

Article

Material Activity in Debris Flow Watersheds Pre- and Post-Strong Earthquake: A Case Study from the Wenchuan Earthquake Epicenter

Yu Yang ¹ , Ming Chen ^{2,*}, Yinghua Cai ³, Chenxiao Tang ⁴, Wenli Huang ³ and Chenhao Xia ⁵

¹ School of Emergency Management, Xihua University, Chengdu 610039, China; yangyu.cdut@gmail.com

² State Key Laboratory of Geohazard Prevention and Geo-Environment Protection, Chengdu University of Technology, Chengdu 610059, China

³ Zhaozhi Future Technology (Chengdu) Co., Ltd., Chengdu 610096, China; yinghuacai214@gmail.com (Y.C.); 18280406282@163.com (W.H.)

⁴ Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610044, China; c.tang@imde.ac.cn

⁵ Nuclear Industry Southwest Geotechnical Investigation and Design Institute Co., Ltd., Chengdu 610052, China; xchlll520@163.com

* Correspondence: chenminggeo@163.com

Abstract: The 2008 Wenchuan earthquake released vast quantities of loose material, significantly influencing post-earthquake material dynamics, particularly through recurrent debris flow disasters that posed long-term threats to the earthquake-affected area. To explore the transport and involvement of loose materials in debris flow events within earthquake-affected basins, this study focuses on a representative area near the Wenchuan epicenter, creating a multi-temporal database of active landslides and channel materials pre- and post-earthquake, quantitatively assessing material transport and source replenishment in debris flow basins, and categorizing debris flows based on channel material activity, post-earthquake historical activity, and sustainability of activity. This study revealed that pre-earthquake material activity was concentrated in the watershed's upper regions, while post-earthquake materials were progressively transported from the central to the lower regions, with many small co-seismic landslides ceasing activity. The supply area ratio from active landslides capable of recharging debris flows, i.e., those connected to channels, consistently remained at approximately 72%, with the peak area of channel material activity comprising approximately 2.5% of the total watershed area. Channel material activity areas serve as valuable indicators for hazard assessment in regions lacking historical debris flow data, with the watershed area predominantly determining the sustainability of post-earthquake debris flow activity.

Keywords: Wenchuan earthquake; remote sensing interpretation; landslide; channel material; debris flow



Citation: Yang, Y.; Chen, M.; Cai, Y.; Tang, C.; Huang, W.; Xia, C. Material Activity in Debris Flow Watersheds Pre- and Post-Strong Earthquake: A Case Study from the Wenchuan Earthquake Epicenter. *Water* **2024**, *16*, 2284. <https://doi.org/10.3390/w16162284>

Academic Editor: Maurizio Barbieri

Received: 26 June 2024

Revised: 6 August 2024

Accepted: 8 August 2024

Published: 13 August 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Gradual transport of large amounts of loose material induced by strong earthquakes, such as the Chi-Chi and Wenchuan earthquakes, from the watershed into downstream channels can intensify landslides, debris flows, and other related activities until conditions revert to their pre-earthquake state [1–6]. The 1935 magnitude 7.9 earthquake in Papua New Guinea's Torricelli Range triggered landslides that resulted in surface erosion averaging between 74 and 400 mm, which can promote the development of debris flows [7]. Similarly, the 1950 magnitude 8.6 earthquake in Assam, Tibetan Himalayas, produced an estimated 47 km³ of erodible material [8]. Immediately after the earthquake, there was a period of intensified erosion leading to significant material depletion and increased evacuation of river sediments due to factors such as intense rainfall, slope destabilization, and human activities [9–11]. Following the 1999 Chi-Chi earthquake in Taiwan, river suspended sediment

concentrations in the affected area surged to approximately four times the pre-earthquake levels [12]. Scholars have employed hydrological and multi-temporal topographic measurements and other methods to quantify the movement rate of co-seismic loose materials and evaluate the time required for their transport and depletion in watersheds to revert to pre-seismic conditions [13–16]. Similarly, some researchers have utilized numerical modeling to investigate the entrapment, transport, and deposition of co-seismic loose materials, as well as to examine the post-earthquake evolution of ground material activity [17–20].

The spatial distribution of landslides during material transport within the watershed is heterogeneous; certain landslides, linked to channels, are readily mobilized and transported by water or debris flows, whereas others, distant from channels, scarcely participate in channel material dynamics [21,22]. In the area affected by the 1999 Chi-Chi earthquake in Taiwan, only 8% of co-seismic landslides were connected to the river network [8,12]. After the 2015 Nepal earthquake, the spatial distribution of co-seismic landslides in relation to the river network was evaluated by analyzing the mean slope drop and upstream catchment area, leading to an estimation that about 50% of landslides were directly linked to the river system and that the total transport of co-seismic loose materials to the river could take centuries [23,24]. Following the Wenchuan earthquake, researchers utilized co-seismic landslide data and geomorphic analysis to quantify landslide-channel connectivity based on the count, area, and volume of landslides, discovering that this connectivity varied across different watersheds, with volumetric connectivity ranging from 20% to 90% [25]. Over a decade post-earthquake, intense rainfall on August 20, 2019, reactivated a significant debris flow in the Wenchuan area, leading to 26 missing individuals, 12 fatalities, and economic losses nearing 3.6 billion dollars [26]. Following years of dormancy, the “8.20” debris flow mandates prolonged monitoring of material activity in the earthquake-affected area for future research [26–28].

In summary, extensive research has focused on the characteristics of post-earthquake material transport and sediment supply capacity. The transport of loose materials from landslides following strong earthquakes is a prolonged process, primarily evident in post-earthquake landslides and debris flow activities [29,30]. However, the long-term evolution of post-earthquake surface material transport and its correlation with debris flow activities in the Wenchuan earthquake region remains inadequately understood [31]. The rapid advancement of remote sensing technology and high-resolution optical imagery now enables monitoring of landslides on a large scale in mountainous regions. Additionally, creating a multi-temporal active landslide database through various period interpretations offers a dependable method for tracking post-earthquake surface material transport studies [32,33]. This study selected a representative area near the epicenter of Wenchuan earthquake to develop a database for interpreting multi-temporal active landslides and channel materials pre- and post-strong earthquakes, thereby analyzing the activity patterns of loose materials and their contribution to debris flow activities. Lastly, this study examined debris flow activities’ characteristics, including channel material activity, historical post-earthquake activity, and sustainability, serving as a reference for hazard assessments in regions with scarce historical debris flow data. It also evaluated the impact of the local rainfall and watershed area on the historical activity and sustainability of debris flows in mountainous regions.

2. Study Area

The magnitude 7.9 Wenchuan earthquake in 2008 represented a critical geological event that had profound effects on the region at the eastern edge of the Tibetan Plateau, close to its boundary with the Sichuan Basin. This study focuses on the epicenter, covering 31 watersheds extending from Yingxiu to Yinxing over an area of 233.5 km² (Figure 1). The region, characterized by its rugged terrain, exhibits significant elevation variation, ranging from 606 m to an impressive 4560 m above sea level. Notably, the area’s topography features steep slopes, with the steepest inclines reaching up to 88° and more than half of these slopes exhibiting gradients exceeding 38°. The combination of such dramatic topographic features

and the significant upheaval from the Wenchuan earthquake provides critical insights into the dynamics of sediment transport processes following intense seismic disturbances.

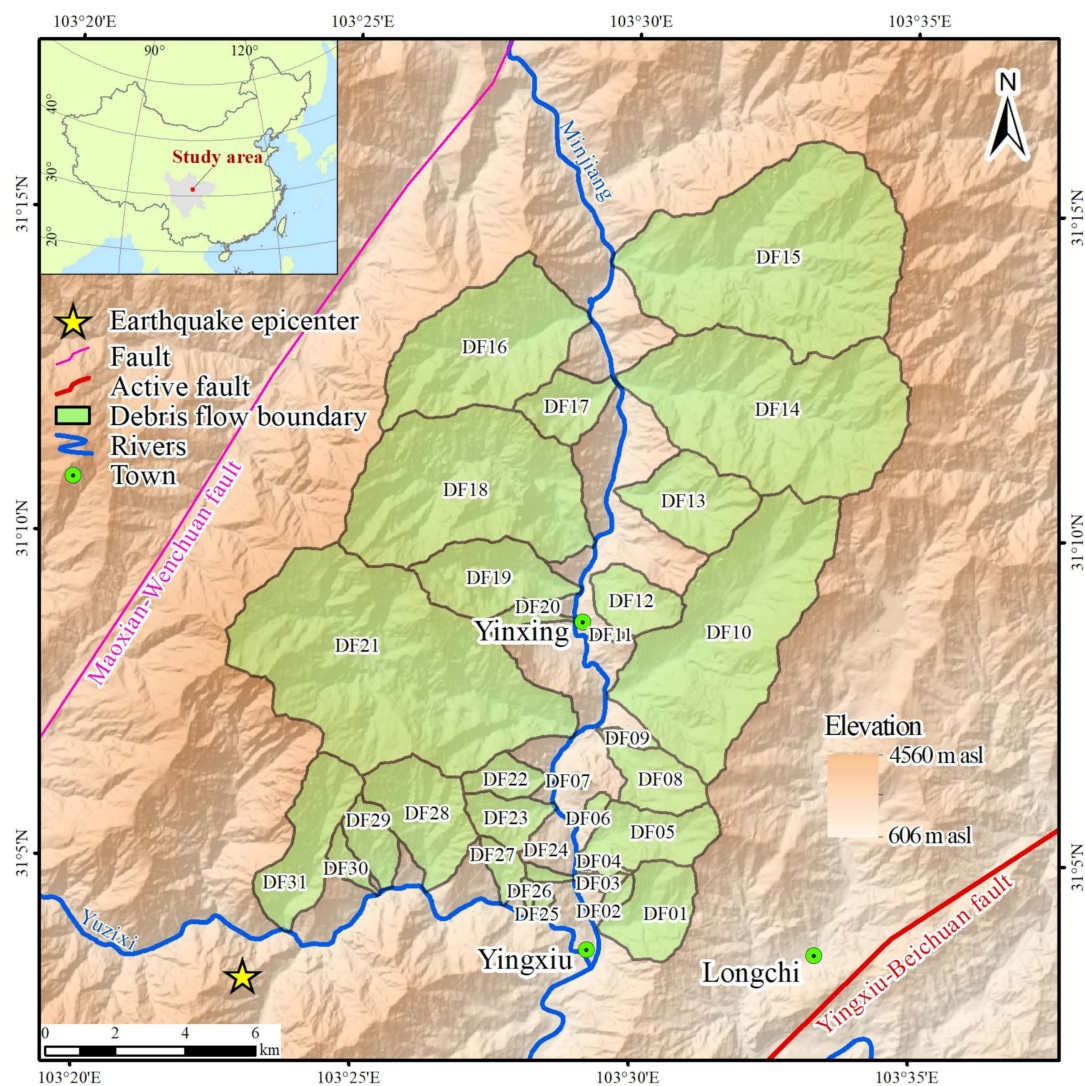


Figure 1. A focus on our study area, which is primarily situated between two major faults: the Maoxian-Wenchuan fault (pink) and the Yingxiu-Beichuan fault (red), with yellow stars marking the location of the Wenchuan earthquake epicenter. Mapped debris flows (DF) are depicted in light green with grey boundary lines, numbered sequentially. The main trunk of the Minjiang River and its major tributaries are highlighted in blue and all mapped sub-catchments flow into this river. Key locations such as Yinxing and Yingxiu are indicated with green dots. Elevation, represented with a gradient color scale ranging from 606 m above sea level (light brown) to 4560 m above sea level (dark brown), is sourced from ALOS-PALSAR RTC with a resolution of 30 m.

The study area is primarily situated between two major faults—the Maoxian-Wenchuan fault and the Yingxiu-Beichuan fault—as shown in Figure 1. Underneath the vegetation and soil cover, more than 87% of the region features highly fractured and weathered bedrock, primarily consisting of igneous rocks, including diorite and granite. The remaining 13% is composed of metamorphic and sedimentary rocks, accompanied by Quaternary Neogene deposits distributed as terraces and alluvial fans. The discontinuities in the land parcels result from tectonic faults, with the predominant orientation of stratification and jointing being northeast–southwest.

This region exhibits a subtropical humid monsoon climate, with an average annual temperature of approximately 13 °C. The region receives annual precipitation exceeding 1250 mm, primarily concentrated from June to September, constituting 70–80% of the annual total. The highest recorded annual rainfall, observed in 1964, reached 1688 mm, with the maximum daily intensity recorded at 269.8 mm. Two main rivers traverse the area: the Minjiang River, flowing through Wenchuan and Yingxiu, and the Yuzixi River, situated closest to the earthquake’s epicenter. The Minjiang River, a tributary of the upper Yangtze River, maintains an average annual discharge of 452 m³/s and recorded a peak discharge of 2790 m³/s in 1958. The Minjiang River constitutes the primary watershed, with the majority of designated catchment areas draining into it.

3. Data and Methods

3.1. Remote Sensing Images and Other Data

Extending the work of eight landslide interpretation inventories [34], we collected optical remote sensing imagery from July 2008, April 2011, September 2013, April 2015, April 2019, and August 2020. In addition, we obtained a Digital Surface Model (DSM) from ALOS-PALSAR RTC and used ArcGIS 10.8 software to extract river networks and catchment boundaries. The workflow included filling sinks, calculating flow direction and accumulation, defining the stream network, and delineating watersheds using the ‘Watershed’ tool to ensure accurate boundaries for debris flow basins. Integrating and importing these data into ArcScene for a 3D visualization allowed us to revise, refine, and categorize the vector data. This process enabled the construction of a comprehensive, long-term database of active materials (re-mobilized, new landslides and active channel materials) in the study area. Table 1 details the specific data utilized and their respective applications. To examine the relationship between active materials and rainfall in the study area, we acquired monthly precipitation data from 2000 to 2020 from the Global Precipitation Climatology Centre (GPCC) dataset.

Table 1. Summary information on data use.

Data Types	Source	Acquisition Time	Precision	Application
Landslide interpretation	[34]	2005, 2007, 2008, 2011, 2013, 2015, 2017, 2018	vector	Basic data
Remote sensing image	Spot 5	2008.07	1 m	Correct and categorize the basic interpretation data and establish a database for interpretation of remobilized, new landslides and active channel material.
	Google Earth	2011.04	0.5 m	
	Pleiades	2013.09	2 m	
	Spot 6	2015.04	1 m	
	Sentinel-2B	2019.04 2020.08	10 m 10 m	
DSM	ALOS-PALSAR RTC	/	30 m	For river network and watershed boundary extraction and topographic reference for interpretation.
Precipitation	Global Precipitation Climate Center (GPCC)	2000–2020 (monthly)	1 mm	To analyze the relationship between material activity and rainfall in the study area.

3.2. Multi-Temporal Inventorying

The interpretation process encompasses three primary categories of active materials. The first category, “New Landslide”, comprises landslides induced by external factors like earthquakes and rainfall (refer to Figure 2a,d). The second category, “Remobilized Landslide”, pertains to the remobilization of co-seismic landslides (take the co-seismic landslide in Figure 2a as an example) initially triggered by the Wenchuan earthquake (as

illustrated in Figure 2b,e). The third category, “Active Channel Material”, consists of loose materials transported along the channels in the catchment area (as depicted in Figure 2c,f). This categorization facilitates a comprehensive understanding of the dynamic processes of loose materials under the disturbance of a strong earthquake.

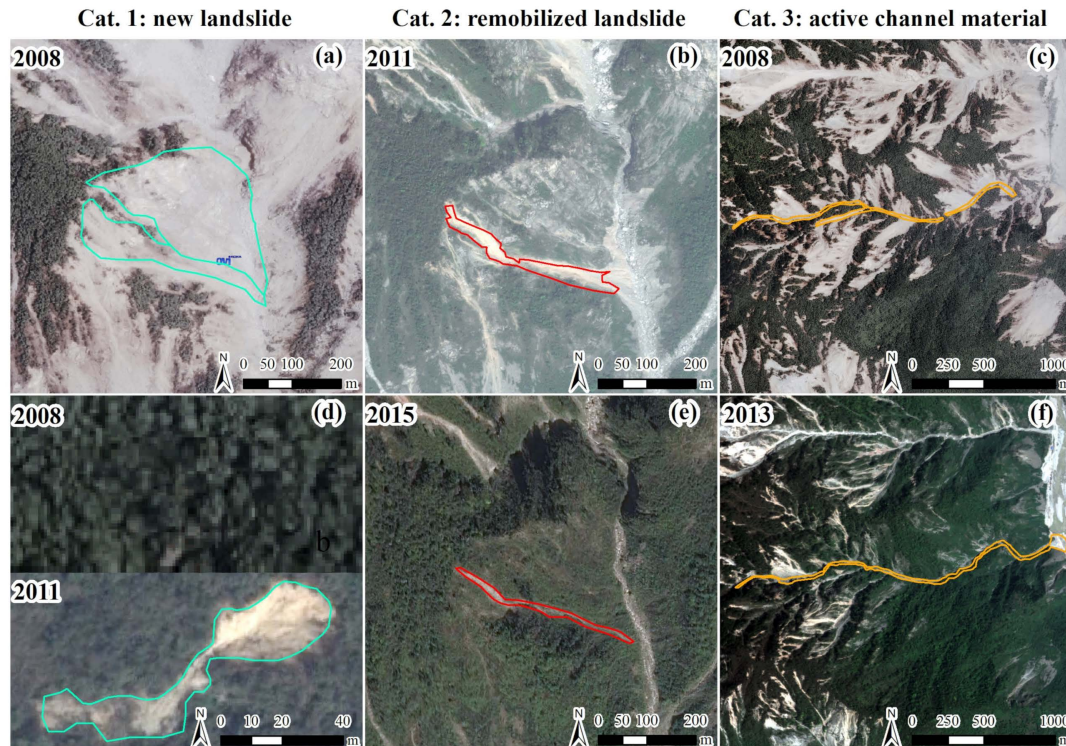


Figure 2. Example of multi-temporal interpretation. (a) Co-seismic landslides triggered by the Wenchuan earthquake; (b,d,e) post-earthquake landslides; (c,f) active channel materials.

3.3. Distance Coefficient

To examine the spatial movement characteristics of materials within debris flow catchments, this study introduces the distance coefficient to the gully outlet (d_g) for positioning each interpreted active material:

$$d_g = D/L, \quad (1)$$

In this equation, d_g denotes the distance coefficient to the gully outlet for each active material. D represents the horizontal projection length from the centroid of each interpreted material to the tangent at the gully outlet. L is defined as the maximum horizontal projection length from the upstream watershed divide of the debris flow catchment to the tangent at the gully outlet, as shown in Figure 3. The value of d_g ranges from 0 to 1, with higher values signifying a greater distance from the gully outlet.

3.4. Landslide Connectivity

Long-term monitoring of debris flow events in the earthquake-affected area revealed that not all landslides within the catchments contribute to the active channel materials of debris flows. A prerequisite for contribution is the establishment of a spatial connection between the active landslide and the channel. As depicted in Figure 4a, co-seismic landslides appeared in the main channel of the debris flow on the left bank in July 2008, as indicated by both the purple and yellow arrows. The landslide indicated by the purple arrow was directly connected to the channel, whereas the area marked by the yellow arrow was not.

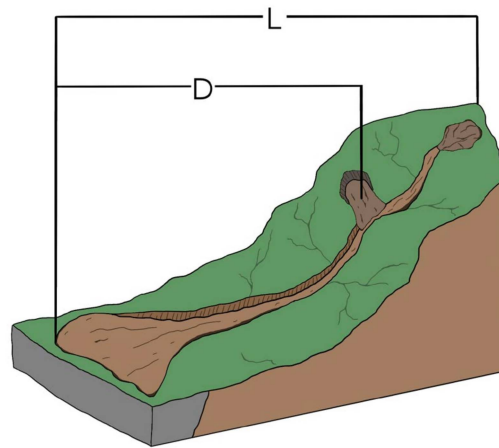


Figure 3. Schematic calculation of d_g . D represents the horizontal projection length from the centroid of each interpreted material to the tangent at the gully outlet, while L denotes the maximum horizontal projection length from the upstream watershed divide to the tangent at the gully outlet.

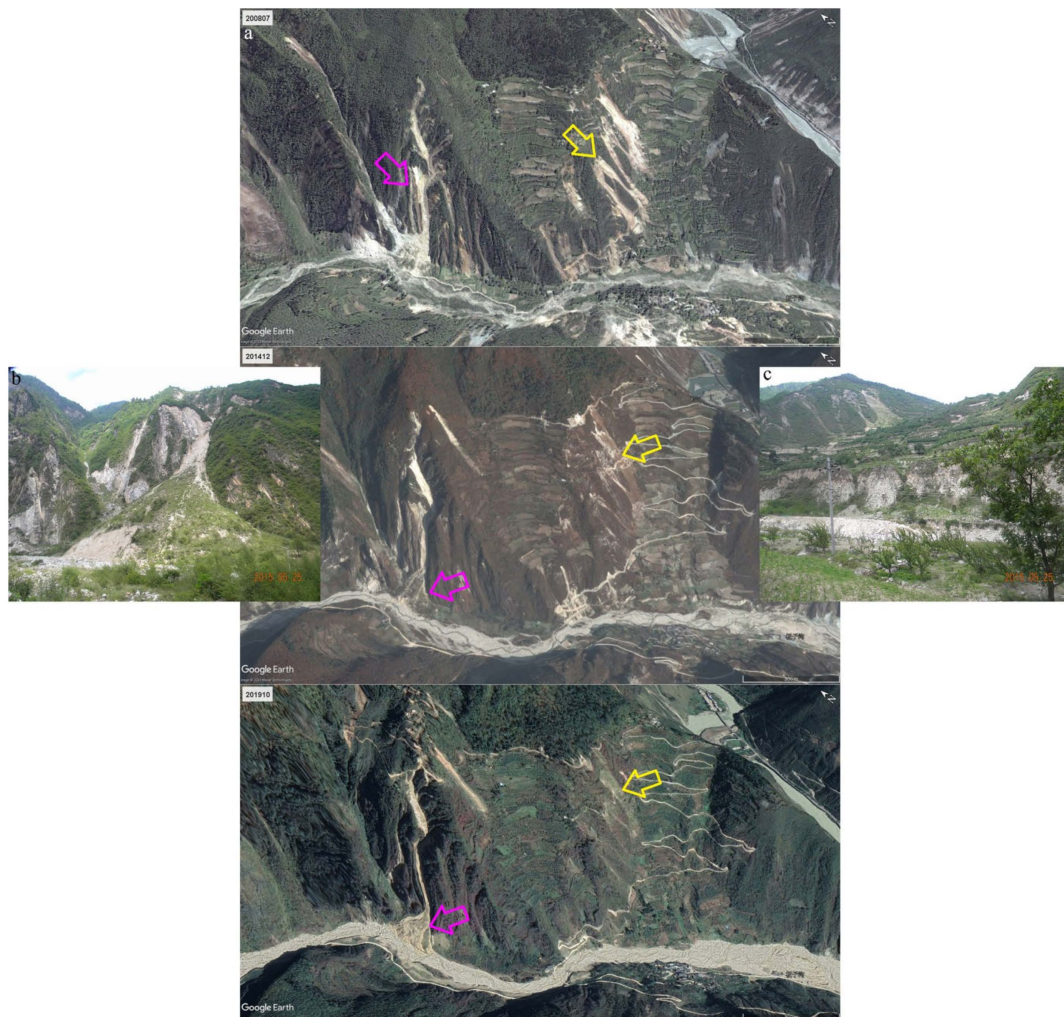


Figure 4. A demonstration of landslide and channel material activity within the watershed. (a) Google satellite imagery of the demonstration area captured in July 2008, December 2014, and October 2019. (b) Photograph documenting the 2015 field investigation of the landslide identified by the purple arrow. This photo was taken by the author. (c) Photograph documenting the 2015 field investigation of the landslide identified by the yellow arrow. This photo was taken by the author.

By December 2014, a significant accumulation of loose material was observed in the main channel, with contributions from both upstream sources and landslides along the channel. Although the channel materials had not been flushed out of the gully by this time, the landslide deposits in the purple arrow area were already contributing material to it. As shown in Figure 4b, the loose deposits on the upstream-facing side of the purple arrow area were continuously eroded by channel materials, gradually detaching and entering the channel. On the downstream-facing side, vegetation was able to adhere and grow over extended periods, maintaining relative stability. Conversely, despite their spatial proximity to the purple arrow area, the landslide deposits in the yellow arrow area did not contribute to channel material movement, as they were not connected to the channel, as depicted in Figure 4c.

By October 2019, subsequent to a debris flow event, the activity within the landslide area marked by the purple arrow had intensified, exhibiting a larger active area than before the event. Concurrently, vegetation in the area indicated by the yellow arrow had naturally regenerated, suggesting that the loose deposits here did not participate in channel material dynamics nor contribute to the debris flow from their formation to their eventual stabilization, as shown in Figure 4a. Using DF28 (Xiaoja Gully) as an example, illustrated in Figure 5, this study classified the interpreted active landslides from each period according to their connectivity to the channel. This method facilitates a quantitative evaluation of the landslide's potential to contribute materials to the channels.

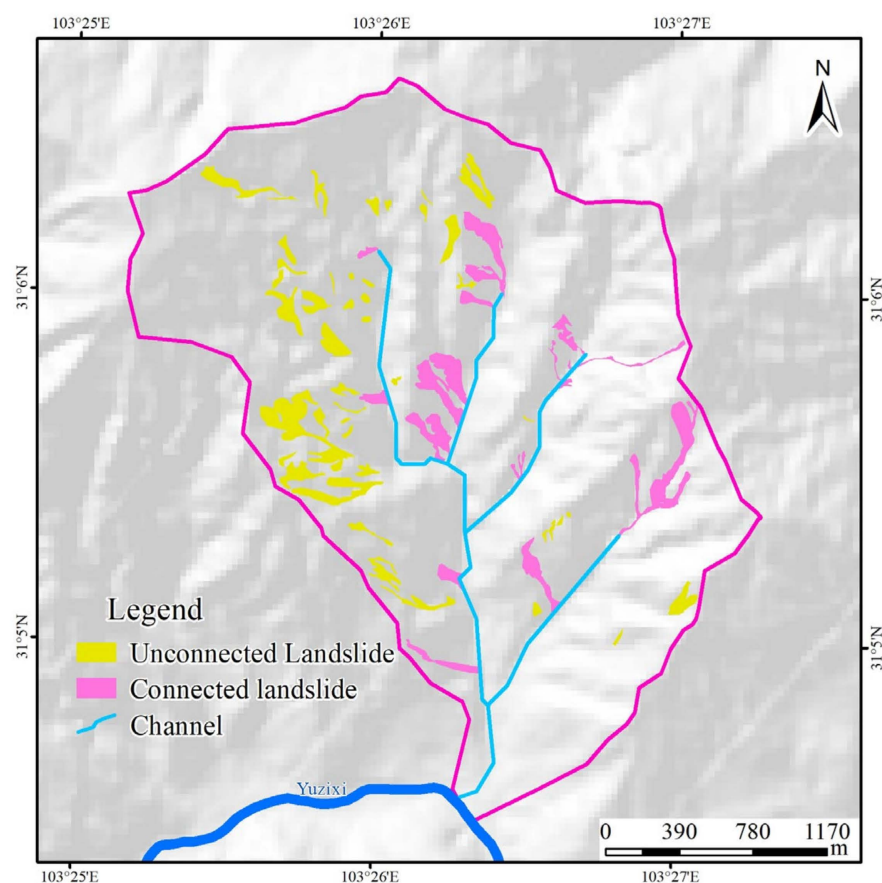


Figure 5. Classification of interpreted active landslides based on their connectivity to the channel, illustrated with an example from Xiaoja Gully.

4. Results

4.1. Multi-Temporal Analysis of Active Material

The interpreted results for the study area, as presented in Figure 6a and Table 2, demonstrate a significant increase in active landslides and channel materials following

the earthquake. In 2008, co-seismic landslides occupied 27.54% of the total debris flow catchment area. Subsequently, there was a rapid decrease in the total area of active landslides. Despite abundant rainfall in 2013, the area of active landslides did not increase during this period, reaching a post-earthquake low around 2018. However, following a period of dormancy, Figure 6b illustrates that active landslides reoccurred in 2020, coinciding with increased rainfall. Among post-earthquake active landslides, new landslides comprised only 2% of the total area, as indicated in Table 2, suggesting that the activity was predominantly the remobilization of co-seismic landslides. Regarding the activity of channel materials, their active area increased post-earthquake compared to landslides, with a gradual decrease commencing only after 2011. This indicates that the activity of channel materials was relatively delayed, being influenced by the material supply from landslides, as depicted in Figure 6c.

4.2. Material Transportation

By computing the d_g values for all interpreted active materials in the study area and plotting their respective areas on the horizontal axis, we constructed a graph that delineates the relationship between the d_g values and the area of active materials for each time period, as depicted in Figure 7. Before the earthquake, material activity in the study area was primarily concentrated upstream, driven by weathering and erosion, with affected areas predominantly ranging from 10^3 to 10^4 km². Co-seismic landslides triggered by the Wenchuan earthquake were mainly located in the central section of the debris flow catchment. In the first three years following the earthquake, influenced by rainfall, the range of material activity expanded, with a significant increase in the upper sections of the streams. Over time, material activity progressively migrated downstream within the debris flow catchment, while the average area of active materials gradually expanded. This trend suggests that, following the earthquake, loose materials within the debris flow catchment gradually moved towards the gully outlet, with the activity from numerous small-scale landslides gradually diminishing. A decade post-earthquake, a significant reduction in the quantity of active materials within the debris flow catchment was observed, yet the average area of activity expanded by an order of magnitude. This phenomenon can be attributed to the coarsening of particles, the increase in soil shear strength due to vegetation recovery, and the transition of erosion from hillslopes to channels. Collectively, these factors led to a reduction in the number of active materials and an expansion in the average area of activity. This alteration implies a shift in the catchment's material activity towards a pattern dominated by channel materials, with minimal landslide contribution.

4.3. Supply of Material Sources for Debris Flows

Figure 8 depicts the distribution of active landslides connected to channels in the study area over various periods. To enable a comparative analysis across different catchments, this section determines the proportions of active landslides, actively connected landslides and active channel materials relative to the total area of the study area's debris flow catchments for various periods. This analysis aims to explore potential correlations among these three types of active materials. The findings seek to offer a reference for future assessments of material activity and hazard evaluations related to debris flow in this region. Furthermore, this analysis provides data support for comparative studies in other regions.

(1) The Relationship Between Active Landslides and Actively Connected Landslides

As noted earlier, not every active landslide within debris flow catchments contributes to channel material replenishment. For the area significantly affected by the Wenchuan earthquake, the supply ratio from active landslides is approximately 72% of their total area, as illustrated in Figure 9a. The recharge ratio remained unaffected by the strong earthquake and maintained consistency over time post-earthquake, as dictated by the characteristics of the watershed.

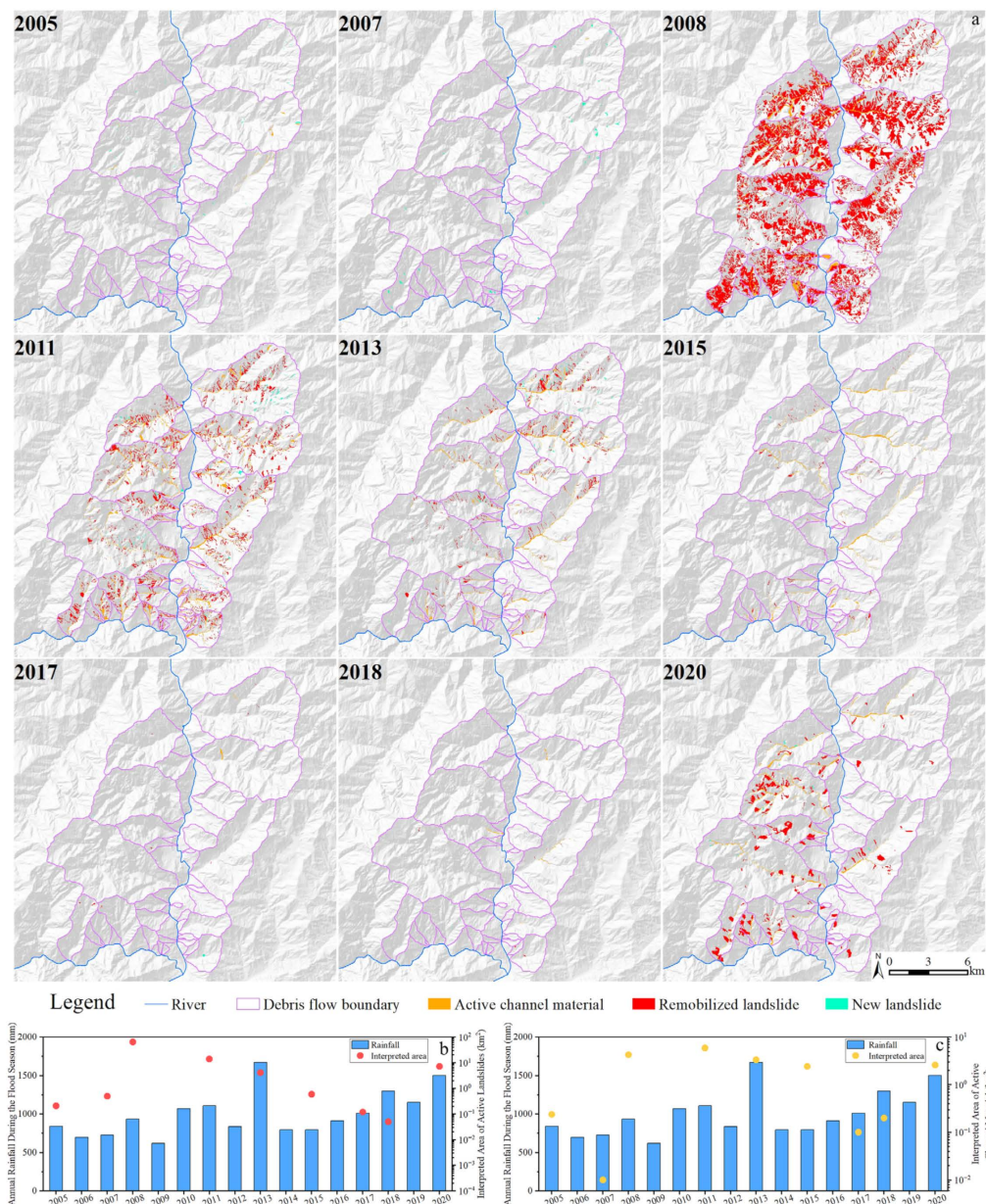


Figure 6. (a) Interpretation across different time periods shows active landslides, including new and remobilized landslides, mapped in blue and red, respectively. Active channel materials are mapped in orange. (b) Variations in the area of active landslides relative to rainfall are shown. Red dots represent active landslide areas, while blue bar charts depict annual rainfall during the flood season. (c) Variations in the area of active channel materials relative to rainfall are shown. Yellow dots represent active channel material areas, while blue bar charts depict annual rainfall during the flood season.

(2) The Relationship Between Actively Connected Landslides and Active Channel Materials

The proportion of the active channel material area within the debris flow watershed, relative to the total watershed area, increases with the expansion of the area of actively connected landslides. However, after surpassing this threshold, the active area of channel materials within the catchments stabilized and did not increase further. Based on the currently available measured data, the maximum proportion of the active channel material area is approximately 2.5%. This indicates that the channel capacity within the catchments is inherently limited. Furthermore, abundant rainfall consistently transports materials

downstream, ultimately discharging them into the Minjiang River via the channels, with debris flow events serving as the most violent transport mechanism. It is crucial to note that the aforementioned statistical data are derived from interpretations of data spanning from 2005 to 2020, both before and after the Wenchuan earthquake. Beyond 2020, owing to the accumulation of loose deposits in the catchment channels and diminishing landslide activity, the relationship between channel materials and actively connected landslides is expected to gradually converge towards the region delineated by the curve in Figure 9b and the Y-axis, and it is unlikely to exceed the maximum value of 2.5%.

Table 2. Statistics on the area of active landslide and channel material in the study area over various periods.

Year	New Landslide		Remobilized Landslide		Active Channel Material
	Area (km ²)	Number (km ²)	Area (km ²)	Number (km ²)	Area (km ²)
2005	0.21	61	/	/	0.24
2007	0.49	38	/	/	0.01
2008	64.32	4352	/	/	4.25
2011	1.92	358	13.97	1945	5.95
2013	1.00	162	4.15	586	3.33
2015	0.13	6	0.59	92	2.42
2017	0.03	2	0.12	13	0.10
2018	0.01	3	0.05	13	0.20
2020	0.75	23	7.21	202	2.61

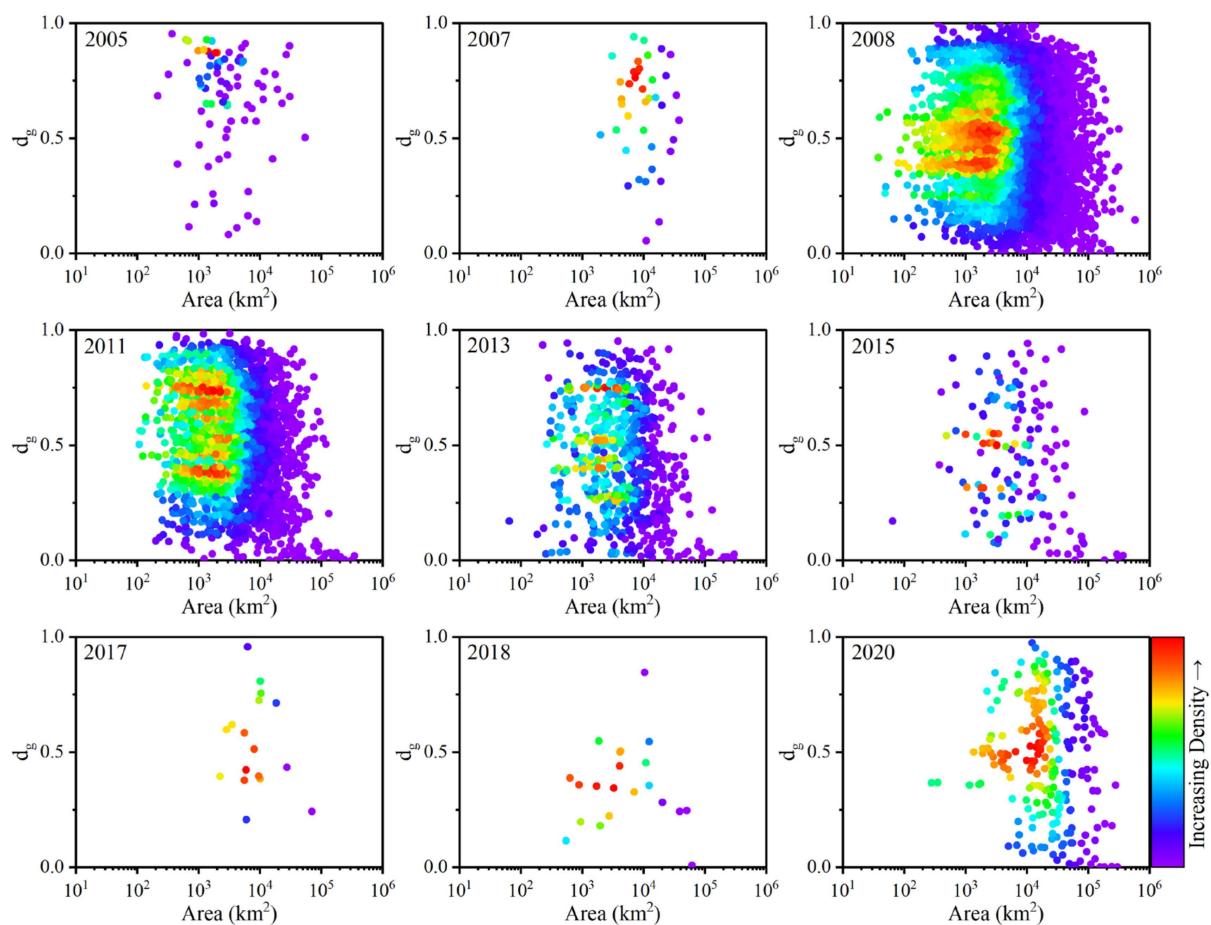


Figure 7. Dynamics of active material relative to area across different periods.

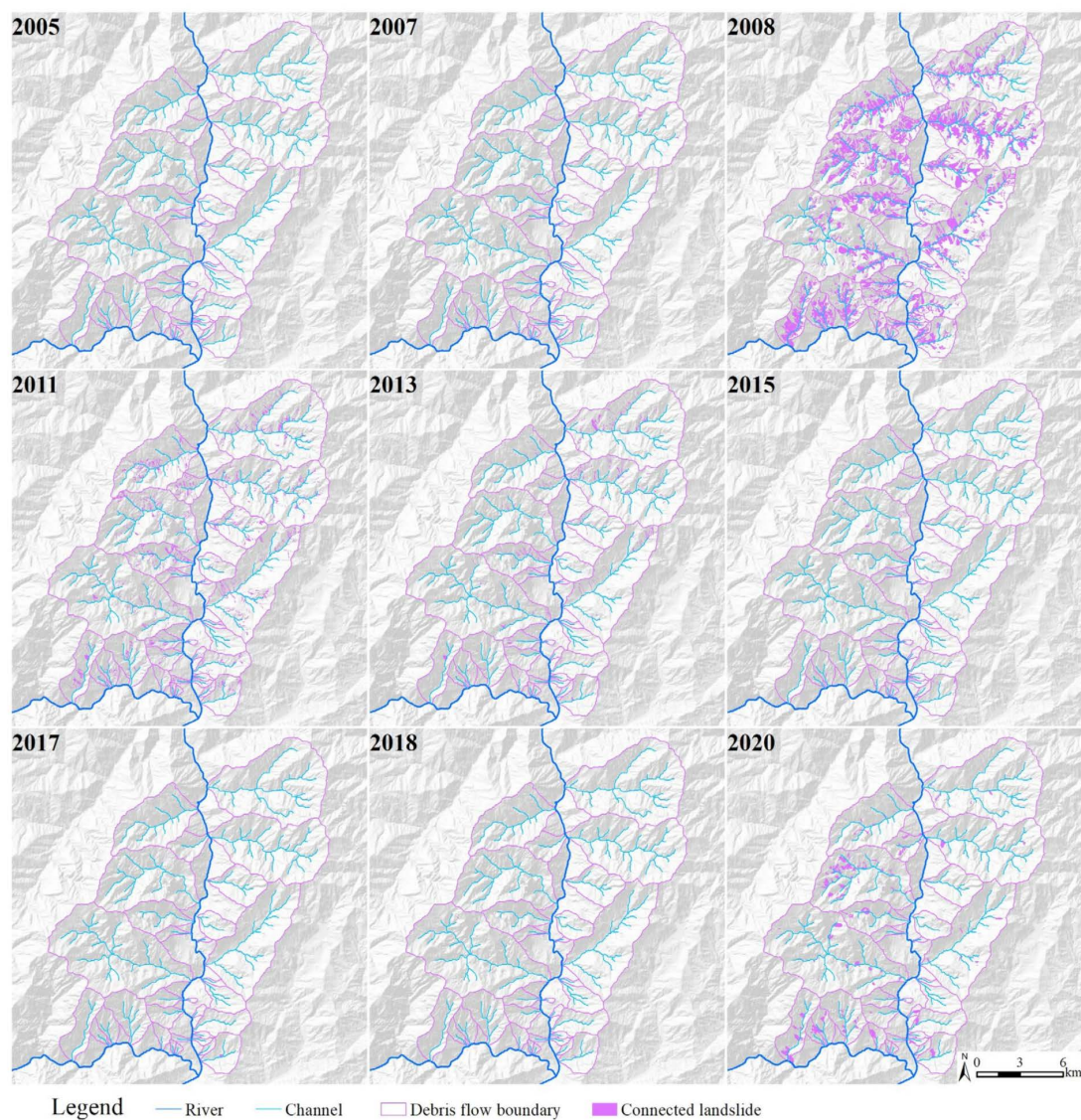


Figure 8. Active landslides connected to channels over various time periods, with interpretation showing active connected landslides mapped in purple. The maps illustrate the evolution of the area of active connected landslides from 2005 to 2020, highlighting significant increases post-2008 due to the Wenchuan earthquake.

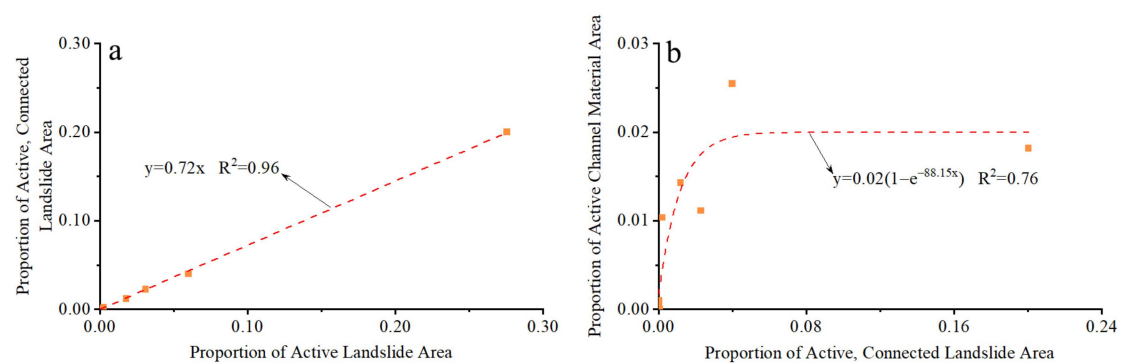


Figure 9. (a) The relationship between active landslides and actively connected landslides. (b) The relationship between actively connected landslides and active channel materials.

5. Discussion

Many studies have shown that post-earthquake debris flow channel material receives landslide recharge, with the principal objective of material dynamics in debris flow catchments being the removal of extensive deposits from the gully following an earthquake [35–37]. Thus, regardless of the source, the material had to be transported through the channel. Although channel material activity in debris flow catchments may not directly lead to debris flow events, it serves as an indicator of material activity intensity, setting the stage for potential debris flow events [38–40]. Chen et al. [31] tracked the NDVI index after the Wenchuan earthquake to characterize the intensity of debris flow activity by calculating the debris flow channel disturbance value. We calculated the area of channel material activity within each of the post-earthquake debris flow watersheds (see Table 3), categorizing them into four levels using the natural breakpoint method (see Figure 10a). Within the study area, the debris flow catchments of Yeniu, Taipingyi, Luoquan, Futangba, and Chediguan exhibited extremely high activity levels in channel materials. Based on field survey data and hazard assessment results from ref. [27], these five debris flow catchments are deemed high-risk. The comparison between channel material activity levels and hazard assessment outcomes resulted in an overall accuracy rate of about 70%. This suggests that long-term remote sensing monitoring of post-earthquake debris flow channel material activity is pivotal in debris flow hazard zoning. Additionally, it offers a hazard assessment methodology for regions without historical debris flow event data.

Table 3. Debris flow activity characteristics for each catchment.

Gully	Active Channel Material Area	Number of Post-Earthquake Events	Occurrence of Events Post-2018	Gully	Active Channel Material Area	Number of Post-Earthquake Events	Occurrence of Events Post-2018
DF01	0.47	3	No	DF17	0.76	6	Yes
DF02	0.12	3	No	DF18	3.00	4	Yes
DF03	0.03	1	No	DF19	0.33	11	Yes
DF04	0	1	No	DF20	0.09	2	No
DF05	0.50	1	Yes	DF21	1.01	4	Yes
DF06	0.33	6	No	DF22	0.26	3	No
DF07	0.22	2	No	DF23	0.31	1	Yes
DF08	0.03	1	No	DF24	0.04	1	No
DF09	0.05	1	No	DF25	0	1	No
DF10	2.40	1	Yes	DF26	0.03	1	No
DF11	0.07	1	No	DF27	0.56	1	No
DF12	0.09	1	No	DF28	0.49	2	Yes
DF13	0.67	2	No	DF29	0.60	2	Yes
DF14	2.33	4	Yes	DF30	0.07	1	No
DF15	2.16	2	Yes	DF31	0.20	2	Yes
DF16	1.88	3	Yes				

How do the frequency and sustainability of debris flow events differ across various catchments? At Serra do Mar, both Kanji et al. [41] and Lacerda [42] found that the frequency of debris flows was largely influenced by heavy rainfall events, as the water mobilizes loose sediment or infiltrates into the soil. This phenomenon is similar to the debris flows observed in the Wenchuan mountain area [43]. Unlike the initial years following the Wenchuan earthquake, Chen, H. et al. [44] found that the hillslope landslide sediment supply for debris flow occurrence is limited 15 years after an earthquake, with materials for debris flow in the later period being mainly obtained from the alluvium deposited along the channel. Thus, the storage capacity of channel material resources can significantly impact the ability to sustain debris flow activity following an earthquake. We draw on the debris flow database (see Table 3) to discuss debris flow activity characteristics from the following aspects: post-earthquake debris flow event counts and post-2018 debris flow disaster incidences (Figure 10b,c). As illustrated in Figure 10b, the findings indicate that debris flow activity in

Mozi Gully is exceptionally high, with east-facing catchments showing more pronounced activity due to the terrain's localized effect on mountainous rainfall. In the study area, the summer monsoon, both wet and warm, travels from the southeast to the northwest, encountering high mountains that often lift it, causing rainfall. As a result, post-earthquake debris flows in this specific region occur with relative frequency [45]. Next, the potential for ongoing debris flow activity post-earthquake was determined by the ability of events to persist ten years following the earthquake, as depicted in Figure 10c. Catchments exhibiting strong debris flow sustainability were characterized by an average area of 15.67 km², an elevation difference of 2.36 km, and a longitudinal slope of 444.52‰. In contrast, catchments with weaker sustainability showed an average area of 1.66 km², an elevation difference of 1.25 km, and a longitudinal slope of 662.60‰. The marked disparity in the catchment area emerges as a pivotal factor influencing debris flow sustainability. This is attributed to the fact that smaller catchment areas possess limited storage for loose materials and typically exhibit steeper longitudinal slopes, promoting swift material discharge from the catchment. Conversely, larger catchments exhibit opposite characteristics [46].

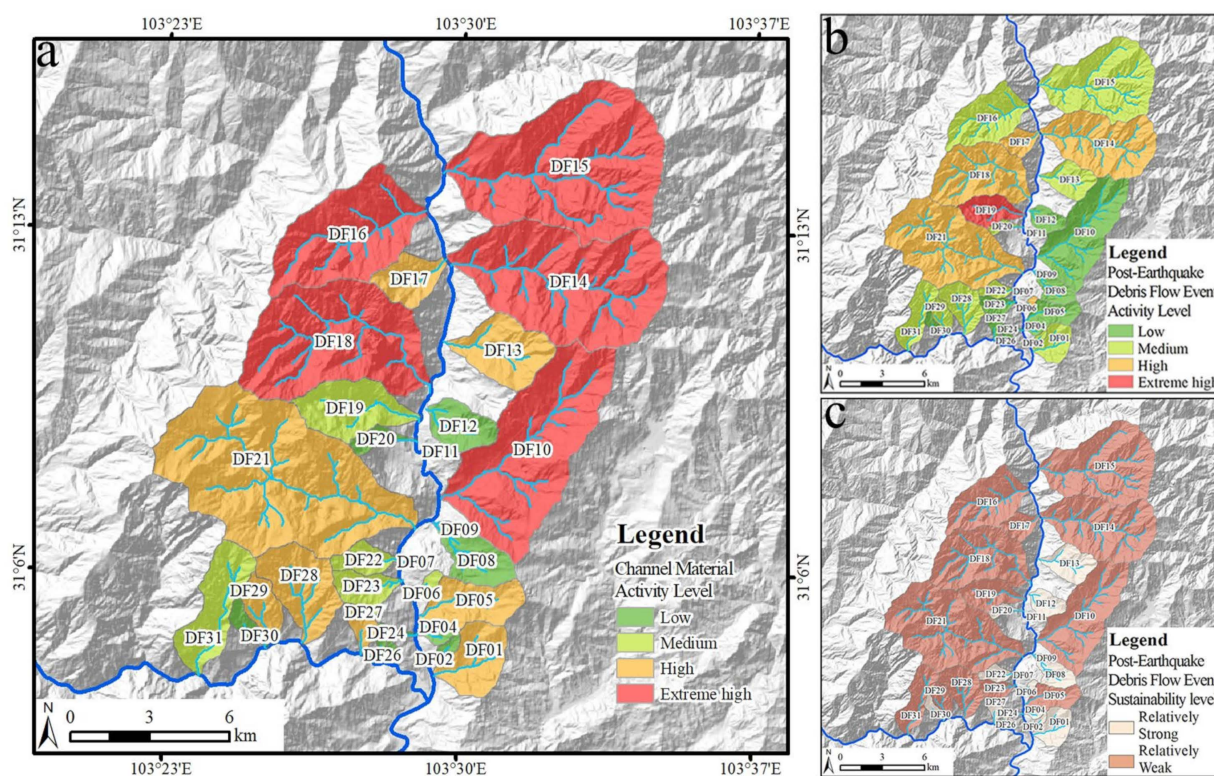


Figure 10. Classification outcomes of debris flows. (a) Utilizing the active channel material area from Table 3 and the natural breaks method, the activity levels of 31 debris flow watersheds were categorized into four groups: extremely active (1.01–3 km²), highly active (0.33–1.01 km²), moderately active (0.12–0.33 km²), and lowly active (0–0.12 km²). (b) Utilizing the number of post-earthquake events from Table 3 and the natural breaks method, post-earthquake debris flow event counts for 31 watersheds were categorized into four activity levels: extremely active (>6 events), highly active (3–6 events), moderately active (1–3 events), and lowly active (1 event). (c) Utilizing the occurrence of events post-2018 from Table 3, post-earthquake debris flow event sustainability levels were categorized into two groups: relatively strong (Yes) and relatively weak (No).

Debris flow events continued to occur in the severely affected regions over a decade after the Wenchuan earthquake. However, the frequency of such events has decreased from widespread occurrences to being concentrated in specific catchments with large drainage areas, abundant channel material sources, and orientations facing the monsoon direction. For instance, on 26 June 2023, sudden heavy rainfall in the Wenchuan area triggered

debris flow in the Banzi Gully, destroying roads and nearly blocking the Minjiang River, resulting in five fatalities. The Banzi Gully catchment covers an area of 54.7 km², with a relative elevation difference of 4000 m, and faces southeast, making it susceptible to the condensation of summer rainwater in its upper reaches. Post-disaster investigations by Zhang et al. [47] revealed that this debris flow was primarily triggered by short-duration intense rainfall, which mobilized channel materials, characteristic of hydraulic-type debris flow formation processes. Therefore, future debris flow risk assessments in the Wenchuan seismic region need to incorporate the intensity of channel material activity and increase the weighting of the catchment area and orientation to align with the new characteristics of debris flow activity.

6. Conclusions

A representative study area was chosen near the epicenter of the Wenchuan earthquake. Before the earthquake, the region's material activity was mainly driven by weathering and erosion, predominantly occurring in upstream landslides within the catchments. After the earthquake, co-seismic loose materials were primarily situated in the central sections of the debris flow catchments. Over time, material activity progressively migrated downstream within the debris flow catchments. Throughout this process, the activity of many small-scale landslides induced by the earthquake gradually diminished, with new landslides comprising merely 2% of the total active landslide area. Loose deposits in the catchments unconnected to the channels did not contribute to the material activity of the debris flow channels or supply materials to the debris flow activities. In the area severely affected by the Wenchuan earthquake, the connectivity rate of active landslides capable of contributing materials to channel activities has consistently remained around 72%. However, limited channel capacity meant that the active area of channel materials could not continue to expand. Ten years after the disturbance, the catchment's material activity towards a pattern was dominated by channel materials, with a minimal landslide contribution.

This study further examines debris flow characteristics from the perspectives of channel material activity levels, historical post-earthquake activity, and sustainability of debris flows. In regions without historical debris flow data, the area of channel material activity serves as a viable metric for a hazard assessment. Variations in localized rainfall across mountainous terrains, influenced by slope orientation, likely contribute to the frequency of debris flow events. The sustainability of debris flows in the study area is significantly determined by the catchment area.

Author Contributions: Conceptualization, Y.Y. and M.C.; methodology, Y.Y. and M.C.; software, Y.Y.; validation, C.T.; investigation, Y.Y., W.H. and C.X.; resources, Y.C.; data curation, Y.Y.; writing—original draft preparation, Y.Y.; writing—review and editing, M.C. and C.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of Sichuan Province (2024NS-FSC0783).

Data Availability Statement: All data can be provided by the corresponding author upon request.

Acknowledgments: This work was supported by the Chengdu Scientific Station for Field Observation and Research on Geological Hazards, the Ministry of Natural Resources. The authors thank the anonymous reviewers for their helpful suggestions to improve the paper.

Conflicts of Interest: The authors declare the following potential conflicts of interest: Zhaozhi Future Technology (Chengdu) Co., Ltd. and Nuclear Industry Southwest Geotechnical Investigation and Design Institute Co., Ltd. are affiliated with some of the authors. However, the authors affirm that the research was conducted independently, and the results presented in this paper are not influenced by their respective affiliations.

References

1. Malamud, B.D.; Turcotte, D.L.; Guzzetti, F.; Reichenbach, P. Landslides, earthquakes, and erosion. *Earth Planet. Sci. Lett.* **2004**, *229*, 45–59. [\[CrossRef\]](#)
2. Yanites, B.J.; Tucker, G.E.; Mueller, K.J.; Chen, Y.-G. How rivers react to large earthquakes: Evidence from central Taiwan. *Geology* **2010**, *38*, 639–642. [\[CrossRef\]](#)
3. Yang, Y.; Tang, C.; Cai, Y.; Tang, C.; Chen, M.; Huang, W.; Liu, C. Characteristics of Debris Flow Activities at Different Scales after the Disturbance of Strong Earthquakes—A Case Study of the Wenchuan Earthquake-Affected Area. *Water* **2023**, *15*, 698. [\[CrossRef\]](#)
4. Yang, Y.; Tang, C.; Tang, C.; Chen, M.; Cai, Y.; Bu, X.; Liu, C. Spatial and temporal evolution of long-term debris flow activity and the dynamic influence of condition factors in the Wenchuan earthquake-affected area, Sichuan, China. *Geomorphology* **2023**, *435*, 108755. [\[CrossRef\]](#)
5. Lin, C.-W.; Shieh, C.-L.; Yuan, B.-D.; Shieh, Y.-C.; Liu, S.-H.; Lee, S.-Y. Impact of Chi-Chi earthquake on the occurrence of landslides and debris flows: Example from the Chenyulan River watershed, Nantou, Taiwan. *Eng. Geol.* **2004**, *71*, 49–61. [\[CrossRef\]](#)
6. Fan, X.; Scaringi, G.; Korup, O.; West, A.J.; van Westen, C.J.; Tanyas, H.; Hovius, N.; Hales, T.C.; Jibson, R.W.; Allstadt, K.E. Earthquake-induced chains of geologic hazards: Patterns, mechanisms, and impacts. *Rev. Geophys.* **2019**, *57*, 421–503. [\[CrossRef\]](#)
7. Simonett, D.S. Landslide distribution and earthquakes in the Bavani and Torricelli mountains, New Guinea. In *Landform Studies from Australia and New Guinea*; Australian National University Press: Canberra, Australia, 1967; pp. 64–84. Available online: <https://cir.nii.ac.jp/crid/1571698600949436032> (accessed on 29 July 2024).
8. Hovius, N.; Meunier, P.; Lin, C.-W.; Chen, H.; Chen, Y.-G.; Dadson, S.; Horng, M.-J.; Lines, M. Prolonged seismically induced erosion and the mass balance of a large earthquake. *Earth Planet. Sci. Lett.* **2011**, *304*, 347–355. [\[CrossRef\]](#)
9. Chigira, M.; Wu, X.; Inokuchi, T.; Wang, G. Landslides induced by the 2008 Wenchuan earthquake, Sichuan, China. *Geomorphology* **2010**, *118*, 225–238. [\[CrossRef\]](#)
10. Pearce, A.J.; Watson, A. Medium-term effects of two landsliding episodes on channel storage of sediment. *Earth Surf. Process. Landf.* **1983**, *8*, 29–39. [\[CrossRef\]](#)
11. Pearce, A.J.; Watson, A.J. Effects of earthquake-induced landslides on sediment budget and transport over a 50-yr period. *Geology* **1986**, *14*, 52–55. [\[CrossRef\]](#)
12. Dadson, S.J.; Hovius, N.; Chen, H.; Dade, W.B.; Lin, J.-C.; Hsu, M.-L.; Lin, C.-W.; Horng, M.-J.; Chen, T.-C.; Milliman, J. Earthquake-triggered increase in sediment delivery from an active mountain belt. *Geology* **2004**, *32*, 733–736. [\[CrossRef\]](#)
13. Korup, O.; McSaveney, M.J.; Davies, T.R. Sediment generation and delivery from large historic landslides in the Southern Alps, New Zealand. *Geomorphology* **2004**, *61*, 189–207. [\[CrossRef\]](#)
14. Tsai, Z.X.; You, G.J.Y.; Lee, H.Y.; Chiu, Y.J. Modeling the sediment yield from landslides in the Shihmen Reservoir watershed, Taiwan. *Earth Surf. Process. Landf.* **2013**, *38*, 661–674. [\[CrossRef\]](#)
15. West, A.; Lin, C.-W.; Lin, T.-C.; Hilton, R.; Liu, S.-H.; Chang, C.-T.; Lin, K.-C.; Galy, A.; Sparkes, R.; Hovius, N. Mobilization and transport of coarse woody debris to the oceans triggered by an extreme tropical storm. *Limnol. Oceanogr.* **2011**, *56*, 77–85. [\[CrossRef\]](#)
16. Zhang, S.; Zhang, L. Impact of the 2008 Wenchuan earthquake in China on subsequent long-term debris flow activities in the epicentral area. *Geomorphology* **2017**, *276*, 86–103. [\[CrossRef\]](#)
17. Ferguson, R.I.; Church, M.; Rennie, C.D.; Venditti, J.G. Reconstructing a sediment pulse: Modeling the effect of placer mining on Fraser River, Canada. *Earth Surf.* **2015**, *120*, 1436–1454. [\[CrossRef\]](#)
18. Zhang, N.; Matsushima, T.; Peng, N. Numerical investigation of post-seismic debris flows in the epicentral area of the Wenchuan earthquake. *Bull. Eng. Geol. Environ.* **2019**, *78*, 3253–3268. [\[CrossRef\]](#)
19. Gerolymos, N. Numerical modeling of seismic triggering, evolution, and deposition of rapid landslides: Application to Higashi-Takezawa (2004). *Numer. Anal. Methods Geomech.* **2010**, *34*, 383–407. [\[CrossRef\]](#)
20. Yang, F.; Fan, X.; Wei, Z.; Subramanian, S.S.; Van Asch, T.W.J.; Xu, Q. Modelling the evolution of debris flows after the 2008 Wenchuan earthquake. *Eng. Geol.* **2023**, *321*, 107152. [\[CrossRef\]](#)
21. Fan, X.; Domènech, G.; Scaringi, G.; Huang, R.; Xu, Q.; Hales, T.C.; Dai, L.; Yang, Q.; Francis, O. Spatio-temporal evolution of mass wasting after the 2008 Mw 7.9 Wenchuan earthquake revealed by a detailed multi-temporal inventory. *Landslides* **2018**, *15*, 2325–2341. [\[CrossRef\]](#)
22. Meunier, P.; Hovius, N.; Haines, A.J. Regional patterns of earthquake-triggered landslides and their relation to ground motion. *Hydrol. Land Surf. Stud.* **2007**, *34*, 121–138. [\[CrossRef\]](#)
23. Roback, K.; Clark, M.K.; West, A.J.; Zekkos, D.; Li, G.; Gallen, S.F.; Chamlagain, D.; Godt, J.W. The size, distribution, and mobility of landslides caused by the 2015 Mw7.8 Gorkha earthquake, Nepal. *Geomorphology* **2018**, *301*, 121–138. [\[CrossRef\]](#)
24. Stolle, A.; Schwanghart, W.; Andermann, C.; Bernhardt, A.; Fort, M.; Jansen, J.D.; Wittmann, H.; Merchel, S.; Rugel, G.; Adhikari, B.R.; et al. Protracted river response to medieval earthquakes. *Earth Surf. Process. Landf.* **2019**, *44*, 331–341. [\[CrossRef\]](#)
25. Li, G.; West, A.J.; Densmore, A.L.; Hammond, D.E.; Jin, Z.; Zhang, F.; Wang, J.; Hilton, R.G. Connectivity of earthquake-triggered landslides with the fluvial network: Implications for landslide sediment transport after the 2008 Wenchuan earthquake. *J. Geophys. Res. Earth Surf.* **2016**, *121*, 703–724. [\[CrossRef\]](#)
26. Yang, F.; Fan, X.; Siva Subramanian, S.; Dou, X.; Xiong, J.; Xia, B.; Yu, Z.; Xu, Q. Catastrophic debris flows triggered by the 20 August 2019 rainfall, a decade since the Wenchuan earthquake, China. *Landslides* **2021**, *18*, 3197–3212. [\[CrossRef\]](#)

27. Zhang, X.; Tang, C.; Li, N.; Xiong, J.; Chen, M.; Li, M.; Tang, C. Investigation of the 2019 Wenchuan County debris flow disaster suggests nonuniform spatial and temporal post-seismic debris flow evolution patterns. *Landslides* **2022**, *19*, 1935–1956. [\[CrossRef\]](#)
28. Chen, M.; Tang, C.; Zhang, X.; Xiong, J.; Chang, M.; Shi, Q.; Wang, F.; Li, M. Quantitative assessment of physical fragility of buildings to the debris flow on 20 August 2019 in the Cutou gully, Wenchuan, southwestern China. *Eng. Geol.* **2021**, *293*, 106319. [\[CrossRef\]](#)
29. Chen, M.; Tang, C.; Li, M.; Xiong, J.; Luo, Y.; Shi, Q.; Zhang, X.; Tie, Y.; Feng, Q. Changes of surface recovery at coseismic landslides and their driving factors in the Wenchuan earthquake-affected area. *CATENA* **2022**, *210*, 105871. [\[CrossRef\]](#)
30. Shi, Q.-y.; Tang, C.; Gong, L.-f.; Chen, M.; Li, N.; Zhou, W.; Xiong, J.; Tang, H.; Wang, X.-d.; Li, M.-w. Activity evolution of landslides and debris flows after the Wenchuan earthquake in the Qipan catchment, Southwest China. *J. Mt. Sci.* **2021**, *18*, 932–951. [\[CrossRef\]](#)
31. Chen, M.; Tang, C.; Xiong, J.; Chang, M.; Li, N. Spatio-temporal mapping and long-term evolution of debris flow activity after a high magnitude earthquake. *CATENA* **2024**, *236*, 107716. [\[CrossRef\]](#)
32. Chen, M.; Tang, C.; Xiong, J.; Shi, Q.Y.; Li, N.; Gong, L.F.; Wang, X.D.; Tie, Y. The long-term evolution of landslide activity near the epicentral area of the 2008 Wenchuan earthquake in China. *Geomorphology* **2020**, *367*, 107317. [\[CrossRef\]](#)
33. Tang, C.; Liu, X.; Cai, Y.; Van Westen, C.; Yang, Y.; Tang, H.; Yang, C.; Tang, C. Monitoring of the reconstruction process in a high mountainous area affected by a major earthquake and subsequent hazards. *Nat. Hazards Earth Syst. Sci.* **2020**, *20*, 1163–1186. [\[CrossRef\]](#)
34. Fan, X.; Scaringi, G.; Domènech, G.; Yang, F.; Guo, X.; Dai, L.; He, C.; Xu, Q.; Huang, R. Two multi-temporal datasets that track the enhanced landsliding after the 2008 Wenchuan earthquake. *Earth Syst. Sci. Data* **2019**, *11*, 35–55. [\[CrossRef\]](#)
35. Jin, W.; Cui, P.; Zhang, G.; Wang, J.; Zhang, Y.; Zhang, P. Evaluating the post-earthquake landslides sediment supply capacity for debris flows. *CATENA* **2023**, *220*, 106649. [\[CrossRef\]](#)
36. Tang, C.; Jiang, Z.; Li, W. Seismic Landslide Evolution and Debris Flow Development: A Case Study in the Hongchun Catchment, Wenchuan Area of China. In *Engineering Geology for Society and Territory*; Springer International Publishing: Cham, Switzerland, 2015; Volume 2, pp. 445–449. [\[CrossRef\]](#)
37. Shieh, C.-L.; Chen, Y.-S.; Shieh, M.-L.; Tsai, Y.-J. Rainfall criteria variation of debris flow occurring at Mt. Ninety-Nine. In Proceedings of the International Symposium Disaster Mitigation of Debris Flows, Slope Failures and Landslides, Niigata, Japan, 25–29 September 2006; pp. 167–175. Available online: <https://www.researchgate.net/publication/285731334> (accessed on 29 July 2024).
38. Bonneau, D.A.; Hutchinson, D.J.; McDougall, S.; DiFrancesco, P.-M.; Evans, T. Debris-Flow Channel Headwater Dynamics: Examining Channel Recharge Cycles with Terrestrial Laser Scanning. *Front. Earth Sci.* **2022**, *10*, 883259. [\[CrossRef\]](#)
39. Loye, A.; Jaboyedoff, M.; Theule, J.I.; Liébault, F. Headwater sediment dynamics in a debris flow catchment constrained by high-resolution topographic surveys. *Earth Surf. Dynam.* **2016**, *4*, 489–513. [\[CrossRef\]](#)
40. Yu, B.; Yang, L.; Chang, M.; van Asch, T.W.J. A new prediction model on debris flows caused by runoff mechanism. *Environ. Earth Sci.* **2021**, *80*, 26. [\[CrossRef\]](#)
41. Kanji, M.A.; Cruz, P.T.; Massad, F. Debris flow affecting the Cubatão Oil Refinery, Brazil. *Landslides* **2008**, *5*, 71–82. [\[CrossRef\]](#)
42. Lacerda, W.A. Landslide initiation in saprolite and colluvium in southern Brazil: Field and laboratory observations. *Geomorphology* **2007**, *87*, 104–119. [\[CrossRef\]](#)
43. Xiong, J.; Tang, C.; Chen, M.; Gong, L.; Li, N.; Zhang, X.; Shi, Q. Long-term changes in the landslide sediment supply capacity for debris flow occurrence in Wenchuan County, China. *CATENA* **2021**, *203*, 105340. [\[CrossRef\]](#)
44. Chen, H.; Xiong, J.; Zhao, W.; Chen, J.; Zhang, X.; Ruan, H.; Fang, C.; Gong, L. Catastrophic debris flow triggered by a June 26, 2023 rainstorm suggests the debris flow is still active 15 years after the Wenchuan seismic. *Landslides* **2024**, *21*, 1883–1897. [\[CrossRef\]](#)
45. Shi, Z.; Wei, F.; Chandrasekar, V. Radar-based quantitative precipitation estimation for the identification of debris flow occurrence over earthquake-affected regions in Sichuan, China. *Nat. Hazards Earth Syst. Sci.* **2018**, *18*, 765–780. [\[CrossRef\]](#)
46. Xiong, J.; Chen, H.; Tang, C.; Chen, M.; Chang, M.; Zhang, X.; Gong, L.; Li, N.; Shi, Q.; Li, M. Application of remote sensing monitoring to the spatiotemporal variation in debris flow activity in the catastrophic Wenchuan seismic area. *CATENA* **2023**, *232*, 107450. [\[CrossRef\]](#)
47. Zhang, X.; Tie, Y.; Ning, Z.; Yang, C.; Li, Z.; Li, M.; Liang, J.; Lu, J.; Lu, T.; Li, G.; et al. Characteristics and activity analysis of the catastrophic “6.26” debris flow in the Banzi catchment, Wenchuan County of Sichuan Province. *Hydrogeol. Eng. Geol.* **2023**, *50*, 134–145. (In Chinese) [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.