

# Characteristics, Impacts and Risks of Dammed Lakes Induced by Debris Flows at the Wenchuan Earthquake Areas

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## Abstract

After the Wenchuan Earthquake, many large-scale debris flows blocked rivers, generated dammed lakes, and produced outburst flood at the seriously hit areas. This paper mainly discussed the formation, outburst, impacts and risks of debris flow dammed lakes. The field investigation showed that the dammed lakes were created by debris flows from gullies and hill-slopes as well as the combination of debris flow and landslides, and also distributed along rivers step-by-step. The height of dams and the length of dammed lakes along river channel varied from 4 m to 18 m and from 400 m to 5000 m, respectively, and the reservoir capacity of dammed lakes were from  $1.5 \times 10^5 \text{ m}^3$  to  $3 \times 10^6 \text{ m}^3$ . Due to geomorphological impact, dammed lakes commonly partially outburst along their front of debris flow deposition dams (1/4 - 1/3 outburst) or the suture between debris flow and landslide, and hardly completely outburst. Moreover, the subsequent debris flows continuously increased the magnitude and height of dams, not only increasing the stability of a single dam, but also improving the risks of outburst flood induced by intensive rainstorm. Dammed lakes produced steep rage in the sites of dams with the 4% - 9% of slope and rapidly raised river channel in the upstream due to a mass of alluvial sediment. As a result, the landscapes of step-dams and step-lakes dominate driver channels, significantly increasing the hazards of floods. Then the hazards, impacts and risk of debris flow dammed lakes along Min River from Dujiangyan to Wenchuan were analyzed. In order to mitigate dammed lakes induced by debris flows, the identification model of debris flow blocking rivers, the process of the formation, outburst and evolvement of

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dammed lakes, and the model of risk assessment for step-dammed lakes were strongly suggested to explore, and be used at the rivers of Min, Yuzi, Caopo, Longxi, Mianyuan, Jian, Shiting, Baishui and Jushui.

## Keywords

**Dammed Lakes, Debris Flows, Outburst, Impacts, Risks**

## 1. Introduction

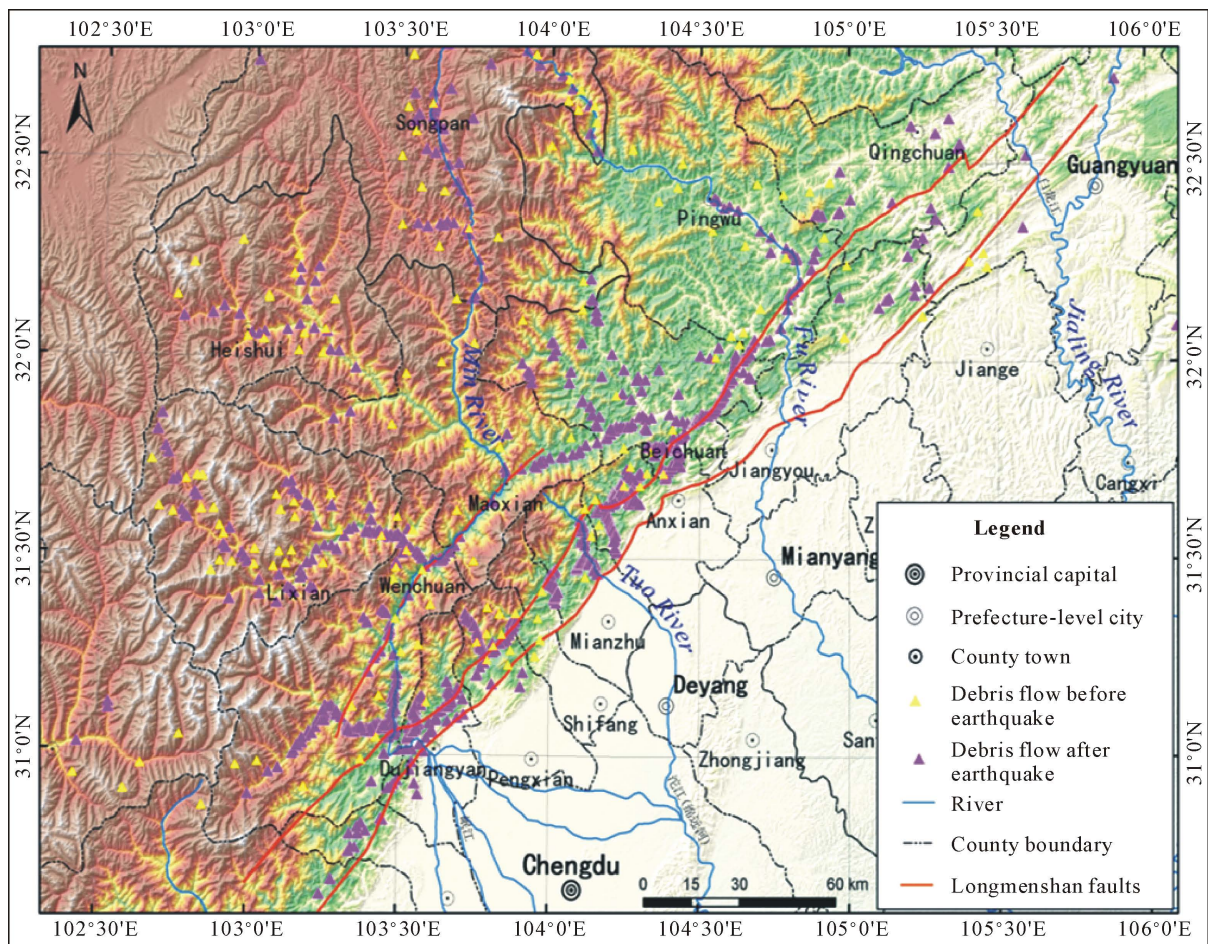
Dammed lakes are generally generated by landslides from torrential rains, earthquakes, lavas from volcanic eruptions, or ice-jams and moraines from glacier [1], and have been concerned and deeply researched to explore the mechanism of dammed lake formation, assess and predict risk, and find the technical measures for mitigating [2]-[11]. The intensive earthquakes at mountain areas generally result in a large number of geo-hazards, including landslides, rock falls, debris avalanches and debris flows, which also block rivers and create dammed lakes so as to endanger mountain environment and local inhabitants' security. The dammed lakes of Mogangling at the Dadu River and Diexi along Min River were triggered by 1786 Kangding-Luding earthquake with MS 7.75 and 1933 Diexi earthquake with MS 7.5 respectively, and attracted many researchers to discovery their mechanism [12]-[14]. The Wenchuan Earthquake in May 12, 2008, with MS 8.0, produced 40,000 - 50,000 landslides, rock falls and debris avalanches [15]-[17], which blocked river and formed 257 dammed lakes. 34 big dammed lakes were prone to outburst and endangered several million local residents' security, rescue and reconstruction [18]. In the beginning 1 month after the major shake, a lot of efforts concentrated on the treatment and mitigation of dammed lakes, especially notably the treatment of Tangjiashan Dammed Lake [2] [19]. Since then, debris flows have become the dominant geo-hazards due to a mass of loose solid materials in gullies and slopes, steep geomorphology and abundant precipitation. In the past 5 years, debris flows have occurred at over 1000 gullies or watersheds in the seriously hit areas [15], moreover, and were characterized by high-velocity, large-discharge, lager magnitude and higher frequency [20] [21]. Debris flows not only directly destroyed local environments and endanger reconstruction, but also blocked rivers, formed dammed lakes, threatened the securities of its upstream and downstream, and posed more serious hazards. This paper concentrated on formation, outburst, impacts and risks of debris flow dammed lakes to give valuable measures for mitigating.

## 2. Formation of Dammed Lakes

Investigation showed that dammed lakes are generally produced by gully debris flow, hill-slope debris flow and landslides at the seriously hit valleys after the Wenchuan Earthquake.

### 2.1. Gully Debris Flows

Since 2008, debris flows have occurred at over 1000 gullies (watersheds), whose dominating areas were less than 5 km<sup>2</sup> (Figure 1), and become the most serious geo-hazards at Wenchuan Earthquake areas [15] [16]. Comparing to the debris flows before the Wenchuan Earthquake, the peak discharge and magnitude of debris flows increased 50% and 100% at least, respectively, due to abundant loose sediment accumulation induced by the deposits of landslides, rock falls and debris avalanches [20] [21]. High-velocity and large discharge debris flow generally delivers a mass of solid materials into mainstream instantaneously, blocks river, produces dammed lakes and outburst flood. As a result, debris flow dammed lakes often occupied in river channels where the large-scale debris flows easily occurred, for example at the rivers of Min, Mianyuan, Yazi, Jian, Jushui and Shiting. At the Wenchuan Earthquake areas, the notable dammed lakes are located at the outlets of the gullies of Mozi, Guanshan, Gaojia, Luoquanwan, Huaxi, Qipan and Hongchunalong Min River, the gullies of Xiaojia, Huangyao, Dayin and Xiezi Gully along Yuzixi River, the gullies of Wenjia, Hui, Hsaoyao and Nanmualong Mianyuan River, the gullies of Shuangyanwo and Xiangshuidong along Yazi River, and the gullies of Sancha and Shuimo along Jushui River.



**Figure 1.** Debris flow gullies distribution at the Wenchuan Earthquake areas.

## 2.2. Hill-Slope Debris Flow

Hill-slope debris flows generally occur at the slopes with over 40% of slope gradient and abundant solid materials accumulation. After the Wenchuan Earthquakes, the deposits of debris avalanches and landslides provided a mass of loose solid materials and accumulated in steep slopes with 50% - 80% slope gradient. Moreover, the height of slope accumulation ranges from 100 - 200 m, which prepare adequate dynamic energy for debris flow formation. When intensive rainfall or rainstorm occurs, loose sediments are easily initiated and formed into debris flow and rapidly discharges into river, blocks it and produces dammed lakes. The dammed lakes induced by hill-slope debris flows appeared along the Rivers of Min, Jian, Yuzi and Mianyuan (**Figure 2** and **Figure 3**).

## 2.3. Debris Flow and Landslides

Some dammed lakes were also generated by the combination of debris flow and landslides. The debris flow and landslide, located at the same section but the different bank, block river partly, respectively, so that the river is blocked completely and the dammed lake was formed, for example the Xiaogangjian dammed lake at Mianyuan River (**Figure 4(a)**). Meanwhile, the nearing debris flow deposit and landslide body at the same bank also can jointly block river and create dammed-lake. The landslide body occupies the partial space of the outlet of debris flow gully and increase the height and magnitude of debris flow deposition dam, moreover, the volume and stability of the whole dam is strengthened (**Figure 4(b)**). As a result, the dammed lake is strengthened and very difficult to outburst completely. These kind of dammed lakes majorly appear in the river section where landslides, rock falls and debris flow gullies densely distribute, for example the sections of from Yinxiu to Gengdaalong Yuzixi River and the Mianyuan River.

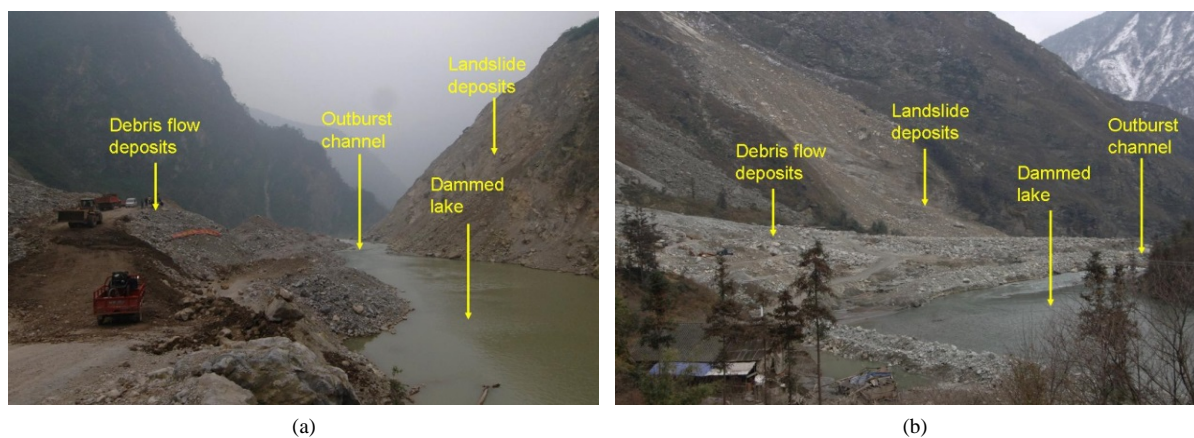




**Figure 2.** Dammed lakes formed by gully debris flow at Min River.



**Figure 3.** Dammed lakes formed by hill-slope debris flow at Min River.



**Figure 4.** Dammed-lake formed by debris flow and landslide ((a) at Mianyuan River; (b) at Yuzi River).

### 3. Characteristics of Dammed Lakes

The dammed lakes induced by debris flows are different to those by landslides, rock falls, glaciers and volcanos and these in Wenchuan Earthquake areas are characterized by their own.

#### 3.1. Distribution

The distribution of debris flow dammed lakes depends on the distribution of large-scale debris flows. After the Wenchuan Earthquake, abundant loose solid materials resulted in the remarkable decrease of debris flow initiation rainfall intensity and the significant rise of discharges and magnitude of debris flow. The antecedent accumulated precipitation and 1 hourly rainfall of initiating debris flow decreased 14.8% - 22.1% and 25.4% - 31.6%, respectively [22]. Local intensive rainfall or rainstorm often triggers multitudinous debris flows in special areas. For example, 72 debris flows occurred on Sept. 24, 2008 in Beichuan county, hundreds of debris flows took place along Min River, Yuzi River, Longchi River and Mianyu River in August, 2010, over 1000 debris flows occurred in the whole Wenchuan Earthquake areas. Many large debris flows blocked river and produced dammed lakes. As a result, most debris flow dammed lakes distributed step-by-step along rivers. For example, 14 dammed lakes in Min River, 13 at Yuzi River, 12 at Mianyu River and 8 at Yazi River Upper in 2010 and 25 along Min River in 2013.

#### 3.2. Geomorphology

The geomorphologic characteristics of debris flow dammed lakes are also very different to those caused by landslides, rock fall, glacial avalanche and volcanos. The related indexes of 17 debris flow dammed lakes at the Wenchuan Earthquake areas are showed in **Table 1**.

**Table 1** expressed that the height of debris flow dam varied from 4 - 30 m, much lower than those of landslide dams. The axes slope gradient of debris flow deposition dam range from 30‰ to 450‰ and the dominating are over 200‰. The shape, height and volume of debris flow dam were in diversity which depend on the dynamic parameters of debris flow, the geomorphology of the outlet of debris flow gullies and river channel and the sediment that was delivered into river. The slope of outburst channel was from 20‰ to 90‰, and the majority were over 40‰ and much higher than those of mountainous river (5‰ - 10‰). According to the height of debris flow dam and river channel slope as well as investigation data, the back water of debris flow dammed lakes generally extended 400 - 5000 m along river upstream and even longer and the reservoir volume of a debris flow dammed lake ranged from 0.15 -  $6.0 \times 10^6 \text{ m}^3$ . Therefore, debris flow dammed lakes generally generate the landscape of continuous step dams and deep lakes.

#### 3.3. Size Components and Stability of Dams

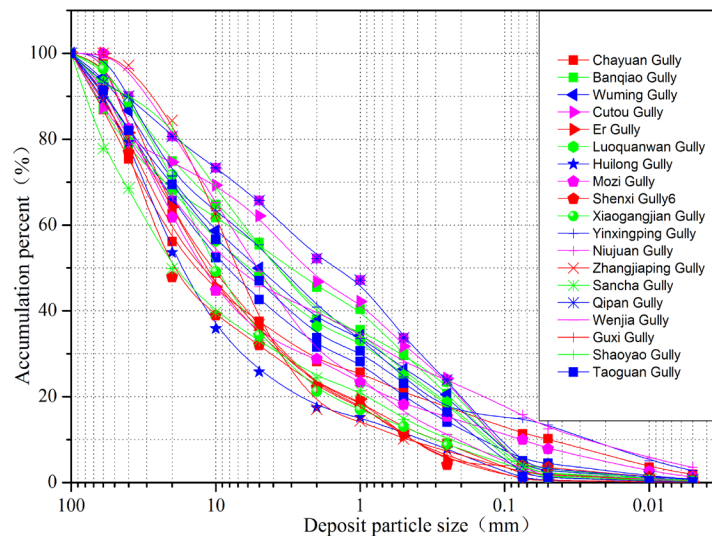
Debris flow deposits, whose sizes of solid grains range from  $\mu\text{m}$  to 10 m, are the dominating of the dams. The investigation showed the materials with bigger than 100 mm and 1000 mm occupy 48% - 56% and 4% - 9%, respectively. The test data of debris flow deposition dam samples ( $<100 \text{ mm}$ ) showed in **Figure 5**, and indicated great particle variation of debris flow deposits due to different material sources and their lithology. The  $D_{50}$  of debris flow deposits ranged from 2.1 mm - 21.5 mm. According to the calculation formula for debris flow density which was established by Yu [23], the density of debris flow deposits were from  $1.88 \text{ g/cm}^3$  to  $2.17 \text{ g/cm}^3$ , and those with over  $2.0 \text{ g/cm}^3$  and more than  $1.95 \text{ g/cm}^3$  occupied 77.7% and 90%, respectively. The high-density debris flow formed dams, which is difficult to completely outburst although their height are generally less than 20 m because that the deposition dam (soil) are complete saturated and no pores, with high viscosity and river flow are not enough to initiate and make debris flow dam failure to outburst. Moreover, after the Wenchuan Earthquake, landslides, rock fall, and debris avalanches provided abundant loose solid materials and the percentage of gravels and stones ( $>1000 \text{ mm}$ ) in debris flow deposits were higher than before the Earthquake. Those stones bigger 1000 mm of some debris flow deposition dam were about 5%, which also improve the stability of the dam. Therefore, debris flow dammed lakes were difficult to outburst completely even though the dam were absolutely overflowed.

#### 3.4. Outburst

Debris flow dammed lakes generally outburst partly by virtue of their shape and geomorphology. After debris

**Table 1.** Geomorphology and features of debris flow dammed lakes in Wenchuan Earthquake area.

Gully name	Mainstream	Dam structure				Outburst	Outburst channel slope (%)	Hazards
		Long (m)	Wide (m)	High (m)	Slope (%)			
Wumin	Yuzixi River	78	90	4 - 5	190	Overflow and outburst partly	60	Low
Yinchang	Yuzixi River	80	337	6 - 14	230	Overflow and outburst partly	45	Low
Xiezi	Yuzixi River	222	321	12 - 14	450	Overflow and outburst partly	70	Low
Xiaojia	Yuzixi River	340	191	15	250 - 270	Overflow and outburst partly	80	Low
Wasi	Yuzixi River	110	300	8 - 10	231	Overflow and outburst partly	40	Low
Xiangshuidong	Baishui River	90	150	12 - 13	140	Overflow and outburst partly	90	Low
Huilong	Baishui River	101	150	15	221	Overflow and outburst partly	40	Low
Gaojia	Min River	230	230	15	200	Overflow and outburst partly	90	Low
Yinxingping	Min River	230	400	15	200	Overflow and outburst partly	40	Low
Mozi-1	Min River	219	189	10	159	Overflow and outburst partly	20	Low
Guanshan Gully	Min River	80	150	5 - 6	280	Overflow and outburst partly	40	Low
Dahuodi-1	Mian yuan River	140	260	10	260	Overflow and outburst partly	40	Low
Dahuodi-2	Mian yuan River	160	400	15	260	Overflow and outburst partly	40	Low
Sanyanyu	Bailong River	80 - 120	500	9 - 10	30 - 50	Overflow and outburst partly	20	Very high
Xiangshui Gully	Dadu River	350	400	9 - 10	100	Overflow and outburst partly	25	Middle
Wada Gully	Fu River	167	150	7 - 8	120	Overflow and outburst partly	50 - 60	High
Hongchun	Min River	470	350	9 - 10	200	Overflow and outburst partly	30	Vey High
Huaxi	Min River	350	370	9 - 10	70 - 90	Overflow and outburst partly	25 - 30	Very high
Qipan	Min River	150	300	12 - 15	30 - 50	Overflow and outburst partly	30 - 35	High
Shaoyao	Mian yuan	130	220	8 - 10	150	Overflow and outburst partly	30 - 35	Middle
Wenjia	Mian yuan	420	1650	12	80 - 100	Overflow and outburst partly	15 - 20	Very high
Sanjia	Chaping	360	360	8 - 10	170	Overflow and outburst partly	25 - 30	Low
Hongshui	Caopo	180	340	8 - 10	90	Overflow and outburst partly	40	Middle
Xiangshuidong	Yazi	150	300	15 - 20	140	Overflow and outburst partly	50	High



**Figure 5.** Particle size curve of debris flow dam at the Wenchuan Earthquake areas.

flow blocks river, the water level of dammed lakes rise rapidly, and then overflow and outburst at the lowest of debris flow dam, where are the conjunction section between debris flow deposits and the opposite bank (debris flow deposition dam front). Moreover, most debris flow dammed lakes could not outburst completely, only 1/4 or 1/3 debris flow deposits were intensively eroded, deep-cut and transported to the downstream due to the impacts of lower dam height, dam structure, local geomorphology and the lower reservoir capacity of dammed lakes. The debris flow deposits composed by solid and water were only transported in very short distance but not in long distance by mainstream so that debris flow dammed lakes were very difficult to treat quickly and safely, which generally endangered the security of dam upstream. For example, the dammed-lake induced by the debris flow of Sanyanyu Gully along the Bailong River, Zhouqu, Gansu province, occurred in Aug. 8, 2010, were disposed successfully and safely by the hard efforts of the departments of hydrology and hazards over 20 days although it was only about 10 m high. During this process, the scheme and methodology were altered and optimized.

### 3.5. Change

After the Wenchuan Earthquake, high-frequent debris flow induced by abundant loose solid materials resulted in the unique of debris flow dam change. Without the disturbance and treatment of the humans, debris flow continuously deposit and bury the previous debris flow deposits so that debris flow dams are strengthened in the height, volume and magnitude and become more stable. As a result, the outburst risk of a single dammed lake significantly reduces. Debris flows even occur over 10 times in one year at a few watersheds or gullies. For example, the frequent debris flows of Mozi Gully, at the right bank of Min River, continuously enlarge the dam by the velocity of 1 - 2 m/a. the dam become more stable and the water level and submerged areas of the dammed lake gradually increase. As a result, Yiwanshui village were deeply submerged. The similar phenomena also appeared at the Gullies of Guanshan, Xiaojia, Xiangshuidong, Niumian, Shaoyao, Hui, Wenjia Gully, Yeniu, Sancha and Xiezi.

## 4. Impacts of Dammed Lakes

The debris flow dammed lakes change and rebuild local environments including mountainous relief, river channels and sediment transportation.

### 4.1. Mountainous Environment

Frequent and large-scale debris flows remarkably change mountainous environment after the Wenchuan Earthquake. Debris flows transport quantity of solid materials and result in extreme soil erosion and vegetation de-



stroy. Investigation data showed bare land rise from 27% to 33% due to debris flows. Then, debris flow deposits at the channel and the outlet intensively and rapidly change local geomorphology, leading to river channel narrowing, sediment deposition, and vegetation destruction. The water level of dammed lake varies from 4 m to 18 m at the range of 400 m - 5000 m, and it also further improve when debris flow dam was strengthened by next debris flows. The nearing step-dammed lakes even probably link each other, and change river into quiet lakes (sequential dammed lakes). For example, the section of Min River mainstream from Yinxiu to Luoquanwan after debris flow on August 13, 2010 and from Yingxiu to Wenchuan (55 km) after July 10, 2013.

## 4.2. River Channel Change

Frequent debris flows and dammed lakes lead to rapid change of river channel. Debris flow deposition dam firstly narrow river channel and rise river bed at the debris flow deposition areas. The investigation data showed the width of river channel generally equals to 1/3 or 1/4 of that before the Earthquake at the outlet section of debris flow gullies, for example, at the Rivers of Min, Mianyu and Yuzi. Moreover, river channels rise from 8 to 20 m and even higher by virtue of the activity of a few large-scale debris flows. The whole river channel of debris flow deposition dam upstream (400 m - 5000 m length) also rapidly rise due to the deposition of a mass of sediment from upstream, meanwhile, they become wide. Furthermore, step-dams induced by debris flow also result in river channel curling and produce the landscape of steep ladders and deep lakes, producing abrupt change of river evolvement.

## 4.3. Sediment Transportation

Debris flow dammed lakes significantly change natural sediment delivery of rivers. Most coarse sediment including sands, pebbles, gravels and boulders and even silts generally deposit in lake bottom and continuously rise river bed and widen river channel, except for the outlet and the channel of dammed lake outburst, where coarse sediment and even river bed were eroded and transported into the lower. After flood, the suspended sediment are deposited in the upper of coarse sediment layer. Step dammed lakes generally block and store the dominant sediment in dammed lakes so that only a few suspended sediment were delivered into the lower. Intensive sediment deposition result in the rapid rise of river channel and wider river channel. For example, the water of Mianyu River increases continuously after the Wenchuan Earthquake and endangers the highway reconstruction from Mianzhu to Mao County (the section from Hanmang town to Qingping town) (**Figure 6**). Researches showed only 10% sediment was delivered from this tributary into the superior tributary or mainstream, which explain the phenomena of non-rise of sediment in Min River and Jianglin River after the Wenchuan Earthquake.



**Figure 6.** Dammed lakes preventing highway reconstruction at Mianyu River.



## 5. Hazards of Dammed Lakes

Dammed lakes, as a following hazard of debris flow, generally further deteriorate hazards and loss of debris flows, for example, destroy land and farmland, interrupt mountainous traffic, endanger villages and towns as well as destruct reconstruction.

### 5.1. Land and Farmland Destruction

Debris flow and the following dammed lakes exasperate the destruction of land and farmland, endangering the living of local peasants and destroying mountainous eco-environment. Step dammed lakes made more land and farmland along rivers and in the first terrain destructed and submerged. Investigation showed that the almost all farmlands in the drainage channel and the outlets of debris flow gullies were destructed due to debris flow bury, and dammed lakes submerged most farmlands at the Yuzi River from Yinxiu to Qicenglou Gully, at the Min River from Yinxiu to Wenchuan, at Mianyuan River from Hanwang to Qingping, at Baishui River from Longmenshan town to Dalong lake as well as at Huilong Watershed and Subaohe Watershed. Moreover, forest and shrub are destructed extensively and land degradation increase remarkably after this Earthquake, especially at drought valleys.

### 5.2. Mountainous Highway

Debris flow and the following geo-hazards imposed large hazards on mountainous traffic by destroying bridge, burying highway, scouring roadbed and submerging bridges. The highways, including from Yinxiu to Wenchuan, from Yinxiu to Gengda, from Qingping to Hanwang, from Leigu to Yuli, from Jushui to Gaochuan, are blocked and interrupted several times every year. Moreover, dammed lakes and the following outburst flood further deteriorate highway destruction. The water level of a dammed lake rapidly rises and easily submerges the highway in the upstream and interrupts local traffic. When dammed lake outburst, the torrent flood can intensively scour and erode the roadbed near the front of debris flow deposition dam and even make the roadbed completely collapse. For example, the road base from Dujiangyan to Wenchuan highway at the outlet of Luoquanwan gully an Qipan gully were ruined 500 m and 400 m, respectively, which were produced by the outburst flood of dammed-lake by debris flow of Gaojia Gully and Qipan Gully ([Figure 7](#) and [Figure 8](#)). Once regional intensive rainfall or rainstorm occurring, multitudinous debris flows and dammed lakes generally destroy highway at many sites and interrupt traffic by different means. For example, the debris flows and the following dammed lakes, occurred on Aug. 13 and 14, 2010 and July 10, 2013, interrupted the traffic from Yinxiu to Gengda and from Hanwang to Qingping.

### 5.3. Mountainous Inhabitants and Reconstructions

Debris flow and the following hazards has become the dominating threatens to mountainous inhabitants and



**Figure 7.** Outburst flood of dammed lake induced by Gaojia Gully destructed Dujiangyan-Wenchuan High-way at the outlet of Luoquanwan Gully.



**Figure 8.** Outburst flood of dammed lake induced by Qipan Gully destroyed Dujiangyan-Wenchuan Highway at the outlet.

reconstruction. Many peasants and reconstruction projects had better face the great hazards of debris flow and the following dammed lakes, which produced increasing risk. The dammed lake induced by the debris flow of Mozi Gully submerged Yiwanshui village of Yinxing town in 2008, and that induced by Xiaojia Gully and Xiezi Gully destroyed the reconstructing projects for tourism in 2010, including the Nanhua Tunnel of Yingxiu to Gengda. The dammed lakes, induced numerous debris flows occurred in Aug. 14, 2010, and their outburst flood submerged, buried and destructed the reconstructing projects and seriously endangered inhabitants of Qingping town. The outburst flood of the dammed lake induced by the debris flow of Hongchun Gully carried quantity of solid materials and washed out the reconstruction of Yinxu Town. Flood and debris flow submerged the first floor and endanger the security of most areas of Yinxu town and over 8000 persons were displaced to other safe places. Additionally, the debris flows and the following dammed lakes on July 10, 2013, destructed villages, towns and factories in the Mountainous areas of the counties of Wenchuan, Dujiangyan, Pengzhou, Shifang, Mianzhu, An, Beichuan, Mao and Pingwu.

## 6. Risks of Dammed Lakes along Min River

The section of Yingxiu to Wenchuan along Min River, a region that suffered intensive disturbance of the Wenchuan Earthquake and many geo-hazards, is always seriously damaged since 2008.

### 6.1. Identification of Debris Flow Blocking River

Almost all non-debris flow gullies changed into debris flow gullies after the Wenchuan Earthquake and over 50 debris flow gullies distributed along Min River from Yingxiu to Wenchuan. Whether debris flow could block river and produce dammed lake depend on the magnitude and peak discharge of debris flow and the flux of the mainstream. Comparing to the current identification formulae of debris flow blocking river, that formed by He [24] was used to assessed the probability of dammed lake forming. It was established by analyzing the data of debris flow blocking river from Jiangjia Gully and stimulation experiment, and as following:

$$C_F = \ln(Q_M/Q_P) - 0.883(1 - \cos\theta)^2 - 2.587\gamma < -8.572 \quad (1)$$

where,  $C_F$  indicates the comprehensive index of debris flow blocking river,  $Q_M$  is the unit peak discharge of the main river ( $\text{m}^3/\text{s}\cdot\text{m}$ ),  $Q_P$  is the maximum unit discharge of debris flow ( $\text{m}^3/\text{s}\cdot\text{m}$ ),  $\theta$  is the junction angle of channels between debris flow gully and main river, and  $\gamma$  is the mass density ratio of debris flow to the main river. In order to reflect the discrimination degree of river blocking, this equation is revised into Formula (2):

$$K = \left| \frac{\ln(Q_M/Q_P) - 0.883(1 - \cos\theta)^2 - 2.587\gamma}{-8.572} \right| \quad (2)$$

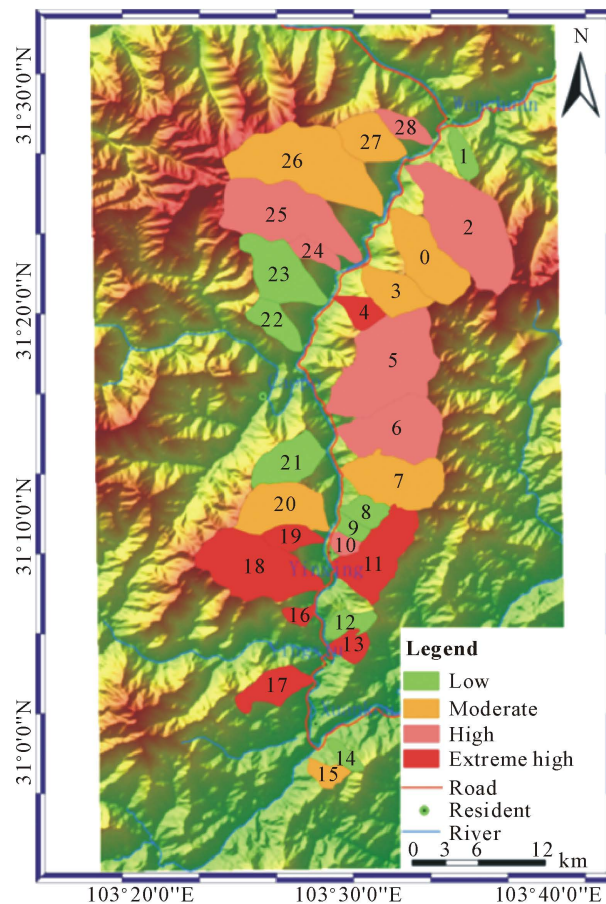
where,  $K$  is the probability degree of a debris flow block river. The larger the value of  $K$  is, the higher the possi-

bility of debris flow blocking will be. When the value of  $K$  is over 1 or close to 1, debris flow is likely to completely block river.

After the Wenchuan Earthquake, the magnitude and peak discharge of debris flow rise remarkably than before. The peak discharge of over 50 years of Min River ( $2237.74 \text{ m}^3/\text{s}$ ) and the peak discharge of debris flow triggered by the rains intensity of less 5% probability were used to discriminate the potential debris flow gullies that could block river from 29 gullies along Min River from Yinxiu to Wenchuan. The result showed in **Figure 9**. Debris flows from the gullies of Er, Guanshan, Mozi, Niujuan, Hongchun, Taiping and Gaodianzi were very easily to block Min River, and from the gullies of Yiwanshui, Taoguan, Futangba, Qipan, Guozhupu, Manianping and Sucun are also easily.

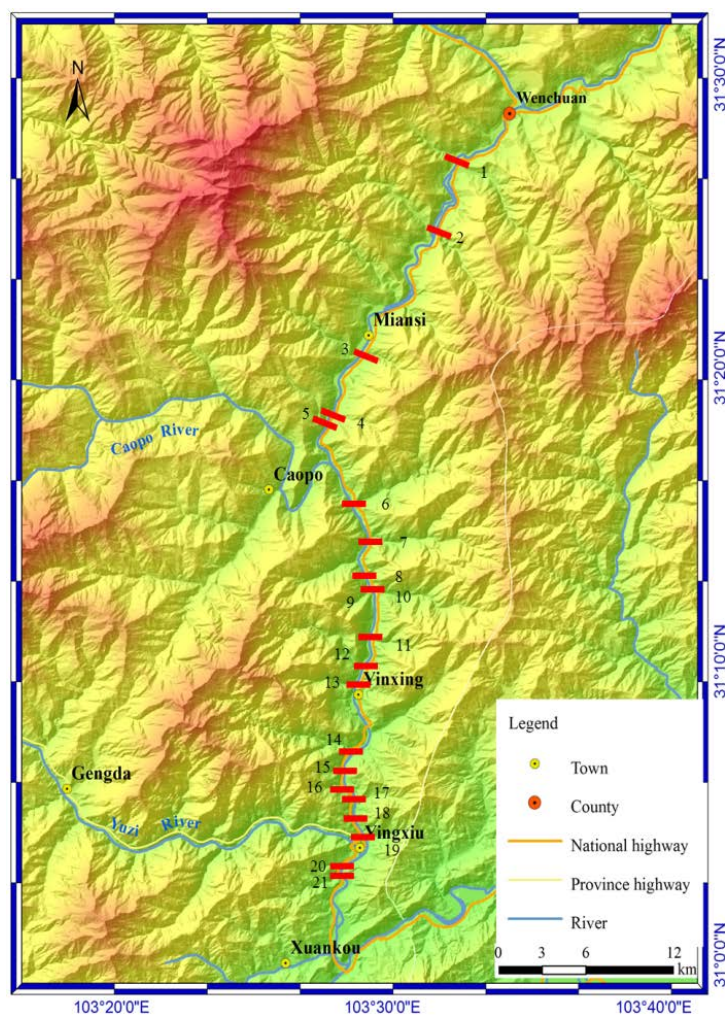
## 6.2. Distribution of Dammed Lakes

After the Wenchuan Earthquake, debris flows frequently and extensively occur along the Min River from Yinxiu to Chediguan. In the past over 5 years and 6 rain seasons, 25 debris flow dammed lakes ever were or are being kept in Min River, which were formed by debris flows from hill-slopes and gullies. The distribution of dammed lakes showed in **Figure 10**.



**Figure 9.** Probability evaluation of debris flow block river along Min River from Yinxiu to Wenchuan (Gully name: 0: Banqiao; 1: Cili; 2: Qipan; 3: Daxi; 4: Gaodianzi; 5: Taoguan; 6: Futangba; 7: Luoquanwan; 8: Yinxingping; 9: Maojiawan; 10: Yiwanshui; 11: Taipingyi; 12: Shaofang; 13: Hongchun; 14: Fengdan; 15: Qianjin; 16: Guanshan; 17: Niujuan; 18: Er; 19: Mozi; 20: Yeniu; 21: Chediguan; 22: Huaxi; 23: Cutou; 24: Sucun; 25: Manianping; 26: Banzi; 27: Xinqiao; 28: Guozhupu).





**Figure 10.** Dammed lakes distribution along Min River from Yinxiu to Chediguan (Gully name: 1: Qipan; 2: Banqiao; 3: Cutou; 4: Gaodianzi; 5: Huaxi; 6: Taoguan; 7: Futangba; 8: Wuming; 9: Gaojia; 10: Luoquanwan; 11: Yingxingping; 12: Yeniu; 13: Mozi-1; 14: Er; 15: Guanshan; 16: Mozi-2; 17: Mozi-3; 18: Shaofang; 19: Hongchun; 20: Zhangjiaping; 21: Niujuan).

Comparing the result of identification model, it was found that the gullies of Niujuan, Hongchun, Er, Guanshan, Mozi-1, Taipingyi, Guanshan, Gaodianzi, Qipan and were discriminated. However, the gullies of Gaojia, Shaofang, Yingxingping, Xiaojia, Mozi, Cutou, Huaxi, Luoquanwan, Banqiao, Zhangjiaping, Yeniu and other gullies were not confirmed. Moreover, some debris flows from hill-slopes were also not discriminated. Especially, the catastrophic numerous debris flows on July 10, 2013 that were triggered intense rainstorm and blocked Min River did not be identified. Therefore, this identification model could evaluate the phenomena of debris flow block river but not precisely. It is required to optimize and revise based on the deep learning on dynamic mechanism of debris flow blocking river to discover the actual process and mechanism.

### 6.3. Impacts and Risk

#### 6.3.1. Environmental Impacts

Step dammed lakes of debris flow produce significant environmental impacts. They occupied and narrowed channel of Min River due to the deposit fan of debris flow, and also curve river channel. Moreover, the landscape of Min River from Yinxiu to Wenchuan changed from the narrow channel into step dams and the torrent



flow also changed into quiet lakes. As a result, the flow velocity and the capability of sediment transportation of Min River decrease remarkably and the most sediment was deposited in the lakes, resulting in the continuous rise of river channel and the wider channel. The vertical profile of Min River channel has changed from curve line into step folds line in this section due to debris flow deposition dams. Step dammed lakes also increase the water areas of Min River, which conduce to improve the humidity of local climate and ecology recovery.

### 6.3.2. Risk and Losses

Step dammed lakes induced by debris flow take huge risk and loss to local inhabitants, reconstruction and the traffic. Dammed lakes almost submerged all farmland along the channel of Min River and debris flows also burry farmlands at gullies. Moreover, steep slope farmland had been reclaimed into forest before the Wenchuan Earthquake. Nowadays, farmland shortage seriously is endangering the living of the peasants that lived at the areas from Yinxiu town to Wenchuan. Outburst flood, especially from step dammed lakes, have become great threaten to inhabitants, for example the hazards of outburst flood from dammed lakes at the outlets of the gullies of Mozi, Wangyima, Xiaojia, Shaofang, Hongchun, Huaxi, Cutou and Qipan. Debris flow dammed lakes destroy highway by submerging, scouring and burying and interrupt the traffic from Yinxiu to Wenchuan, as a result, the east passage to Aba region was blocked, for example at the outlet of Qipan Gully and Chediguan. Yinxiu town was submerged by debris flow and outburst flood from Hongchun Gully (Figure 11). The debris flow materials from Hongchun Gully,  $700 \times 10^3 \text{ m}^3$  deposited at the outlet and  $400 \times 10^3 \text{ m}^3$  were transported into Min River, which formed a dam with the width of 350 m, the length of 470 m and the height of 10 m at Aug 14, 2010. Debris flow deposit dam buried the highway of G213 and reconstructing bridge, and the rapid increase water of dammed lake submerged about 500 - 600 m highway. The debris flow dam narrowed the channel of Min River and changed the flow direction of Min River, and outburst flood climbed up about 5 - 6 m and submerged the reconstructing Yinxiu town. The dammed lakes induced by the debris flow from Gaojia Gully blocked Min River in July 3, 2011 and the outburst flood scoured and ruined about 500 m road base so that the traffic from Yinxiu to Wenchuan was interrupted for 12 days and made huge loss. Furthermore, the 21 dammed lakes induced by debris flows on July 10, 2014 made more loss along Min River, especially the hazards on the highway of G213 and the Express Highway from Dujiangyan to Wenchuan.

Moreover, some big watersheds with over  $5 \text{ km}^2$ , including the gullies of Yeniu, Taipingyi, Er and Luoquanwan, Cutou and Qipan also occurred large debris flows under the condition of rainstorm in 2013, which could block Min River and form bigger dammed lakes and further increase the risk of outburst flood. Step debris flow dammed lakes also prevent the recovery of water power plants along Min River due to water level increase and quantity of sediment deposition. For example, a dammed lake caused by hill-slope debris flow on July 10, 2013 at the southern exit of Chediguan tunnel not only submerged Futang Water Power Plant, but also bury some



**Figure 11.** Yinxiu town threatened by 8.14 debris flows and outburst flood of dammed lakes.

equipment due to a mass of sediment from upstream. Debris flows and the following dammed lakes will continuously endanger Yinxiu town and the highway from Yinxiu to Wenchuan, especially the high risk section where road bed is lower or close to the height of water level of dammed lakes or highway is easily scoured or destructed, for example, the highway Yinxiu to Laohuzui and from Gaojia Gully to Huaxi Gully.

## 7. Conclusion and Countermeasures

### 7.1. Conclusion

After the Wenchuan Earthquake, dammed lakes are easily produced by slope debris flow, gully debris flow and the combination of debris flow and landslides. Local rainstorm and intensive rain trigger numerous debris flows occurring in simultaneity, as a result, debris flow dammed lakes distribute step-by-step along river channel. Debris flow dammed lakes generally overflow and outburst along the front of deposition dam in decades minutes or several hours after dammed lake forming. The solid size components and the geomorphology of debris flow deposition dam make dammed lakes easily outburst partly but hardly completely. After the Wenchuan Earthquake, high-frequent debris flows continuously increase the magnitude of debris flow deposition dam so that the stability of a single dam further strengthens; however, the hazards and risks of step dammed lakes probably increase. Debris flow dammed lakes significantly change local eco-environment, raise local river bed, and impose huge dangers on inhabitants, highways, and lands by means of the scouring, burying and submerging of debris flow, outburst flood and lake water. Step-dammed lakes have produced continuously hazards and risk on habitants, reconstruction, highways, farmland, and water power stations along the rivers of Yuzixi, Min, Mian yuan, Tongkou and Qian, especially at the rivers of Yuzixi, Min and Mian yuan.

### 7.2. Countermeasures

Concerning the characteristics of debris flow dammed lakes and their problems on mitigating, the following suggestions were recommended:

- 1) The identification model for debris flow blocking river and the evaluation model of dammed lakes outburst, based on the dynamic mechanism of debris flow movement and sediment transportation, are required to be researched and developed to find potential hazard site and reduce risks.
- 2) The processes of debris flow dammed lakes, including formation, outburst and change, are suggested to deeply research based on field investigation and monitoring and stimulation experiment to discover dynamic mechanism of debris flow blocking river and dammed lake outburst, and provide valuable technical indexes for protecting construction design and risk evaluating.
- 3) For the Wenchuan Earthquake areas, the methodology and model of risk assessment for step debris flow dammed lakes are strongly recommended to explore and establish to identify risk area in advance, and provide reliable suggestions to reconstructing, regional mitigating and inhabitants' security.
- 4) For Min River, the hazards of debris flows and debris flow dammed lakes should be assessed to find the high-hazard areas to avoid. The reconstruction of inhabitant settlements, highways and waterpower stations are suggested to concern and avoid the hazards of debris flow dammed lakes. Moreover, the dangerous step-dammed lakes, located along Min River from Yingxiu to Miansi, should be treated.

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