Mechanism of post-seismic floods after the Wenchuan earthquake in the upper Minjiang River, China

DING HAIRONG^{1,2}, LI YONG^{3,*}, SHAO CHONGJIAN³, LAUVENCE SVIRCHEV⁴, XU QIANG^{1,2}, YAN ZHAOKUN³, YAN LIANG³, NI SHIJUN¹ and SHI ZEMING¹

¹State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu 610059, Sichuan Province, China.

²College of Environment and Civil Engineering, Chengdu University of Technology, Chengdu 610059, Sichuan Province, China.

³National Key Laboratory of Oil and Gas Reservoir Geology and Exploration, Chengdu University of Technology, Chengdu 610059, Sichuan Province, China.

⁴Chengdu University of Technology, Chengdu 610059, Sichuan Province, China.

*Corresponding author. e-mail: liy@cdut.edu.cn

MS received 12 January 2016; revised 16 April 2017; accepted 19 April 2017; published online 6 October 2017

By analyzing the multi-year runoff and rainfall data at 15 hydrological stations from 1980 to 2007, as well as monthly runoff data from 1964 to 1984 at the Zipingpu hydrologic station, the relationship between precipitation and runoff has been established and the trend was explored. Based on the catastrophic floods of August 13 and August 18, 2010, characteristics and control factors on the post-seismic floods are summarized. Firstly, the Wenchuan earthquake and rupture zone provides the background for post-seismic floods to develop in the upper Minjiang River, which follows a post-seismic disaster-chain pattern: earthquake collapse to landslide debris flows to floods. Secondly, heavy rainfall controlled by the orographically-enhanced precipitation after the Wenchuan earthquake is the trigger factor for the development of devastating post-seismic floods. Thirdly, the post-seismic floods contain high sediment discharge, cause abrupt and severe damages, and have a large of volume and higher frequency.

Keywords. Wenchuan earthquake; Minjiang River; heavy rainfall; post-seismic floods; orographically-enhanced precipitation.

1. Introduction

On May 12, 2008, a major earthquake measuring 8.0 on the Richter scale (Ms 8.0) struck Wenchuan, Longmen Shan area, Sichuan Province, China (hereafter referred as the Wenchuan earthquake), which is characterized by high magnitude, long rupture zone, severe damage, strong and frequent aftershocks (Densmore *et al.* 2010; Li *et al.* 2011; Zhou *et al.* 2011). Because the main disaster area

is located in a zone of high mountains with deep valleys and of complex geological structure, the earthquake triggered a large number of collapses, landslides, dammed lakes and other secondary disasters. On September 24, 2008, four months after the Wenchuan earthquake, Beichuan County was attacked by heavy rainfall, which triggered a large-scale debris flow that killed more than 40 people and washed away thousands of acres of fertile land and houses (Tie and Tang 2011). On August 13,

2010 and August 17, 2012, heavy rainfall triggered severe multiple post-seismic floods in the upper reaches of Minjiang River causing huge loss of lives and property (Luo 2011; You *et al.* 2011). Out of the 5 years since the Wenchuan earthquake, flood disasters occurred in 3 years, repeatedly causing significant hazard to post-disaster reconstruction. As a consequence, post-seismic flood has become one of the most important natural disasters in Sichuan.

Experts have done research on the post-seismic disasters after Kanto earthquake in Japan and the Chi-Chi earthquake in Taiwan, the results showing that large-scale multiple landslides, debris flows and flood disasters are inevitable in parallel with the influence of extreme weather, such as typhoon and heavy rainfall after strong earthquake (Lin *et al.* 2006). Numerous experts have done copious research on the disaster chain of heavy rain floods, landslides and post-disaster events (Cui *et al.* 2008; Wang and Cheng 2008; Xu *et al.* 2010; Tang *et al.* 2011; Tie and Tang 2011; Ding *et al.* 2014a; Li *et al.* 2014; Wang *et al.* 2015). In this paper, on the basis of data collection for the flood and debris flows of 2010 August in the upper Minjiang River, empirical research methods are used, and the causes and post-seismic development characteristics of mountain flood are analyzed. Citing the August 13 and 18, 2010 devastating floods in the zone, this paper analyzes the relationships among rainfall, runoff and flood, and studies the control factors and the mechanism of the post-seismic flood. The paper provides a scientific basis for post-disaster reconstruction work and a reference for future post-seismic flood control and integrated river basin planning.

2. Hydrological characteristic in the upper Minjiang River

The Minjiang River originates in the southern part of Minshan Mountain, a tributary of the upper reaches of the Yangtze River, a pass-through river type at the eastern edge of the Tibetan Plateau (Li *et al.* 2006). The river flows through the Minshan Mountain area, crosses the Longmen Shan, and into the Sichuan Basin. The segment from Dujiangyan city to the upstream source of the river is known as the upper reaches of Minjiang River. It is a typical mountain river, showing the landform of high mountains, deep valleys, steep slopes and swift rivers. The river length is 340 km, with

a watershed area of approximately 23 km² (Li *et al.* 2007). The average slope ratio of the river course is 7.5‰ from the northwest to southeast (Li *et al.* 2007). There are five tributaries in the upper reaches, including Xiaoxing River, Heishui River, Zagunao River, Yuzixi River, Shouxi River, and all of them are located on the right bank of the Minjiang River. The profile of valley section is steep 'V' shape with elevation between 700 and 6253 m. The annual average precipitation is 500–850 mm and mean annual runoff is 14.4 billion m³, in which accounting for 75% of the annual runoff is in the wet period from May to October, while only 25% is in the dry season from November to April of the following year. The Zipingpu hydrological station is the watershed control station in the Minjiang River (figures 1 and 2).

3. Correlation between precipitation and runoff in the upper Minjiang River

The data of runoff used in the paper include annual runoff data at 15 hydrological stations from 1980 to 2007, as well as monthly runoff data station from 1964 to 1984 at the Zipingpu hydrologic station (figure 2). The precipitation data during the period of 1980–2007 come from 21 rainfall stations, and monthly precipitation data from 1964 to 1984 at the Dujiangyan meteorological station (figure 2). Excel software is used to integrate the precipitation, runoff statistical data and to establish relationship between rainfall and runoff.

3.1 Trend analysis of precipitation and runoff

The average precipitation at Zipingpu hydrologic station during the period of 1980–2007 is 1201 mm, the minimum value of 763 mm appearing in 2007, while the maximum value of 1805 mm appeared in 1990. The peak precipitation interval is about 2–4 years and the peak precipitation is appearing in 1983, 1990, 1992, 1995 and 2001. The statistical results show that the precipitation is in a downward trend since 1980, decreased by about 300 mm in 2007, accounting for about 25% of the average annual precipitation. The inter-annual variation coefficient of precipitation is 0.18 (figure 3).

The annual average runoff is 13.26 billion m³ at Zipingpu hydrologic station during the period 1980–2007, which means the converted average runoff depth is 587.4 mm. The minimum annual runoff is 9.87 billion m³, appearing in 2002 with converted runoff depth of 437.4 mm. The

Figure 1. Topography and drainage in the Longmen Shan and Sichuan basin.

maximum value of 15.86 billion m^3 , appearing in 1992 and converted runoff depth of 702.9 mm. The inter-annual variation coefficient of runoff is 0.11. The statistical results show that the peak runoff interval is 1–3 years, for example, peak runoff appears in 1981, 1988, 1989, 1990, 1992, 1995, 1998, 1999 and 2001. The peak runoff also shows as a downward tendency. From 1980 to 2007, it decreases by approximately 1.5 billion m^3 , with converted runoff depth about 44 mm, accounting for about 11% of the average annual runoff (figure 3). The above statistical results show that in the 27 years before the Wenchuan earthquake, runoff and precipitation are both in a downward trend in the upper Minjiang River, and the variation ratio of them is consistent.

3.2 Correlation between annual precipitation and runoff

In the upper Minjiang River, precipitation and runoff is of a consistent time trend. The precipitation within May–October accounts for 75–90% of total annual precipitation (Li *et al.* 2007, Ding *et al.* 2013b), while from November to March of the following year, the decreased precipitation accounts for only about 10% of the year. The distribution of precipitation and runoff is similar, in which the floods occur mainly in the May–October, and concentrate in the July–September periods (figure 4).

The results by correlation of annual precipitation and runoff at Zipingpu hydrological station indicates that the correlation coefficient $R = 0.5223$

Figure 2. Distribution of rainfall in the upper Minjiang River drainage (Xu 2006).

Figure 3. Trend of runoff and precipitation in the upper Minjiang River (1980–2007).

(figure 5), and the annual precipitation and runoff trend are consistent (figure 5). The correlation formula of precipitation and runoff is $Y = 0.1436X + 399.47$, which shows that before the Wenchuan earthquake in 2008, the runoff was mainly controlled by precipitation. With the increase of precipitation, runoff was also congruously increased, which indicates that flood is mainly caused by rainfall.

4. Floods before the Wenchuan earthquake in the upper Minjiang River

Precipitation in the upper Minjiang River is mainly affected by topography and the southeast monsoon, which varies with season. Rainstorm occurs frequently in wet season, generally during June–September, especially concentrates in July and August, in which maximum flood peak occurs with the most opportunities. The annual precipitation is also affected by topography. For example, the average annual rainfall in the high mountain zone from Songpan County to Wenchuan is 400–700 mm, while it is 1100–1600 mm at the foot of the Longmen Shan from Yingxiu of Wenchuan County to Dujiangyan. The measured maximum annual precipitation is 2434.8 mm at the Zipingpu station in 1947.

4.1 Inter-annual variation of maximum monthly mean runoff in the upper Minjiang River

According to peak flow data at the Zipingpu hydrological station (figure 6), the minimum value

of monthly mean flow of 700 m³/s appeared in 1972. The maximum value appears in 1983, which is 1220 m³/s during the flood season from 1964 to 1985. On the whole, the annual flow in flood season trends downward in the region.

4.2 Inter-annual variation trend of maximum flood peak flow

The peak flow of disaster flood is greater than 2500 m³/s in the upper Minjiang River (Zhang 2006). From 1964 to 1984, most of peak flows at Zipingpu hydrologic station are greater than 2500 m³/s, and the maximum flood flow is 5840 m³/s in 1964 (figure 7). After that, the annual maximum peak flow appears to be in decreasing trend from 1964 to 1984 (figure 7).

According to measured maximum peak flow data of Dujiangyan hydrological station from 1964 to 1984, the peak flow and flood return period are calculated through experience frequency formula ($P = \frac{m}{n+1} \times 100\%$), which refers to table 1. The results show that from 1964 to 1984, the frequency of flood with return period of 4 years is 32.8% (whose peak flow is 2500–2750 m³/s), the frequency of flood with return period of 7 years is 13.6% (whose peak flow is 4000–4300 m³/s), while the frequency of flood with return period of 22 years is 4.5% (whose peak flow is greater than 4500 m³/s).

5. Post-seismic floods after the Wenchuan earthquake in the upper Minjiang River

Many floods and debris flows occurred after the Wenchuan earthquake in the Longmen Shan region

Figure 4. The monthly average precipitation in the upper Minjiang River.

Figure 5. Correlation of precipitation and runoff in the upper Minjiang River.

Figure 6. Maximum monthly mean flow and the corresponding month precipitation (1964–1985) in the upper Minjiang River.

Figure 7. Peak flow of floods at Zipingpu hydrologic station in the upper Minjiang River.

Table 1. Frequency calculation table of the peak flow at Zipingpu hydrological station.

Year	Peak flow (m ³ /s)	Peak flow (descending order)	Sequence no.	Frequency (P)
1964	5500	5500	1	4.5
1965	1900	4300	2	9.1
1966	4300	4000	3	13.6
1967	2100	2750	4	18.2
1968	2500	2700	5	22.7
1969	1800	2600	6	27.3
1970	1820	2500	7	32.8
1971	1830	2500	7	32.8
1972	2600	2500	7	32.8
1973	2700	2500	7	32.8
1974	1850	2400	11	50
1975	2500	2100	12	54.5
1976	2100	2100	12	54.5
1977	4000	2100	12	54.5
1978	2750	2100	12	54.5
1979	2500	1900	16	72.7
1980	2100	1900	16	72.7
1981	2400	1850	18	81.8
1982	2500	1830	19	86.4
1983	2100	1820	20	90.9
1984	1800	1800	21	95.5

(figure 8). Here we summarize the floods after the Wenchuan earthquake in the upper Minjiang River (Ding *et al.* 2013a, 2014b).

5.1 Post-seismic floods at Yingxiu town on August 13–18, 2010 (Ding *et al.* 2013)

On August 13 and 18 of 2010, heavy rainfall attacked Yingxiu town in the upper Minjiang River (table 2, figures 8 and 9), and triggered a mass of

flood disaster in Yingxiu town. According to data at the Yingxiu meteorological station, the total rainfall on August 12 in Yingxiu town was 19.9 mm. On August 13, the daily cumulative rainfall was 126.8 mm, and the maximum hourly rainfall intensity was 32.2 mm/hr. On August 14, the cumulative rainfall was 23.4 mm. The total rainfall amounted to 162.1 mm, and the maximum hourly rainfall intensity was 16.4 mm/hr. So a flash flood and debris flow broke out in the Hongchun Gully. The

Figure 8. The distribution of floods and debris flows after Wenchuan earthquake in Longmen Shan region.

debris flow destroyed roads and houses, blocked the 120-m wide river channel, and a barrier dam with an average height of 7 m (Tang *et al.* 2011). When the huge barrier body burst, the resulting powerful flood destroyed the Road 213 and the Dujiangyan–Wenchuan expressway. Because the barrier dam blocked the left river course, its course was changed which caused the flood to rush into Yingxiu town, destroying parts of the town which had just been reconstructed after the Wenchuan earthquake (Xiang *et al.* 2010).

5.2 Post-seismic floods Longchi town on August 13–18, 2010

On August 13, 2010, heavy rainfall attacked Longchi town in Dujiangyan. According to precipitation data at the Chaguan meteorological station (table 2, figure 10), total rainfall was 156.9 mm, and maximum hourly rain intensity was 75 mm/hr from August 13 to 14. At 16:00, large-scale debris flow

formed. At 17:40, the debris flow changed into a flood flow (figure 10). The total August 18 rainfall was 252.2 mm, and maximum hourly rain intensity was 69 mm/hr from August 18 to 19. At 20:00, a flash flood and debris flow formed (figure 10). This post-seismic flood trapped nearly 800 persons, mortality was 1, with 12 were missing, 137 houses collapsed or destroyed (Ding *et al.* 2013a).

6. Mechanism of post-seismic floods in the upper Minjiang River

6.1 The heavy rainfall is controlled by the orographically-enhanced precipitation

The upper Minjiang River is a typical high- and steep-slope mountain river basin. The distribution of precipitation is mainly affected by warm air of the southeast monsoon and relief. Because the east side of the Longmen Shan is windward, the warm air of the southeast monsoon rises and

Table 2. The post-seismic floods information in the upper Minjiang River on August 13 and August 18, 2010.

Location	Time	Flood character	Hydrological parameter	Tectonic position	Damage	Data source
Hong Chun Gou (on the left bank)	Aug. 12	Day accumulative rainfall 19.9 mm	Annual mean precipitation 1253.1 mm, maximum annual precipitation 1688 mm (1964), minimum annual precipitation 836.7 mm (1974). Maximum velocity 6.9 m/s, minimum velocity 1.44 m/s	Yinxu—Beichuan fault, which is the seismogenic fault of Wenchuan earthquake	13 dead, 59 missing, 8000 people were affected. Barrier lakes were formed, Jiuzhaigou Ring Road and National Road 213 were submerged 200 m, traffic, communication, electric power, water supply were broken	Tang <i>et al.</i> (2011)
	Aug. 13	Day accumulative rainfall 126.8 mm, maximum rainfall intensity 32.2 mm				
	Aug. 14	Day accumulative rainfall 23.4 mm, total rainfall 162.1 mm, maximum rainfall intensity 16.4 mm				
Shuang Yangzi Gou (on the right bank of tributary Longxihe)	Aug. 13	Maximum rainfall intensity 75 mm/hr at 5 PM, maximum rainfall with return period of 20 years	Annual mean precipitation 1134.8 mm, maximum monthly mean precipitation 289.9 mm, rainfall intensity 71.3 mm/hr with return period of 10 years, rainfall intensity 74.8 mm/hr with return period of 20 years	Yinxu—Beichuan fault, which is the seismogenic fault of Wenchuan earthquake	1 dead, 12 missing, 137 rooms were destroyed	Wu <i>et al.</i> (2011)
	Aug. 14	Day accumulative rainfall 156.9 mm				
	Aug. 19	Day accumulative rainfall 252.2 mm, maximum rainfall intensity 69 mm/hr, maximum rainfall with return period of 10 years

Figure 9. Sichuan precipitation maps, in mid-August, 2010 (Yan *et al.* 2011). (1. The orographic precipitation outbreak many times in earthquake disaster area after the earthquake in 2008, and the most serious storms occurred on August 13 of 2010; 2. Heavy rains coincide with the earthquake rupture zone).

orographically-enhanced precipitation is formed, as in figure 11 (Li *et al.* 2014). So the rainfall center shall be formed at piedmont region of Longmen Shan. Therefore, heavy rain occurs frequently in the upper Minjiang River, which causes the storm floods with high frequency, large magnitude, and serious disaster (Ding *et al.* 2013c).

6.2 Wenchuan earthquakes provide the conditions for the development of post-seismic flood (Ding *et al.* 2013a)

In the region, the strong rainstorm area roughly coincides with the Yingxiu–Beichuan fault zone as in figure 12 (Densmore *et al.* 2007; Li *et al.* 2010, 2011; Zhou *et al.* 2011). The Wenchuan earthquake on May 12, 2008 induced a significant collapse and landslide, providing important sources of unconsolidated solids for the formation of debris flow (figure 12) and the occurrence of strong rainstorm can easily trigger debris flow and post-seismic

flood. The Wenchuan earthquake of 2008 caused the collapse, landslide, debris flow and other secondary disasters, which led to serious damage of forest in the area (Tang *et al.* 2012; Parker *et al.* 2011; Li *et al.* 2014). According to preliminary estimates in the zone, damaged forest is 89326.31 hm^2 (Huang *et al.* 2009). The vegetation coverage decreasing by 20% in the core area of the earthquake (Bao 2008).

Flood kinetics are generally inversely proportional with vegetation cover, that is to say, the decreasing vegetation coverage rate has a direct impact on the increasing frequency of flood. In addition, after the Wenchuan earthquake, soil erosion is significantly greater than that before earthquake. The average soil erosion modulus before the earthquake is 3703 $\text{t}/(\text{km}^2\text{a})$ and increased to 4604 $\text{t}/(\text{km}^2\text{a})$ (Deng *et al.* 2008) after the earthquake, and the soil erosion intensity amplitude is amounted to 25%. The average annual amount of soil erosion is $4.98 \times 10^8 \text{ t}$ before the earthquake,

Figure 10. Rainfall process on August 13–18, 2010 at Longchi Town (Ma *et al.* 2011).

Figure 11. The orographically-enhanced precipitation on Longmen Shan (Li *et al.* 2014).

while that is 6.87×10^8 t after the earthquake. Because of the increase of soil erosion, the flood sediment concentration increased. These data suggest that Wenchuan earthquake caused a decline in the efficiency of conservation of forest and soil erosion, so most of precipitation was not absorbed and retained, but instead formed runoff. These phenomena in turn increased the maxima of flood flow, peak, and sediment concentration (Ding *et al.* 2013a, 2014b).

6.3 Heavy rainfall is the trigger to post-seismic floods

No flood occurred in the upper Minjiang River in 2008 and 2009 after Wenchuan earthquake, which

leads some people think that the post-seismic flood would not occur. The reason is that in the period from 2008 to 2009, precipitation is within 834.8–1222.4 mm, which belongs to the category of historic relatively dry years (Ding *et al.* 2013a).

But in 2010, serious flood attacked the Longmen Shan area. The rainfall was 2545.8 mm, and the rainfall was especially concentrated in August. The precipitation was 507.2 mm, which is 239 mm more than the average annual precipitation (figure 10). Due to this heavy rainfall, a large amount of loose material caused by the Wenchuan earthquake could be transported into the river leading to the outbreak of the post-seismic flood. Therefore, heavy rainfall is causation trigger for post-seismic floods (Ding *et al.* 2013a).

Figure 12. The distribution of rainfall and debris flows in the Middle-August of 2010 (Li *et al.* 2014).

For the Wenchuan earthquake post-seismic floods, we propose the following causation chain of events and process: heavy rainfall saturates unconsolidated debris, gravity-induced mass-flow of debris, clearance of debris out of the gully into the river, and formation of barrier lakes. The accumulation of hydraulic back-pressure and over-flow breaches and bursts the barrier dam at its weakest point. The ensuing high-velocity flood impacts and destroys post-earthquake construction. After the Wenchuan earthquake, strong rainstorm weather increased, especially in the main flood season, such as the 2010 August 13 and 18 heavy rainfall (figure 10; Ding *et al.* 2013a, 2014a). The high intensity concentrated in a short period of time triggered serious post-seismic flood disaster. The criterion of rainfall-caused floods was 80–100 mm, and rainfall intensity was 30–50 mm/hr before the earthquake in Longmen Shan area (Ding *et al.* 2013a, 2014b). After the earthquake, the intensity that resulted in flooding was reduced to 16.4 mm/hr, 45–67% less than that before the

Wenchuan earthquake (Tang *et al.* 2011). Therefore, the criterion of rainfall-caused floods also has been reduced significantly after the Wenchuan earthquake. In addition, after the Wenchuan earthquake, flood volume and frequency increases in the upper Minjiang River (Tang *et al.* 2012).

6.4 Channel aggradations and outburst of barrier lakes aggravate the abruptness and destructiveness of post-seismic flood

Wenchuan earthquake induced significant collapses and landslides, causing a large amount of loose material to accumulate at foothills and mountain terraces. After heavy rainfall, those loose materials are transported into rivers which would occupy the channel space and reduce the capacity to deliver water during flooding (figure 13), and exacerbate the destructiveness of flash flood (Korup 2004; Li *et al.* 2014). For example, in 2010, there was large-scale debris flow outburst in Shenxigou of Baisha River catchment. The debris flowed into channel

Figure 13. Debris flows on August 13, 2012 Hongchun Gully (aerial photograph from the Sichuan Geological Environment Monitoring Station; [Li et al. 2013](#)).

Figure 14. Debris flowed into channel of Baisha River.

of Baisha River and induced larger flood disaster (figure 14).

The seismic landslides block river course and the barrier outburst exacerbate emergency and destructiveness. The Wenchuan earthquake prompted unstable rock mass collapses, landslide, river blockage, and formation of barrier lakes.

There are numerous tributaries and appropriate locations to form barrier lakes in the area. So when strong rainstorm occurs, floods rapidly concentrate, and when the flood volume is more than storage ability of the barrier lake, overflow is generated, causing the collapse of the barrier weir, formation of post-seismic flood, and serious flood disaster.

For example, in 1933, a magnitude of 7.5 earthquake hit Diexi. Landslides ensued blocked the main course of Minjiang River and branch river courses, with more than 10 barrier lakes forming. Forty-five days after the earthquake, the Diexihaizi barrier lake burst and caused a series of down-stream barrier lakes break. The flood affected 250 km downstream, killed 20,000 people and destroyed most villages and towns of Maoxian, Wenchuan and Guan county (now Dujiangyan city), resulting in one of the serious historic flood disasters in China and the world. While the earthquake itself killed nearly 7000 people ([Jiang et al. 1989](#)), the geo-hazards generated by post-seismic events may be far more serious than the earthquake itself.

7. Conclusions

Based on the correlation among precipitation, runoff and floods in 2010 in the upper Minjiang River, post-seismic floods caused by heavy rainfall

after Wenchuan earthquake have been studied in this paper. Some conclusions are summarized as following: (i) The Wenchuan earthquake provides the essential conditions for the post-seismic floods. The upper Minjiang River just located at the epicenter of Wenchuan earthquake, shows the post-seismic disaster chain: earthquake–collapse–landslide–debris flows–floods; (ii) the heavy rainfall controlled by the orographically-enhanced precipitation is one important factor inducing post-seismic floods, and (iii) river channel aggradations and outburst of barrier lakes aggravate the abruptness and destructiveness of post-seismic flood. Research results show that, Wenchuan earthquake caused plenty of loose material, and frequency of post-seismic floods caused by heavy rainfall shall increase. The next 5–10 years will be the crest time of post-seismic floods in the area. Therefore, detailed investigation and cataloging work should be carried out urgently on quake barrier lakes caused by Wenchuan earthquake, and rain-storm real-time monitoring and warning system should be established. Post-seismic floods disaster prevention and control engineering should be carried out, and conference communication should be strengthened with large and medium-sized hydropower stations in the upper Minjiang River. Those will be beneficial to improve flood forecast accuracy and scientific and foresight of decision-making in the flood control and disaster mitigation.

Acknowledgements

This study was sponsored by the Natural Science Foundation of China (Grant Nos. 41602306, 41402159, 41340005, 41372114), the Research Project of Sichuan Education Department (No. 14ZB0072), and the Research Project of Sichuan Province and Technology Development. We are grateful to the Bureau of Hydrology and Water Resources Survey in Sichuan province for the data. We are thankful to Prof. Cao Shuyou for the help and suggestions during the preparation of this manuscript. We are also thankful to our reviewers for their useful suggestions.

References

- Bao W K 2008 Ecological degradation and restoration and reconstruction countermeasures for severe calamity regions in Wenchuan earthquake in Sichuan; *Sci. Techno. Disa. Relf.* **23**(4) 324–328 (in Chinese with English abstract).
- Cui P, Wei F Q and Chen X Q *et al.* 2008 Geo-hazards in Wenchuan earthquake area and countermeasures for disaster reduction; *Sci. Techno. Disa. Relf.* **23**(4) 317–323 (in Chinese with English abstract).
- Deng Y L, Meng Z X and Wang Y K *et al.* 2008 Study on soil erosion changes and controlling strategy in the Minjiang River valley; *J. Soil Water Conserv.* **22**(5) 55–60 (in Chinese with English abstract).
- Densmore A L, Li Y and Richardson N J *et al.* 2010 The role of late Quaternary upper-crustal faults in the 12 May 2008 Wenchuan Earthquake; *B. Seismol. Soc. Am.* **100**(5B) 2700–2712.
- Densmore A L, Ellis M A and Li Y *et al.* 2007 Active tectonics of the Beichuan and Pengguan faults at the eastern margin of the Tibetan Plateau; *Tectonics* **26**(4) 113–127.
- Ding H R, Li Y and Ma G W 2013a Post-seismic floods after the 2008 Wenchuan (Ms 8.0) earthquake in the Minjiang River, Sichuan; *Acta Geol. Sin-Engl.* **87** 629–630.
- Ding H R, Li Y and Yan L *et al.* 2013b The Jianjiang drainage pattern in Longmenshan area and its response on Wenchuan earthquake; *Quat. Sci.* **4** 802–811 (in Chinese with English abstract).
- Ding H R, Li Y and Yan L *et al.* 2013c Influences of disaster chain driven by Wenchuan earthquake on sediment discharge in upper reaches of Minjiang River, Sichuan, China; *J. Chengdu Univ. Techno. (Sci. Technol. Ed.)* **40**(6) 712–720 (in Chinese with English abstract).
- Ding H R, Li Y and Ni S J *et al.* 2014a Increased sediment discharge driven by heavy rainfall after Wenchuan earthquake: A case study in the upper reaches of the Min River, Sichuan, China; *Quat. Int.* **333** 122–129.
- Ding H R, Li Y and Ma G W *et al.* 2014b Study on sediment discharge increase caused by Wenchuan earthquake landslide and heavy rainfall in the upper reaches of the Min River; *J. Sichuan Univ. (Eng. Sci. Ed.)* **46**(3) 49–55 (in Chinese with English abstract).
- Huang G Z, Liu X D and He F 2009 Earthquake damaged vegetation and its restoration and reconstruction countermeasures in the upper reaches of Minjiang River; *J. Sichuan Fst. Sci. Techno.* **30**(3) 95–99 (in Chinese with English abstract).
- Jiang Z X, Xu J T and Li T H 1989 Post-seismic flood of Diexi in 1933 and flood damage of Minjiang in 1986; *J. Catastrophol.* **4** 63–67 (in Chinese with English abstract).
- Korup O 2004 Landslide-induced river channel avulsions in mountain catchments of southwest New Zealand; *Geomorphology* **63** 57–80.
- Li Y, Li B and Steffen D *et al.* 2006 Provenance analysis and drainage evolution in late cenozoic Chengdu Basin on eastern margin of Tibetan plateau; *Acta Sedim. Sin.* **24**(3) 309–320 (in Chinese with English abstract).
- Li Y, Li B and Zhong R J *et al.* 2007 The quantitative correlation between denudation volume and sedimentary flux in the denudation–accumulation system: Examples from Minjiang River drainage system; *Acta Sedim. Sin.* **3** 32–343 (in Chinese with English abstract).
- Li Y, Huang R Q and Zhou R J *et al.* 2010 The Ms 8.0 Wenchuan earthquake and co-seismic river response; *J.*

- Sichuan Univ. (Eng. Sci. Ed.) **42**(5) 20–33 (in Chinese with English abstract).
- Li Y, Zhou R J and Densmore A L *et al.* 2011 Spatial relationships between surface ruptures in the Ms 8.0 earthquake, the Longmen Shan region, Sichuan, China; *J. Earthq. Tsunami*. **5**(4) 329–342.
- Li Y, Yan Z K and Zhou R J *et al.* 2013 Surface process and fluvial landform response to the Ms 8.0 Wenchuan earthquake, Longmenshan, China; *J. Earthq. Tsunami*. **7**(5) 26p.
- Li Y, Zhou R J and Zhao G H *et al.* 2014 Tectonic uplift and landslides triggered by the Wenchuan earthquake and constraints on orogenic growth: A case study from Hongchun Gully, Longmen Mountains, Sichuan, China; *Quat. Int.* **349** 142–152.
- Lin C W, Liu S H and Lee S Y *et al.* 2006 Impacts on the Chi-Chi earthquake on subsequent rain-induced landslides in central Taiwan; *Eng. Geol.* **86** 87–101.
- Luo Z C 2011 Cause analysis of “8.13” flood disaster in Xihe; *Water Conserv. Sci. Techno. Econ.* **17**(3) 70–73 (in Chinese with English abstract).
- Ma Y, Yu B and Wu Y F *et al.* 2011 Research on the disaster of debris flow of Bayi Gully, Longchi, Dujiangyan, Sichuan; *J. Sichuan Univ. (Eng. Sci. Ed.)* **43**(1) 92–98 (in Chinese with English abstract).
- Parker R N, Densmore A L and Rosser N J *et al.* 2011 Mass wasting triggered by the 2008 Wenchuan earthquake is greater than orogenic growth; *Nat. Geosci.* **4**(7) 449–452.
- Tang C, Li W L and Ding J *et al.* 2011 Field investigation and research on giant debris flow on August 14, 2010 in Yingxiu town, epicenter of Wenchuan earthquake; *Earth Sci.-J. China Univ. Geosci.* **36**(1) 172–180 (in Chinese with English abstract).
- Tang C, Van Aschtwj and Chang M 2012 Catastrophic debris flows on 13 August 2010 in the Qingping area, southwestern China: The combined effects of a strong earthquake and subsequent rainstorms; *Geomorphology* **139** 559–576.
- Tie Y B and Tang C 2011 Response characteristics between Wenchuan earthquake and the rainfall induced debris flow in Beichuan Country, Sichuan; *J. Catastrophol.* **26**(4) 73–75 (in Chinese with English abstract).
- Wang G X and Cheng G W 2008 Some thoughts on hydrology and water environment problems in reconstruction in earthquake-hit areas; *J. Mt. Sci.* **26**(4) 385–389 (in Chinese with English abstract).
- Wang J, Jin Z D and Hilton G R *et al.* 2015 Controls on fluvial evacuation of sediment from earthquake-triggered landslides; *Geology* **43**(2) 115–118.
- Wu Y F, Yu B and Ma Y *et al.* 2011 Debris flow of Shuangyangzi gully, Dujiangyan City in Wenchuan earthquake area; *Sci. Soil Water Conserv.* **9**(3) 13–17 (in Chinese with English abstract).
- Xiang L Z, Cui P and Fang H 2010 Mechanism of disaster chain after earthquake and the impact to urban reconstruction in Wenchuan earthquake area; *J. Catastrophol.* **25**(S0) 278–281 (in Chinese with English abstract).
- Xu L X 2006 The upper reach of the Min Jiang River runoff analysis and its forecast; PhD thesis, *Sichuan University* (in Chinese with English abstract).
- Xu M Z, Wang Z Y and Shi W J *et al.* 2010 Mountain disaster chain induced by the Wenchuan earthquake in the Huoshiguo Gorge; *J. Tsinghua Univ.* **50**(9) 1338–1341 (in Chinese with English abstract).
- Yan Z K, Li Y and Huang R Q *et al.* 2011 Effects of Wenchuan earthquake on sediments transport of river systems in Longmen Shan area; *Chinese J. Nat.* **33**(6) 337–340 (in Chinese with English abstract).
- You Y, Chen X Z and Liu J F 2011 ‘8.13’ Extra large debris flow disaster in Wenjia gully of Qingping Township, Mianzhu, Sichuan Province; *J. Catastrophol.* **26**(4) 68–72 (in Chinese with English abstract).
- Zhang Q D 2006 A study on the relation of between runoff and sediment variations and deforestation in the upper of Minjiang River; Master thesis, Southwest University (in Chinese with English abstract).
- Zhou R J, Li Y and Densmore A L *et al.* 2011 The strong motion records of the Ms 8.0 Wenchuan Earthquake by the digital strong earthquake network in Sichuan and the neighboring region; *J. Earthq. Tsunami*. **5**(4) 343–361.