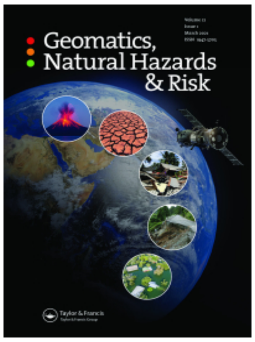

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Largest scale successful real-time evacuation after the Wenchuan earthquake in China: lessons learned from the Zengda gully giant debris flow disaster

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ABSTRACT

A catastrophic debris flow occurred in the Zengda gully, a branch of the Dajinchuan River in Zengda town, Jinchuan County, Sichuan Province, China. The successful implementation of a real-time evacuation avoided 820 casualties for people living in 200 settlements. This was the largest-scale successful real-time evacuation for a debris flow disaster after the Wenchuan earthquake in China. In order to better reveal the causes of the successful real-time evacuation process of the giant debris flow disaster, the characteristics, formation and movement process of the debris flow were studied using multi-temporal remote sensing images, field investigation, laboratory analysis, and empirical formula calculations. It was found that the successful real-time evacuation was possible because of a well-executed monitoring system, timely release of early warning information, a highly effective operation disaster prevention system, and decisive and advanced avoidance. It also transferred strategies through in-depth analysis of several important stages in the real-time evacuation process. Finally, an exemplary mode of community-based warning is proposed based on the Zengda gully giant debris flow disaster real-time evacuation. Specifically, the mode was led by government, implemented by local residents and proceeded with the guidance by experts in the field. The experience and effective risk avoidance mode presented in this paper can be shared and employed by other countries or regions at serious risk for debris flow disasters.

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1. Introduction

In the last five years, several catastrophic debris flows have occurred in China (Deng et al. 2018; Chen et al. 2020; Raymond et al. 2020; Zhao et al. 2020a, 2020b). For example, on 7 July 2020, four people died due to a debris flow in Chenghuangmiao gully, Xiaojin County, Sichuan Province (Peng et al. 2021). On 17 June 2020, a debris flow occurred in Meilong gully, Danba County, Sichuan Province, and two people died in this disaster (Hu et al. 2020). On 20 August 2019, debris flows were triggered in Wenchuan County, Sichuan Province, causing the deaths of 36 people (Jin et al. 2019). Furthermore, on 2 September 2018, 21 people died or went missing due to a debris flow in Malipo County, Yunnan Province (Chen et al. 2019). On 8 August 2017, a debris flow occurred in Tongzilin gully, Puge County, Sichuan Province, in which two people died (Chen et al. 2019). On 8 May 2016, 36 people died or went missing due to a debris flow in Taining County, Fujian Province (Zhang et al. 2020). As a result of continuous efforts and improvement to geological disaster prevention strategies implemented by the Chinese government (Zhuang et al. 2015; Ouyang et al. 2019; Hu et al. 2020), China has analyzed a large number of cases and gained valuable experience in successful evacuations during geological disasters (Hu et al. 2019). For example, in 2019, in Sichuan Province alone, fifteen typical cases of geological disasters, including seven debris flows, were successfully averted, and 2,058 casualties were avoided (http://www.chinajyzb.com.cn/news_detail-5-6595.html). In addition, catastrophic debris flow events are common around the world. For example, a giant debris flow in Colombia on 1 April 2017 caused 419 deaths (Cheng et al. 2018); a debris flow with a recurrence interval of 300 years in Venezuela caused more than 30, 000 deaths in December, 1999 (Pérez 2001); 10 debris flow events hit the region of Northern Italy during the most severe storms and caused casualties and significant damages to infrastructures (Borga 2019); a debris flow in Seoul in 2001 resulted in 11 casualties and 100 cars were destroyed (Lee and Winter 2019) and the 2018 Montecito, California, America debris flow in event not only caused over $200 M property loss and a death toll of 21 people (Tiwari et al. 2020).

Another successful evacuation occurred in Jinchuan County. At approximately 20:30 local time on 27 June 2019, a catastrophic debris flow occurred at Nijiaping village in Zengda town, Jinchuan County, Sichuan Province, southwestern China. A giant debris flow disaster destroyed 1,326 farmhouses, 137 public facilities, 0.51 km^2 of farmland, 50.1 km of rural roads, 39 bridges, and killed 2,258 head of livestock. The total economic losses were on the order of 152 million RMB (Bureau of Land and Resources of Aba City, Sichuan Province 2019). Fortunately, the area affected was successfully evacuated in time, saving 820 people from 200 families. The government of Sichuan province launched emergency rescue and disaster relief operations soon after the event. A day later, experts from the Key Lab of Mountain Hazards and Surface Processes, Chinese Academy of Sciences in Chengdu (i.e. the authors of this paper), along with the emergency response team from the Sichuan Land and Resources Department, reached the site. Through the first-hand data collected, the causes of debris flow disaster and the prevention of secondary disasters were analyzed in time.

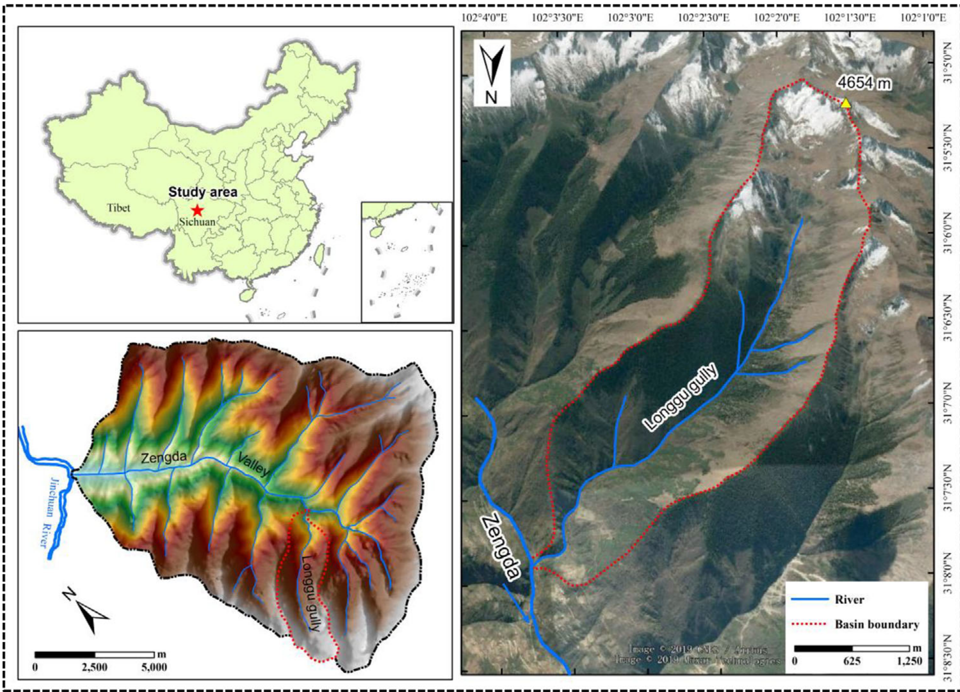

Figure 1. Location of the '6.27' Zengda gully debris flow, Jinchuan, China. Source: Author.

After the event, the following research questions have received increased attention: (1) what were the characteristics of the debris flow disaster, and how did the debris flow form and move?; (2) what factors played an important role in the debris flow disaster evacuation?; and (3) what implications can be drawn from this experience? To answer the above questions, the catastrophic event was documented and the debris flow occurrence process was explored through multi-temporal remote sensing interpretations, field investigation, laboratory analysis, and empirical formula calculations. In the investigation, the dynamic characteristics, formation, and movement processes of the debris flows that occurred on 27 June 2019 were analyzed. The real-time evacuation process was well documented and a mode combining a community-based warning system with a technical defense system was constructed. In addition, the experience gained from the events surrounding the catastrophic debris flow are summarized in this paper, which may contribute to the prevention of larger scale debris flow and the mitigation of its damages not only in Jinchuan County, but also in other countries or regions of the world at risk for these natural disasters.

2. Study area

2.1. Geographic location and topography

The Zengda valley is located in the southeastern part of Jinchuan County, Sichuan Province. It is a primary tributary of the Jinchuan River, with a length of 21.96 km, and an area of 125.53 km^2. The channel is deeply cut, and the average gradient is approximately 12.6%. The elevation ranges from 2,056 to 4,720 m, and the maximum

Table 1. Basic features of the branch ditch in Zengda valley.

1	Xiaodaidu	1.06	2.86	41.1	1269
2	Daidu	6.37	5.74	29.3	2165
3	Longdeng	3.63	3.73	40.4	1712
4	Baila	6.18	5.57	27.4	1759
5	Kazi	4.85	5.77	34.3	1929
6	Sika	11.49	5.79	25.2	1890
7	Tanguanyao	2.76	2.64	39.8	1420
8	Danji	5.77	6.08	28.4	1863
9	Aierluo	15.15	8.24	21.0	1824
10	Boyan	9.36	7.22	22.8	1814
11	Nijiaping	4.37	6.88	28.3	1332
12	Longgu	8.82	7.17	23.1	1686
13	Shuikazi	9.25	5.11	21.0	1684
14	Zhangjia	3.6	3.31	25.1	980
15	Ganhaizi	4.56	5.73	22.6	1520
16	Shuanhaizi	6.62	5.91	20.3	1584

relative height difference is 2,664 m (Figure 1). There are 16 large branches in the valley (Table 1). The middle and lower sections of the branch gully are narrow with a width of 15–40 m. The slope of the valley on both sides is steep, approximately 35–60°. The slope of the exposed section of the local bedrock is over 70°.

2.2. Geological environment

Metamorphic rocks from the Middle and upper Triassic are distributed in the valley. The primary lithology is metamorphic sandstone and slate, and quaternary loose deposits and ice water deposits from the Cenozoic era are also widely distributed (Figure 2). The study area is located in the compound part of the western half arc of the Jintang arc-shaped structure and the periphery of the ETA-type structure in Yunnan and Tibet. The main structures in the area are the Lengdu anticline, Chachangsi syncline, SaiRihao anticline, Rusri anticline, Xiangyang fault, and Shaori fault. The study area is located between the Xianshui River and the Songpan seismic zones, where the seismic intensity is VII degrees.

2.3. Meteorology and hydrology

In study area, the perennial average temperature is 12.8 °C, the lowest recorded temperature is −11.1 °C, and the highest recorded temperature is 37.8 °C. The average and maximum annual precipitation are 621 and 858.1 mm, respectively, while the maximum daily rainfall, maximum hourly rainfall, and maximum rainfall over 10 minutes are 56.2, 21, and 5 mm, respectively.

2.4. History of debris flows and mountain torrents in Zengda gully

According to previous survey data (Bureau of Land and Resources of Aba City, Sichuan Province 2019) and this survey, we preliminarily determined that there were five mountain torrents and debris flow disasters in Zengda gully since the 1990s (Table 2).

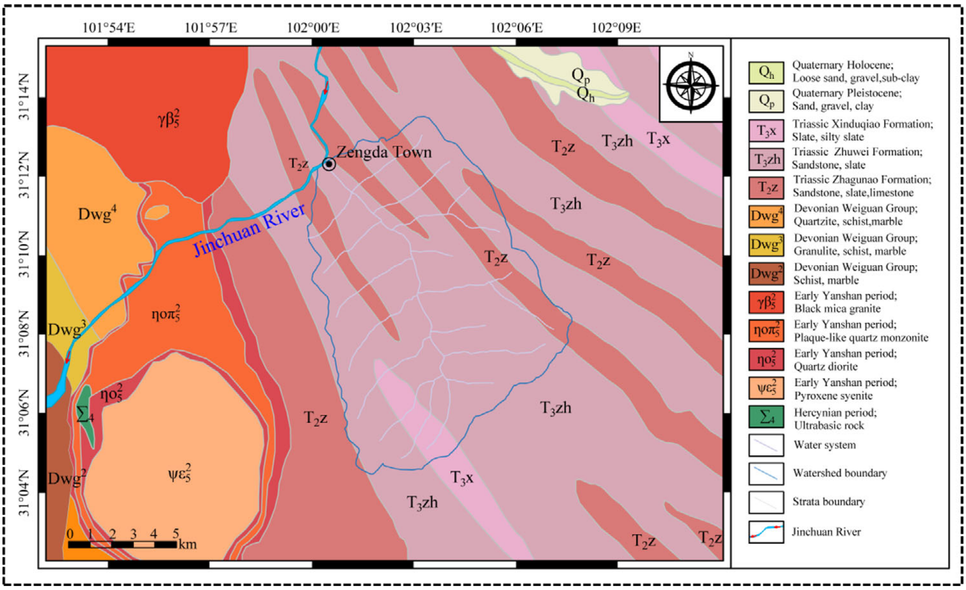

Figure 2. Geological map of the study area. Source: Author.

3. Dynamic characteristics of debris flows

The density, velocity, peak discharge, and solid volumes of debris flows are the most critical dynamic parameters for assessing hazards and designing protective measures (Rahman and Konagai 2017; Liu et al. 2021. During our research, we carried out field investigations, remote sensing interpretations, and empirical formula calculations to determine the dynamic characteristics of debris flows. According to the specifications of Geological Investigation for Debris Flow Stabilization in China (Hydrological and Water Resources Survey Bureau of Sichuan Province 2010; National Land Resources Department, China 2018; The Geological and Mineral Industry Standard of the People's Republic of China 2018), the calculation methods of debris flow dynamic parameters are summarized in Table 3. The results for the debris flow dynamic parameters are listed in Table 4.

4. Formation, movement, and evacuation process

4.1. Formation and movement process

According to field investigations and interviews with disaster monitoring personnel, we found that on June 27 at 20:30 local time, after more than three hours of heavy rainfall, the first debris flow disengaged from the Longgu gully tributary, quickly flowing into the main gully. Owing to the large longitudinal gradient of Longgu gully, especially the longitudinal gradient downstream of the mouth of Longgu gully (40%), the velocity of the debris flow at the confluence of the main gully reached 8 m/s. In addition, Longgu gully and the main gully converge at nearly 90°, causing the debris flow of Longgu gully to hit the opposite bank slope and the debris flow splash height to reach approximately 30 m (Figure 3a). After the debris flow in Longgu gully

Table 2. History of debris flow and mountain torrent disasters in Zengda gully.

1	June 1992	Mountain torrents	Zengda gully	Small	Farmland and homes were destroyed
2	26 June 1994	Mountain torrents, debris flows	Zengda gully and branch gully	Medium	One person was missing, more than 20 households and 0.4 km^2 of farmland were damaged, 220 head of livestock were killed
3	June 2010	Debris flows	Nijiaping gully (Branch gully of Zengda)	Small; the total amount of solid material flushed out was approx. 4000 m^3	Rural roads were buried
4	June 2011	Debris flows	Nijiaping gully (Branch gully of Zengda)	Small, the total amount of solid material flushed out was approx. 4500 m^3	Rural roads were buried
5	28 June 2014	Debris flows	Zengda gully and branch gully	Medium; the total amount of solid material flushed out was approx. 65,600 m^3	Four houses were destroyed, and 133 houses were damaged; 0.26 km^2 of crops were destroyed, and many rural roads and bridges were destroyed
6	27 June 2019	Debris flows	Zengda gully	Giant; the total amount of solid material flushed out was approx. 132×10^4 m^3	1,326 farmhouses, 137 public facilities, 0.51 km^2 of farmland, 50.1 km of rural roads and 39 bridges were destroyed, and 2,258 head of livestock were killed. Direct economic losses were 152 million Yuan

Table 3. Formulas for debris flow dynamic parameters.

Dynamic parameters of debris flow	Formula	Parameters in the formula
Density	$\gamma_c = -1320x^7 - 513x^6 + 891x^5 - 55x^4 + 34.6x^3 - 67x^2 + 12.5x + 1.55$	γ_c is the debris flow density; x is the clay content in the debris flow soil sample
Velocities	$U_m = \frac{1}{n_c} H_c{}^{2/3} I_c{}^{1/2}$ $V_c = \frac{M_c}{a} H_c{}^{2/3} I_c{}^{1/2}$ $a = (1 + \varphi\gamma_s)^{1/2}$ $\varphi = (\gamma_c - \gamma_w)/(\gamma_s - \gamma_c)$	U_m and V_c are the velocities of the viscous and liquid debris flows, respectively; I_c is the hydraulic gradient of the debris flow section of the gully obtained by on-site measurement; n_c and M_c are the roughness coefficients for debris flows; H_c is the hydraulic radius (m) defined as the mud depth of the debris flow section obtained by on-site measurement. a is the drag coefficient; φ is the increase coefficient; γ_w is the density of water (kg/m^3) determined as 1,000 kg/m^3; γ_s is the density of the solid material (kg/m^3) determined as 2,650 kg/m^3.
Peak discharge	$Q_p = 0.278\psi \frac{S}{\tau^n} A$ $n = 1 + 1.285\left(\lg \frac{\bar{H}_1 K_p}{\bar{H}_6 K_p}\right)$ $S = \bar{H}_1 K_p$ $\tau = \left(\frac{0.383}{mS^{1/4}/\theta}\right)^{\frac{4}{4-n}}$ $m = 0.318\theta^{0.204}$ $\theta = \frac{L}{J^{1/3}A^{1/4}}$ $\psi = 1 - \frac{\mu}{S}\tau^n$ $\mu = 3.6K_p A^{-0.19}$ $Q_C = (1 + \varphi)Q_P D_U$	A is the watershed area of the debris flow gully; ψ is the runoff coefficient of the peak flow; S is the rainfall intensity; τ is the runoff confluence time of the rainstorm; and n is the attenuation index of the rainstorm. To calculate the above parameters, rainfall data, including the 1- and 6-hour average rainfall intensities ($\bar{H}_1$ and $\bar{H}_6$) and the corresponding coefficients of variation (C_V and C_S), were obtained from the rainfall contour maps in 'The Rainstorm and Flood Calculation Manual of Medium and Small Basins in Sichuan Province' (Hydrological and Water Resources Survey Bureau of Sichuan Province 2010). K_p is the modulus coefficient for the variation coefficient (C_V) under different return periods, which can be obtained from the Pearson Type III distribution table; m is the runoff confluence parameter; θ is the catchment characteristic parameter; L is the length of the debris flow gully; J is the mean gradient of the debris flow gully bed; and μ is the infiltration intensity (mm/h). D_U is the blockage coefficient in the debris flow gully; Q_C is the peak discharge of debris flow (m^3/s).
Total volume	$W_C = 0.246T_C Q_C$	W_C is the total volume of the debris flow (m^3) and T_C is the total process time of the debris flow (s). As T_C is difficult to monitor, it is treated as an empirical and statistical parameter. In general, when the area of the debris flow gully is $>$25 km^2, T_C is usually $>$1,800 s. When the area of the debris flow gully is $<$25 km^2, T_C is $<$1,800 s according to previous statistical data and a small amount of monitoring data.
Solid volume	$W_S = (\gamma_c - \gamma_w)W_C/(\gamma_s - \gamma_w)$	W_S is the solid volume of the debris flow.

Table 4. Results of debris flow dynamic parameters.

Name of the gully	Density (g/cm^3)	Velocity (m/s)			Debris flow peak discharge in different return periods (m^3/s)			
					100-year	50-year	20-year	10-year
Zengda	1.8	8.1			875	631	451	292
Longgu	1.7	7.4			113	81	58	35
Nijiaping	1.6	6.5			50	35	24	14
Aierluo	1.7	6.9			194	140	101	64
Name of the gully	Total volume in different return periods (10^4 m^3)				Solid volume in different return periods (10^4 m^3)			
	1 %	2 %	5 %	10 %	1 %	2 %	5 %	10 %
Zengda	166.3	60.0	42.8	27.7	78.3	28.2	20.1	13.1
Longgu	8.1	5.8	4.1	2.5	3.3	2.4	1.7	1.1
Nijiaping	2.4	1.6	1.1	0.7	1.0	0.7	0.5	0.3
Aierluo	18.4	13.3	9.6	6.1	7.6	5.5	4.0	2.5

entered the main gully, it mixed with flash floods in the main gully, the speed of the flow continued to increase, and the impact force was strengthened, which resulted in more notable scraping and undercutting of the main gully along its path (Figure 3b). An increasing number of loose solid materials were involved in the debris flow activities and combined with debris flows of different sizes under heavy rainfall in two tributaries (Nijiaping gully and Aierluo gully); the debris flow in the main gully increased in size continuously, finally forming a giant debris flow.

In the process of the debris flow movement, a part of the debris flow fluid accumulation formed due to the low longitudinal gradient upstream from the mouth of Aierluo gully (Figure 3c). The longitudinal length of the accumulation was approximately 500 m, and the volume was approximately 21.0×10^4 m^3. When the debris flow moved down to the #1 blocking dam, it was blocked by the dam and a part of the debris flow fluid again accumulated, causing the back of the dam to fill up completely (Figure 3d). The longitudinal length of this accumulation was approximately 250 m, and the volume was approximately 3.7×10^4 m^3. When the debris flow moved down to the rib bottom groove, it was blocked and a part of the debris flow fluid accumulation formed again (Figure 3e). Here, the longitudinal length was 40 m, and the volume was approximately 0.6×10^4 m^3. Moreover, when the debris flow moved to the mouth of the main gully, it was affected by the low longitudinal gradient of the channel. Most of the debris flow fluid accumulated in the original flood discharge channel near the mouth of the gully and on both sides, and some of the fluid also entered the main river (Figure 3f). Part of the original flood discharge trench at the mouth of the gully was filled with debris flow, as well as part of the debris flow over the protection embankment, which destroyed some buildings and vehicles on both sides. In addition, the siltation length was approximately 1,800 m, and the volume was approximately 88.2×10^4 m^3.

4.2. Real-time evacuation process of the debris flow disaster

The real-time evacuation process of the Zengda gully debris flow disaster is documented in Figure 4. The real-time evacuation process consists of two parts, including

Figure 3. Characteristics of debris flow formation and movement. Source: Author.

the time point of evacuation and the corresponding event and response measures. In order to better analyze the real-time evacuation process of this giant disaster, the real-time evacuation process is displayed in the form of inverted coordinates. The horizontal axis shows the corresponding event and response measures. The vertical axis shows the time node of evacuation. The time of real-time evacuation process began at 17:38 on 27 June and ended at 22:10, including nine critical time nodes. The corresponding event and response measures of real-time evacuation process consist of four parts, including process of debris flow disasters, promulgator, responder and measures and ways of response. Take the 17:39 time node as an example, the Natural Resources Bureau of Jinchuan County immediately released early warning information to those responsible for disaster prevention and monitors of Zengda Township through QQ, WeChat, SMS platform, telephone notification, and other means when the geological disaster warning level was at level 2.

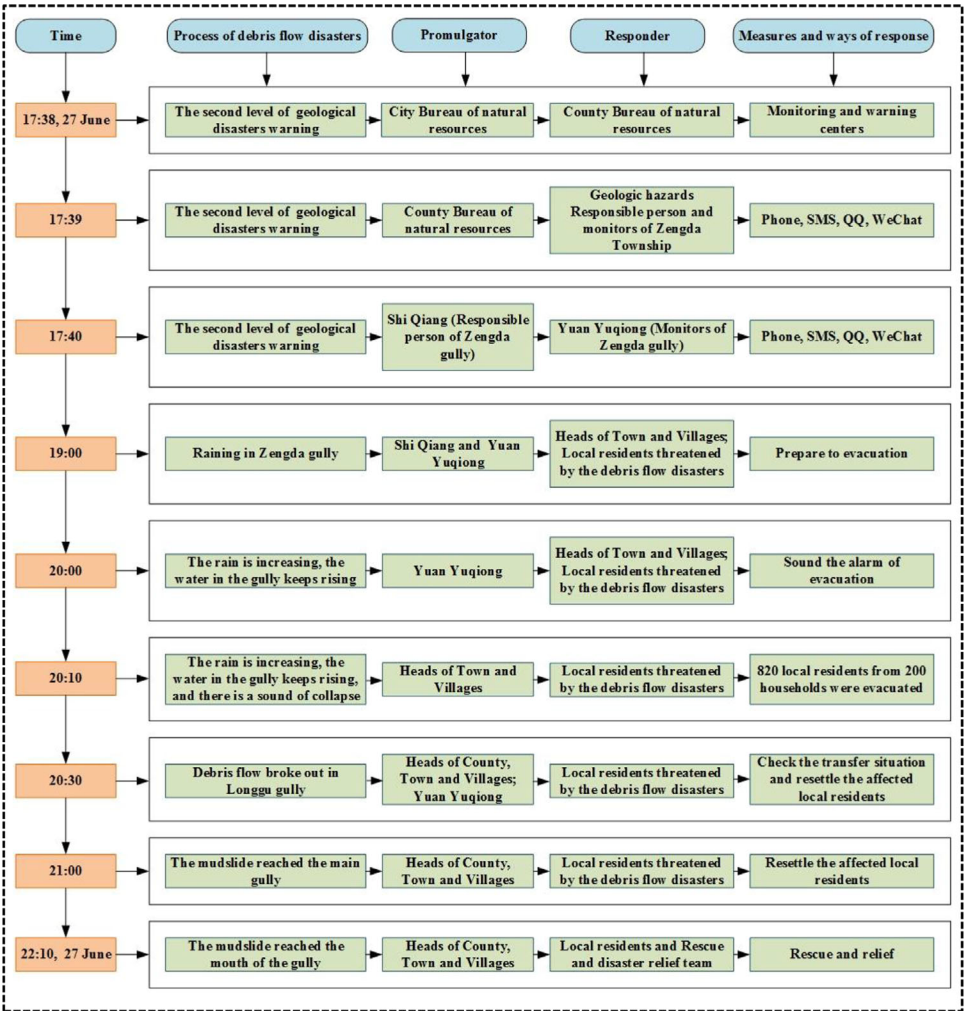

Figure 4. Real-time evacuation process for the Zengda gully debris flow disaster. Source: Author.

5. Lessons learned from the successful real-time evacuation

- The implementation of debris flow control engineering and automatic rainfall stations in Zengda gully laid the foundation for the successful real-time evacuation.
  i. The completed control project has achieved remarkable results for debris flow disasters. In 2015, Zengda town has invested 20.07 million RMB in debris flow control. Three blocking dams and silting yards with a volume of approximately 11.7×10^4 m^3 have successfully blocked debris flows. The ribbed bottom groove, which is 140.8 m in length with a volume of approximately 219.72×10^4 m^3, stabilized the Shujiapo landslide, preventing a larger scale debris flow. In addition, the fending groyne, which is 2,781.5 m in length with a volume of approximately 120×10^4 m^3, has successfully dredged debris

flow. The debris flow control engineering in Zengda gully has played an important role in stabilizing the soil and drainage, effectively dredged and discharged debris flow, slowed down the speed of debris flow outbreaks, curbed the damage of debris flow disasters, and allowed for adequate time to evacuate residents and avoid risks.

ii. The completed automatic rainfall monitoring station has improved the ability of group measurement and prevention. In October 2018, the installation and commission of 23 automatic rainfall stations for geological hazards were completed in Zengda gully. A combination of artificial and intelligent monitoring of geological hazards has been conducted, providing a scientific basis for successful hedging and enriching the group measurement and prevention system.

- The division of responsibility for disaster prevention before a debris flow disaster occurs has been clearly identified. Disaster prevention training and emergency drills focus on effectiveness and the disaster prevention and emergency plan are comprehensive and detailed. These measures provide a reliable guarantee that the disaster can be successfully averted.

  i. The establishment of a comprehensive group measurement and prevention system is a prerequisite for successfully avoiding risk. Before 20 April 2019, Zengda Township improved and signed the disaster prevention target responsibility letter, taking responsibility for compaction level by level. In essence, responsible persons for disaster prevention shall be employed and strictly implement their duties and spot check systems during flood seasons. In addition, the disaster prevention and defense plans and emergency plans of each hidden danger point in Zengda Township were established and perfected. For example, the 'three avoidance' (active avoidance, early avoidance, and preventive avoidance) measures were implemented as rigid requirements for specific actions, and threatened residents are notified in advance to make preparations for active risk aversion and evacuation.

  ii. Reliable and robust front-line monitoring and early warning measures in Zengda gully have played a key role in successfully avoiding risks. In response to the debris flow disaster in Zengda gully, three full-time monitors, including Yuan Yuqiong, are employed for 24-hour monitoring to ensure that the persons responsible for disaster prevention and monitoring and the monitoring personnel maintain smooth communication and consistently perform their duties during the flood season. Especially in the case of extreme weather, it is necessary that the monitoring personnel can consciously carry out patrols of hidden danger points, grasp the development trend of hidden danger points in time, preliminarily judge the disaster risk of hidden danger points for geological disasters, and be familiar with all hidden danger points that threaten each household to ensure that once dangerous situations are identified, the transfer of people can be immediately organized.

  iii. Publicity training and risk avoidance drills are a solid foundation for successful risk avoidance. The technical support unit for geological disaster

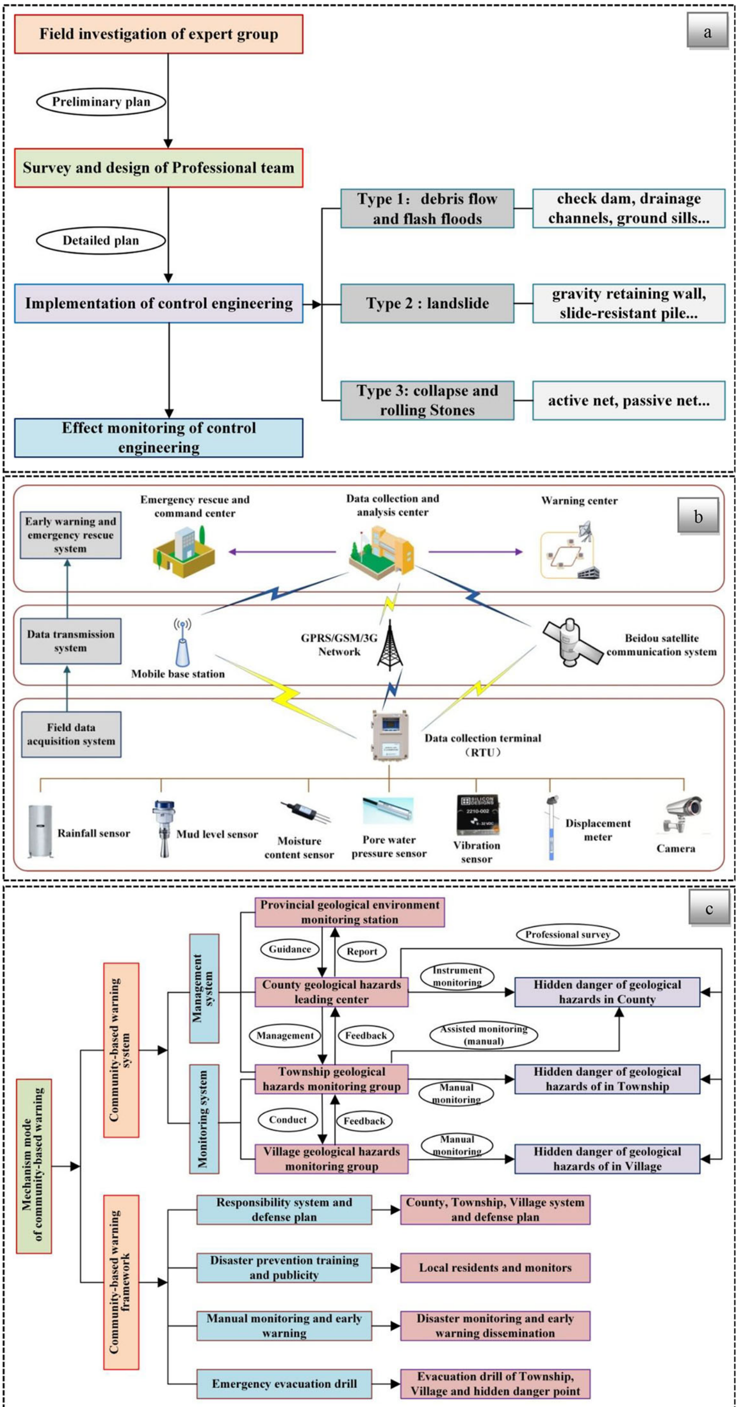

Figure 5. Mode combining a community-based warning system with a technical defense system: (a) control engineering system, (b) monitoring and early warning system, and (c) community-based warning mechanism. Source: Author.

prevention and control carry out geological disaster publicity and training for monitoring personnel and people threatened by disasters every year. Simultaneously, targeted emergency drills have been carried out to ensure that the monitors can master the monitoring methods for geological disasters, preliminarily predict the precursors and report the dangers of geological disasters, orderly guide people during evacuations, and improve their skills in self-rescue and mutual rescue (Figure 5). Notably, owing to the implementation of these measures, without an adult, a 13-year-old student, Wang Dewu, from Nijiaping Village, led his three younger brothers and sisters to a safe place during the initial stage of the disaster.

- During the disaster, the following measures were taken to successfully reduce its impact: conscientious performance of duties by the primary-level monitors, efficient operation of the disaster prevention mechanism, release of comprehensive early warning information, timely reporting of potential dangers, and the safe and orderly evacuation of the masses.
  i. The early warning information for the geological disasters was fully and timely communicated to ensure safe evacuation 'without dead ends'. At 17:38 local time on June 27, the Natural Resources Bureau of Aba Prefecture announced that the geological disaster warning level was at level 2. At 17:39, the Natural Resources Bureau of Jinchuan County immediately released early warning information to those responsible for disaster prevention (Deng Zhigang, Fan Chaoyong, Wen Yu, and Sheng Youqiang, among others), the person responsible for monitoring (Yuan Yuqiong), the management personnel (Shi Qiang), and locals through QQ, WeChat, SMS platform, telephone notification, and other means of communication. In addition, the people who did not respond immediately received a telephone notification to ensure that everyone was aware of the warning and forecast information. Then, Yuan Yuqiong and others immediately notified people threatened by the debris flow in Zengda gully to be vigilant and ask friends and family for help to ensure the implementation of the 'three avoidance' strategy.
  ii. The monitoring personnel conscientiously performed their duties, responded decisively in case of danger, and initiated an evacuation. At 19:00 on June 27, it began to rain in Zengda Valley. At 20:00, Yuan Yuqiong found that the rainfall was continually intensifying and the river in the valley has risen rapidly with the sound of a collapse. She immediately judged that there was a possibility of a landslide and promptly informed the leaders of the village and township. The township government immediately sounded the disaster alarm and organized the village cadres to inform the masses to avoid the danger according to the emergency plan and prescribed route. In the process of the transfer, rural cadres contributed, irrespective of their own safety, and raced against the debris flows to ensure the safety of 200 households and 820 residents. At 20:30 on June 27, a debris flow broke out at Longgu gully in Nijiaping village, which reached the main gully at 21:00 and the mouth of the gully at 22:10.

6. Mode combining a community-based warning system with a technical defense system

Based on this successful real-time evacuation, a response mode for a geological hazard defense system is proposed, i.e. a mode combining a community-based warning system with a technical defense system (Figure 5). This mode is unique in China and consists of three parts: a control engineering system (Figure 5a), a monitoring and early warning system (Figure 5b), and a community-based warning mechanism (Figure 5c). The first and second parts constitute the technical defense system. This mode is a comprehensive and effective geological hazard prevention mode that is government-led, implemented by local residents, and incorporates the participation of experts. These monitors are critical in this mode that they need to collect and analyze information that enable warning messages to help a community to react to a hazard and reduce the resulting loss or harm. In this case, monitoring personnel need to continuously carry out geological disaster knowledge and skills training. This requires a lot of materials and financial resources, but it is very difficult for the poor and disaster-prone mountainous areas, which is the current limitation of this mode.

7. Conclusions

The characteristics, formation, and movement process of the Zengda gully giant debris flow have been presented based on data analysis and field investigation. Successful measures of the real-time evacuation were summarized and discussed, and a mode combining a community-based warning system with a technical defense system was proposed on the basis of the real-time evacuation of the Zengda gully giant debris flow disaster. Some conclusions can be drawn as follows.

1. There are a total of 16 large branches in the Zengda gully, and there have been five mountain torrents and debris flow disasters in Zengda gully since the 1990s. The debris flow was viscous, and debris flow velocities ranged from 6.5 to 8.1 m/s. The maximum debris flow peak discharge is 875 m^3/s with a 100-year recurrence period.
2. The first debris flow broke out in the tributary, i.e. Longgu gully, at 20:30 after more than three hours of heavy rainfall on June 27. Then, it quickly flowed into the main gully along Longgu gully with notable scraping and undercutting of the main gully. Finally, an increasing amount of loose solid materials were involved in the debris flow activities, which combined with the debris flows of different sizes under heavy rainfall in two tributaries allowing the size of the debris flow in the main gully to continuously increase and finally form the giant debris flow.
3. Some lessons from the successful real-time evacuation can be summarized and shared. First, the implementation of the debris flow control engineering and automatic rainfall stations in Zengda gully laid the foundation for the successful real-time evacuation. Second, the division of responsibility for disaster prevention before a debris flow disaster occurs are clear, and the disaster prevention training and emergency drills are fruitful. Finally, the timely release of early warning

information and orderly rapid evacuation of the masses was the key that yielded successful disaster avoidance in this event.

4. A mode of community-based warning, known as government-led mass execution and expert participation, was proposed in this study on the basis of the Zengda gully giant debris flow disaster real-time evacuation. The mode consists of three parts, including a control engineering system, monitoring and early warning system, and community-based warning mechanism.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Data availability statement

The data that support the findings of this study are available from the first author, Guisheng Hu, upon reasonable request.

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