris flow is related to parameters such as the scale and nature of the debris flow and is usually calculated by Equation (10) [23]:

$$Q_{\mathrm{H}} = Q(\gamma_{\mathrm{D}} - \gamma_{\mathrm{W}})/(\gamma_{\mathrm{S}} - \gamma_{\mathrm{W}}) \tag{10}$$

where Q_{H} is a debris flow out of the total amount of solid matter, m^3; the other symbols have the same meaning as above.

Table 2 shows the total amount of solid material washed out by the Niumiangou valley 8 · 14 debris flow calculated using Equation (10).

4.7. The Maximum Height of the Debris Flow Rises

The debris flow can get blocked when it is traveling downwards (kinetic energy is converted into potential energy). Thus, the debris flow can become wrapped with rocks, engulfing fields and destroying houses. The maximum debris flow height can be calculated by Equation (11) [23]:

$$\Delta H = \frac{V_{\mathrm{C}}^2}{2g} \tag{11}$$

where ΔH is the maximum height of the rising debris flow, m; g is the gravitational acceleration and equals 9.8 g/cm^3; the other symbols have the same meaning as above.

According to Equation (11), the maximum height of the Niumiangou valley 8 · 14 debris flow rises is ΔH = 27.08 m.

4.8. Super Elevation in Bend of Debris Flow

The super elevation in the bends of debris flows is usually calculated by Equation (12) [23]:

$$\Delta h = 2.3\frac{V_C^2}{g}\lg\frac{R_2}{R_1} \tag{12}$$

where Δh is the super elevation in the bend of a debris flow, m and R_1, R_2 are curvature radius of convex and concave bank of debris flow bend banks, m; the other symbols have the same meaning as above.

Figure 5 depicts the bend of the Niumiangou valley 8 · 14 debris flow based on the topographic map of Niumiangou valley. According to Equation (12), the super elevation in the bend of the Niumiangou valley 8 · 14 debris flow is Δh = 28.07 m.

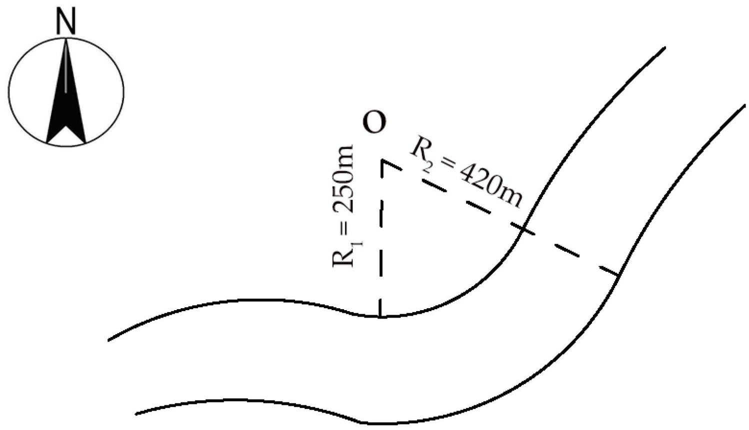

Figure 5. The bend diagram of the Niumiangou valley 8 · 14 debris flow.

Table 2 reports all of the calculated dynamic parameters of the Niumiangou valley 8 · 14 debris flow.

It can be seen from Table 2 that the total volume of solid matter washed out of the Niumiangou valley 8 · 14 debris flow was approximately 290,000 cubic meters. According to the 'Specification of Geological Investigation for Debris Flow Stabilization' [23], the Niumiangou valley 8 · 14 debris flow was a large-scale debris flow disaster. Moreover, the field investigation reveals that about 30% of the solid material rushed into the Minjiang River. This is consistent with previous work [34] in the sense that the debris flow flew into the Minjiang River with about 80,000 cubic meters of solid material, which also shows that the debris flow was induced by 100-year rainfall.

In summary, the 8 · 14 debris flow in Niumiangou valley was a large-scale debris flow disaster induced by rainfall with a 100-year return period. The corresponding dynamic parameters were large, and the debris flow exhibited typical characteristics including being large scale, having strong destructiveness and being high risk.

5. Hazard Assessment of Debris Flows in Niumiangou Valley

The hazard assessment of debris flows in Niumiangou valley can be assessed using the following equation [35,36]:

$$H = 0.29X_1 + 0.29X_2 + 0.14X_3 + 0.09X_4 + 0.06X_5 + 0.11X_6 + 0.03X_7 \tag{13}$$

In Equation (13), H is the hazard index of the debris flow (0–1 or 0–100%); X_1, X_2, X_3, X_4, X_5, X_6 and X_7 are the transformed values (0–1) used to evaluate variables x_1, x_2, x_3, x_4, x_5, x_6 and x_7, respectively, while x_1, x_2, x_3, x_4, x_5, x_6 and x_7 represent, respectively, maximum depositional volumes of a debris flow ($10^3 m^3$), frequency of debris flow occurrence scaled to the times per century (%), drainage basin area (km^2), main channel length (km), drainage basin relief (km), drainage density (km/km^2) and active main channel proportion (%).

Transformation functions used for the evaluating variables can be seen in Table 3.

Table 3. Transformation functions for evaluating variables [35,36].

Transformed Value (0–1)	Transformation Function	
X_1	$X_1 = 0$	for $x_1 \le 1$
	$X_1 = \log x_1/3$	for $1 < x_1 \le 1000$
	$X_1 = 1$	for $x_1 > 1000$
X_2	$X_2 = 0$	for $x_2 \le 1$
	$X_2 = \log x_2/2$	for $1 < x_2 \le 100$
	$X_2 = 1$	for $x_2 > 100$
X_3	$X_3 = 0.2458x_3^{0.3495}$	for $0 \le x_3 \le 50$
	$X_3 = 1$	for $x_3 > 50$
X_4	$X_4 = 0.2903x_4^{0.5372}$	for $0 \le x_4 \le 10$
	$X_4 = 1$	for $x_4 > 10$
X_5	$X_5 = 2x_5/3$	for $0 \le x_5 \le 1.5$
	$X_5 = 1$	for $x_5 > 1.5$
X_6	$X_6 = 0.05x_6$	for $0 \le x_6 \le 20$
	$X_6 = 1$	for $x_6 > 20$
X_7	$X_7 = x_7/60$	for $0 \le x_7 \le 60$
	$X_7 = 1$	for $x_7 > 60$

The observed original data and transformed values of evaluating variables for debris flow in Niumiangou valley are shown in Tables 4 and 5, respectively.

Table 4. Original data of hazard assessment evaluating variables of debris flow in Niumiangou valley.

Evaluating Factors	$x_1/10^3m^3$	x_2/%	x_3/km^2	x_4/km	x_5/km	$x_6/km/km^2$	x_7/%
Original data	800	200	10.57	6.31	1.82	1.73	100

Table 5. Transformed values of evaluating variables of hazard assessment for debris flow in Niumiangou valley.

Evaluating Factors	X_1	X_2	X_3	X_4	X_5	X_6	X_7
Transformed values	0.97	1.00	0.56	0.78	1.00	0.09	1.00

Based on Equation (13) and Table 5, the hazard evaluation result of the debris flow in Niumiangou valley H is equal to 0.82. According to the hazard degree classification standards of debris flow (Table 6), it can be seen that the hazard degree of the debris flow in Niumiangou valley is very high, belonging to a large-scale debris flow disaster. The evaluation result is compared with the debris flows occurring in 2008 and 2013 in Niumiangou valley post-Wenchuan earthquake. The hazard degree of the debris flow in Niumiangou valley is relatively higher than the other debris flows, which is consistent with the actual situation.

Table 6. Hazard degree classification standards of debris flow.

Hazard Degree Grade	Very Low	Low	Moderate	High	Very High
Classification standards	0.00–0.20	0.20–0.40	0.40–0.60	0.60–0.80	0.80–1.00

6. Conclusions

A small amount of studies have performed targeted research on this debris flow disaster. For example, Ding et al. [37] and Han et al. [38] investigated the sediment transport volume in Niumiangou after the earthquake. Ding et al. combined earthquake landslides with heavy rainfall, while Han et al. evaluated the gravity erosion effect in the earthquake area. Furthermore, Liu et al. [39] applied FLO-2D to evaluate the risk of debris flow in Niumiangou valley using numerical simulations. The authors focused on comparing the debris flow disaster on 14 August 2010 with that on 26 September 2008 in order to highlight the severity of the debris flow disaster on 26 September 2008. Guo et al. [40] studied the effect of rainfall on the soil activity of the debris flow source area through artificial rainfall experiments. The results revealed soil activity to increase exponentially with rainfall. Thus, the research performed in our paper enriches the current literature on the debris flow disaster after the Niumiangou earthquake on 14 August 2010, as it is the first time these results have been reported. The conclusions of this work are as follows:

(1) The post-earthquake debris flows occurring in Niumiangou valley exhibit several typical characteristics. For example, they are all rainstorm–viscous-type debris flows, they generally happen between 11 p.m. and 5 a.m., they simultaneously break out in the main channel and six branch gullies and are induced in branches with high vegetation cover.
(2) The dynamic parameters of the Niumiangou debris flows, such as volumetric weight, velocity, peak discharge, impact force, total amount of debris flow, total amount of solid materials washed out by a single debris flow, maximum height of the debris flow rises and the super elevation in the bend, are determined to be relatively large, and then it can be indicated that these debris flow disasters have great destructive power and are extremely harmful.
(3) The hazard degree of the debris flows in Niumiangou valley is very high. The calculated hazard degree has been compared with the debris flows occurring port-Wenchuan earthquake in the years of 2008 and 2013 in Niumiangou valley. The hazard degree of the debris flows in Niumiangou valley is relatively higher compared to the other flows, with is consistent with the actual situation.

According to these results, it can be concluded that debris flows in Niumiangou valley are currently in the development phase and can potently cause large-scale rainfall-induced debris flow disasters and extreme damage. These can easily occur in the rainy seasons during the 20 years proceeding an earthquake.

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