

Landslide Research in China

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During the spring of 2000 (9 April), a 91 Mm³ rock avalanche occurred in Linzhi Prefecture, Tibet (the 'Roof of the World'). The event was accompanied by a deafening noise, with the rock mass traveling from a maximum elevation of 5132 m asl and coming to a rest at an elevation of 2163 m asl. It formed a landslide dam in the Yigong Zangbo River of some 55 m high impounding a reservoir of some 2 Gm³ for a period of 62 days after which it emptied in less than 12 hours (Delaney and Evans 2015). The event forewarning of a period of frequent geological disasters in China during the start of the 21st Century. The ensuing Wenchuan earthquake (surface-wave magnitude Ms 8.0; May 2008), Zhouqu debris flow (August 2010) and Ludian earthquake (Ms 6.7; August 2014) urged China to renew its campaign against geological disasters and the Chinese Government has since invested heavily in scientific research to guide efforts to mitigate the impact of such natural disasters. A thematic set on Landslide Research in China was initiated to highlight this research. This paper provides a brief review of three featured subjects and accompanies the five papers published in the thematic set.

33 **Landslides in areas affected by earthquakes**

34 Large earthquakes severely affect the geological environment and also result in
35 the potential for secondary disasters in the days, months and years that follow. There
36 is continued debate on how quickly landscapes recover following a high-magnitude
37 disturbance. Lin (*et al.* 2006, 2009) studied the Chi-Chi Earthquake of 1999 and
38 found that five years after the earthquake, the area experienced a relatively high
39 number of landslides (including debris flows) followed by a trend of gradual decline.
40 Hovius *et al.* (2011) concluded that it took approximately 6 years for the landslide
41 signal to return to pre-1999 levels. Other examples of long-term landscape recovery
42 are discussed in, for example, Nakamura *et al.* (2000) for the 1923 Ms 7.9 Kanto
43 earthquake in Japan and in Huang (2011) for the 2008 Ms 8.0 Wenchuan earthquake,
44 China. The Wenchuan earthquake took place on 12 May 2008 in Sichuan Province
45 resulting in some 200,000 landslide events (Xu *et al.* 2013) and in the following years
46 the province suffered frequently from further landslide activity. According to the first
47 author's statistics, the province experienced 668, 934, 2,161, 1,997, and 3,147
48 geohazards from 2008 to 2012. The enhanced landslide and debris-flow activity after
49 the 2008 Wenchuan earthquake is highlighted in the Special Issue of Engineering
50 Geology "The long-term geologic hazards in areas struck by large-magnitude
51 earthquakes" (2014, Volume 182, Part B).

52 On 24 September 2008, Beichuan County, previously destroyed by the
53 Wenchuan Earthquake, experienced yet another debris flows which led to a further 42
54 fatalities (Tang and Liang, 2008; Tang *et al.* 2011a; Figure 1).

55 On 13 August 2010, Qingpingxiang (a town in Mianzhu County), Yingxiu (a
56 town in Wenchuan County) and Hongkou Township (in Dujiangyan county), all
57 severely affected by the Wenchuan Earthquake, experienced torrential floods and
58 landslides (dominated debris flows). The total landslide volume for these regions
59 exceeded 13 million m³ causing the partial or total destruction of roads and houses
60 and the interruption of traffic (Figures 2 and 3).

61 Another serious debris flow happened on 9 July 2013 in Qipangou. The flood

62 disaster created a barrier lake that blocked the Mingjiang River. This is the largest
63 recorded debris flow in this region.

64 Conducting rainfall monitoring and the associated provision of timely warnings
65 in seismically-prone regions provide an effective way of limiting the impacts of
66 potential landslides on the local population. However, experience has shown that, as a
67 result of long runout and high relief, the areas most impacted by landslides are not
68 necessarily those affected by the highest intensity of rainstorms. The 7 August 2010
69 Zhouqu debris flow is an example (see Figure 4, Dijkstra *et al.* 2012). Zhouqu County,
70 which was severely damaged by the debris flow, experienced a rainfall intensity of
71 only 10 mm/h, while the Dongshantai Station, close to the top of Sanyanyu where the
72 debris flow was initiated, registered a rainfall intensities as high as 90 mm/h (Tang *et*
73 *al.* 2011b; Dijkstra *et al.* 2012; Dijkstra *et al.* 2014). Figure 5 explains the disaster
74 process from the standpoint of a 2,000 m difference in elevation between the area of
75 intense rainfall and the area affected by the debris flow. For this reason, the Ministry
76 of Land and Resources launched a program to implement a warning system used in
77 high, cold mountainous areas that experience dense fog. A remotely-operating video
78 platform was installed in Zhouqu County, with the purpose of transmitting
79 information to the monitoring and warning center on a real-time basis via sensors and
80 communication satellites (Figure 6).

81 **Geo-hazard Mitigation for the Three-Gorges Project**

82 The Three Gorges Project is the largest hydro-electric complex both in China and
83 the world. However, the area of the reservoir has a significant landslides history. In
84 this area, the hilly and mountainous areas constitute 21.7% and 74% of the total,
85 respectively while the flat surface around the dam is only 4.3%. The river valley in
86 the reservoir area is affected by the geology, its structures and the associated
87 geotechnical parameters. Heavy rainfall and rainstorms are frequent in the reservoir
88 area, and about 70% of the total annual rainfall is concentrated between the months of
89 May to September (Chen *et al.* 2005).

90 At the beginning of the Three Gorges Project, great efforts were made to prevent

91 geological disasters, including landslides, and significant effort was expended in
92 mitigation and control works. The main experience and achievements are summarized
93 below.

94

95 **Transition from frequent geological disasters during the initial impoundment**
96 **stage to the balance and decline stages.**

97 From September 2008 to August 2014, the Three Gorges Project underwent six
98 impoundment trials. The highest water levels in front of dam during the 2010, 2011,
99 2012 and 2013 trial impoundments were uniform at 175.0 m. By 31 August 2014, the
100 reservoir area of the Three Gorges Project sustained a total of 421 significant ground
101 deformation events and landslides, of which 120 occurred in the Hubei reservoir and
102 301 in the Chongqing reservoir. The total volume of landslides and collapses reached
103 350 million m³ and the total length of the 60 river bank slumps was 25 km. Table 1
104 clearly shows that in the following years, the number of slope failures declined
105 rapidly although the water level reached the same elevation of 175 m (Zhen 2010).

106 After the 175m trial impoundment in 2008, the water level rose by 8.32 m from
107 30 October to 4 November, equivalent to 1.66 m/d. Ten days later, 37 landslides
108 occurred at the peak level of the impoundment. Between 1 August and 6 August 2010,
109 the cumulative decline in water level was 5.57 m, equivalent to 1.15/d, the largest
110 daily rate of lowering since the impoundment. No landslides were generated during
111 the ten days that followed. When the rate of lowering of the water level ranged
112 between 0.40 m/d and 1.15 m/d, there was no correlation between the occurrence of
113 landslides and the lowering of the reservoir water level. The first increase of the water
114 level triggered the majority of the landslides while draw-down had little impact on
115 landslide occurrence.

116

117 **Adoption of engineering measures against major potential landslide hazards to**
118 **significantly reduce the threat of geological disasters.**

119 To ensure the safety of more than one million people living in dozens of towns
120 surrounding the reservoir area, potentially hazardous sites were the subject of

121 mitigation works including drainage measures, stressed anchoring cables, anti-slide
122 piles, etc. The hazards associated with 243 landslides sites with the potential to slide
123 into the Yangtze River have been significantly reduced and as a result the risks to 79
124 towns potentially threatened either directly from landslides or from landslide-induced
125 waves have been reduced to acceptable levels.

126 The surface of the bedrock landslide in central Fengjie, the Monkey Stone
127 landslide, had an elevation of 90 m at the front-edge and 250 m at the back-edge, a
128 160 m elevation difference with the water level varying between 145 m and 175 m
129 elevation as shown in Figure 7 (Chen and Feng, 2008) and occupied an area of
130 $12 \times 10^4 \text{ m}^2$ and a volume of $450 \times 10^4 \text{ m}^3$. The engineering mitigation involved two
131 stages (Zou *et al.*, 2008). Stage I consisted of water discharge measures, loading the
132 toe of the slope, and erosion protection of the slope surface. Stage II extended the
133 project and consisted of cascaded slide-resistant shear keys at the level of the slip
134 plane, rock fill dumped underwater to further load the toe, and further slope protection
135 and water discharge measures. The project started in May 2006 and was completed in
136 May 2008, enhancing the safety of the population of this densely populated town as
137 shown in Figure 8 (Chen and Feng, 2008)).

138

139 **Building of systematic landslide monitoring and warning systems**

140 The entire Three Gorges reservoir area has been built with a high-level
141 monitoring and early-warning system that includes three levels (i.e. county, township
142 and village levels) based on mass movement predictions, early warnings of events,
143 and evacuation plans in order to help prevent disasters. The program aims to provide
144 effective monitoring and warning of 3,049 sites of potential collapse, landslide and
145 bank slump within the reservoir area. Over 12,200 people, 5,200 from the Hubei
146 Province and 7,000 from Chongqing, have been evacuated during the period since
147 2003 when the reservoir was first impounded.

148 The landslide forecast at Qianjiangping in the Zigui County has proven to be
149 very successful. A landslide occurred on the night of 13 July 2003 ($1,542 \times 10^4 \text{ m}^3$
150 volume) and caused a blockage and silting of the Qinggan River, a tributary of the

151 Yangtze River. However, relying on a timely warning, more than 1,200 people were
152 safely evacuated. Table 2 presents two typical field monitoring schemes taken from a
153 report summarizing this and 12 similar cases.

154 **Emergency response to landslide dams**

155 Combatting the risks associated with barrier lakes created by large-scale
156 landslides has been one of the principal geological disaster prevention programs of
157 China in the past 15 years.

158 In 2000 the Yigong-Zangbo River formed the Yigong Lake due to a mountain
159 landslide which generated an overtopping flood of two billion m³ of water having a
160 peak flow of 95,000 m³/s (Yin 2000). After the Wenchuan Earthquake (Ms 8.0) of 12
161 May 2008, the main area affected by seismic tremors saw the formation of 34 barrier
162 lakes of different sizes. The Tangjiashan landslide lake had a storage capacity of 316
163 million m³ becoming the largest rainwater catchment lake with the highest
164 impoundment and posing the most severe threat (Lin *et al.* 2010). The isograms of
165 seismic intensity are also shown in Figure 9 which reveals a consistent trend in the
166 distribution of earthquake-induced barrier lakes as they are clustered in the area that
167 experienced a seismic intensity of X degrees (Cui *et al.* 2009).

168 In August 2010, Gansu Province was affected by very heavy rainfall with a
169 cloudburst in the mountainous Sanyanyu and Luojiayu catchments above the town of
170 Zhouqu triggering large debris flows. The debris flow deposits blocked the Bailong
171 (White Dragon) river forming a barrier lake that flooded part of the town (Tang *et al.*
172 2011b; Yu *et al.* 2010; Dijkstra *et al.* 2012).

173 In 2014, an earthquake of magnitude Ms 6.5 hit Ludian County of Zhaotong in
174 Yunnan Province and caused mountain collapses on both sides of Hongshiyuan Village,
175 blocking the Niulanjiang River and forming a barrier lake that flooded the area
176 upstream of the Hongshiyuan hydropower station (Liu 2015).

177 The emergency response to a barrier lake normally involves evacuating a large
178 number of people and mobilization of large amounts of human and mechanical
179 resources. After the Wenchuan earthquake, the Chinese government issued the

180 *Standard for Classification of Risk Grade of Barrier Lake* (SL450-2009; MWS 2009a)
181 to provide a technical and legal basis for emergency response actions. Barrier lake
182 dams were classified into several types, including high dams, narrow dams, short
183 dams, *etc.* According to the standard requirements (MWS, 2009a), the lakes are
184 classified into large size, medium size, small size (1) and small size (2) as shown in
185 Table. 3. They are then rated as extremely high risk, high risk, medium risk and low
186 risk according to Table. 4.

187 Of the 34 barrier lakes following the Wenchuan Earthquake, the Tangjiashan
188 barrier lake was classified as posing an extremely high risk, the Laoyingyan,
189 Xiaogangjian, Xiaojiaqiao and Nanba barrier lakes were classified as posing high risk,
190 with the remainder posing medium or low risks.

191 Controlled blasting is a common method of eliminating the hazard and thus
192 reducing the risk associated with barrier lakes as shown in Figure 10 (Liu et al., 2016).
193 It is usually adopted on occasions where the risk posed is judged to be significant and
194 to require urgent action: such situations include those in which recovery construction
195 works are hampered and transportation corridors required by the emergency services
196 are blocked, obstructed field construction and transportation conditions (*Technique*
197 *guideline for emergency disposal of landslide lake, SL 451-2009; MWS. 2009b*). For
198 instance, the blasting of a drainage channel followed by mechanical excavation was
199 adopted for reducing the risk associated with barrier dam outburst at three barrier
200 lakes on the Shiting River (i.e. Yanziyan, Upper Macaotan and Muguaping barrier
201 lakes), the Shibangou (Jialing River), the Ma'anshi (Fujiang River basin) and the
202 Xiaogangjian (Jinyuan River) barrier lakes. Channel drainage is the most common
203 method of reducing the risk associated with barrier dam outburst both in China and
204 other countries. Other examples include the Yigong, Tangjiashan, Xiaojiaqiao and
205 Hongshiyan barrier lakes as shown in Figure 11 (Liu, et al., 2016).

206

207 **Landslide Research in China special set**

208 The papers published in this thematic set represent a small part of a large number
209 of scientific reports and publications on landslide research in China.

210 Tu and Huang (2016) present an analysis of infiltration in embankments
211 constructed in sandy clay and gravel and evaluate the effects of rainfall intensity and
212 duration on the stability of the embankment slopes. Their numerical analyses provide
213 further insights into the differences in behaviour of the two materials, including a
214 lesser sensitivity to rainfall intensity of the stability of the sandy clay slope relative to
215 the gravel embankment slope but a larger and longer lasting reduction in slope
216 stability of the sandy clay embankment slope for longer duration rainfall events.

217 Two papers provide a contribution to landslide research in the Three Gorges area.
218 Shi *et al.* (2016) discuss landslide stability evaluation using High-Resolution Satellite
219 SAR (Synthetic Aperture Radar) data and Huang *et al.* (2016) describe a case study of
220 a pillar-shaped rock mass failure. Shi *et al.* (2016) used TerraSAR-X InSAR data pairs
221 with short normal baselines and temporal baselines to map landslide-prone areas and
222 the point-like target offset tracking (PTOT) approach to identify large displacements
223 to characterize potential landslides. Their methods provide a clear way forward to
224 evaluate landslide stability in this geodetically challenging terrain characterized by
225 steep slopes and dense vegetation. Huang *et al.* (2016) describe in detail a case study
226 of an unstable pillar-shaped rock mass in the Three Gorges area. Their calculations
227 show that this rock mass is only marginally stable (FoS 1.08) and that the collapse of
228 the pillar is related to local failure in a slowly deteriorating block at the foot of the
229 pillar that is periodically affected by the 175 m impoundment level of the reservoir.
230 Were this rock mass to fail, an estimated 360,000 m³ is likely to catastrophically enter
231 the Yangtze forming a substantial threat to local residents and passing tourists.

232 The effects of the magnitude 8.0 Wenchuan earthquake on the performance of
233 engineered interventions of the reinforced right abutment slope of the Zipingpu Dam
234 are analysed by Ren *et al.* (2016). This 156 m high rockfill dam experienced peak
235 ground acceleration in excess of 2g. The nearby natural slopes were severely affected
236 by the earthquake. However, the reinforced abutment slope coped very well and a
237 stable slope was maintained. The paper describes how this abutment slope
238 experienced stresses and strains during the earthquake as these were monitored
239 through multiple extensometers and load cells.

240 Zhou *et al.* (2016) provide a further example of monitoring and stability analysis
241 and discuss this using a case study of the left bank slope at the Jinping-I hydropower
242 station. This complex 530 m high excavated rock slope was instrumented with a
243 monitoring system comprising surface deformation observations, multi-point
244 extensometers and graphite bar extensometers. The complex geology of the site
245 provided challenging conditions for the construction of a safe slope, particularly as it
246 transpired that a large central section of the slope could potentially become unstable.
247 Detailed 3D slope stability analyses assisted with the design of a stable slope and the
248 observations from the monitoring network support the results from these design
249 analyses.

250 These five papers provide a further showcase and snapshot of research
251 currently being carried out on this topic in China and compliment the earlier thematic
252 set on Geohazards in China (Dijkstra *et al.* 2014).

253

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260

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Tables

359 **Table 1** Annual landslide events as a result of 175m trial impoundments from September 2008

360 until September 2014.

361 **Table 2** Two case studies of typical geological disasters as a result of a 175m impoundment in the

362 Three Gorges reservoir (Lu *et al.* 2014; Chen *et al.* 2014).

363 **Tab. 3** Classification of barrier lakes by size.

364 **Tab. 4** Risk factors of barrier lakes.

365

366

367 **Figures**

368 **Fig. 1** A view of Beichuan County town shortly after it was buried by the Weijiagou landslide of
369 the 24th of September 2008

370 **Fig. 2** Aerial photo of the August 13th landslide in Qingpingxiang Town, Mianzhu. Along a 3km
371 section through Qingpingxiang more than ten valleys saw the outbreak of simultaneous
372 mudslides and debris flows.

373 **Fig. 3** The market town of Qingpingxiang covered by silt and buried by the “8.13” torrent and
374 mudslide. The mudslide volume reached 6,000,000m³ and far exceeded that of the Zhouqu
375 mudslide (i.e. 1,800,000m³) (Extracted from www.nandu.com).

376 **Fig. 4** Cumulative rainfall recorded at the rainfall stations in Zhouqu and Dongshantai (from
377 Dijkstra *et al.* 2012).

378 **Fig. 5** A longitudinal section of the Dayu valley, one of the tributaries to the Bailong River
379 draining the Sanyanyu catchment where the Zhouqu debris flow originated. Steps in the
380 longitudinal profile are predominantly formed by palaeo-rock avalanches. The critical change
381 in behaviour occurred at an altitude of 2300 m; above this level discharge is characterized by
382 turbulent flow and large bedload transport, while below this step in the terrain the torrent
383 regime changed, eroded substantial quantities of valley-based deposits and took on the
384 characteristics of a debris flow (modified after Dijkstra *et al.* 2012)

385 **Fig. 6** Geological disaster monitoring and warning apparatus used in cold alpine and
386 densely-fogged mountainous areas.

387 **Fig. 7** The Monkey Stone landslide prevention and control projects and relocated households in
388 Fengjie County. The red line indicates the outline of the landslide.

389 **Fig. 8** Layout profile of the prevention and control project of the Monkey Stone landslide (See
390 also Figure 7).

391 **Fig. 9** Diagram showing the location of the barrier lakes related to the Wenchuan Earthquake. The
392 Roman numerals represent the earthquake intensity.

393 **Fig. 10** The large volume of material generated by the Zhouqu debris flow blocked the Bailong
394 river, causing extensive upstream flooding. Explosives were used to enlarge drainage

395 channels during the first phase of the emergency response mission.

396 **Fig. 11** Excavation of a drainage channel at the Hongshiyuan barrier lake during the first phase of
397 the emergency response mission.

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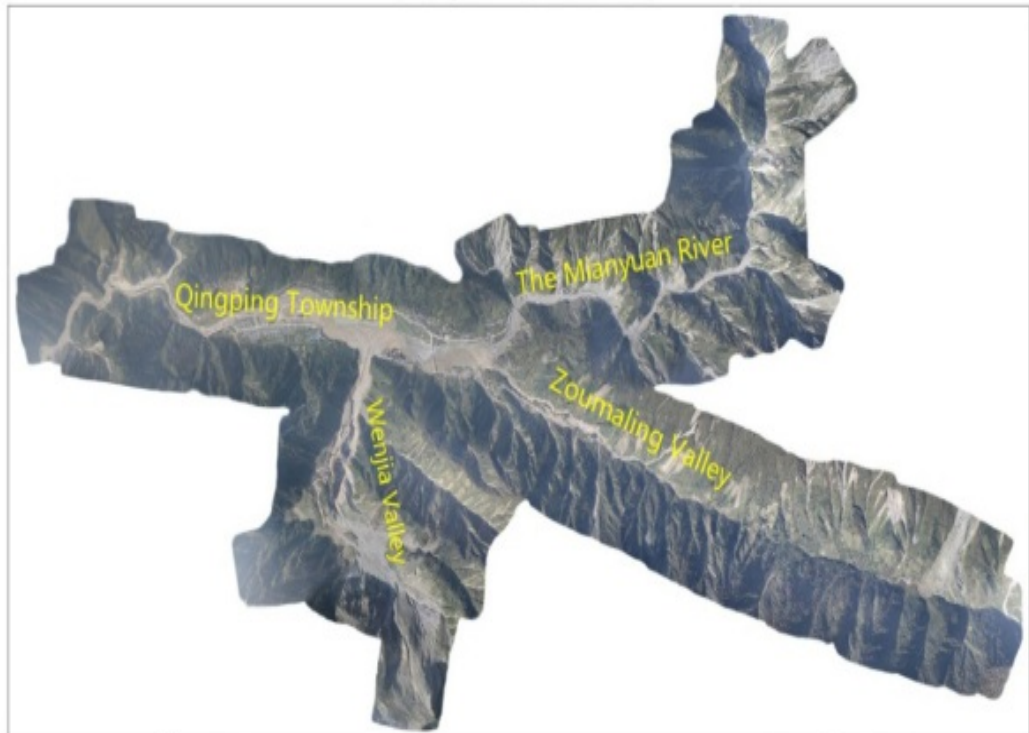
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Figure 1

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Figure 2.

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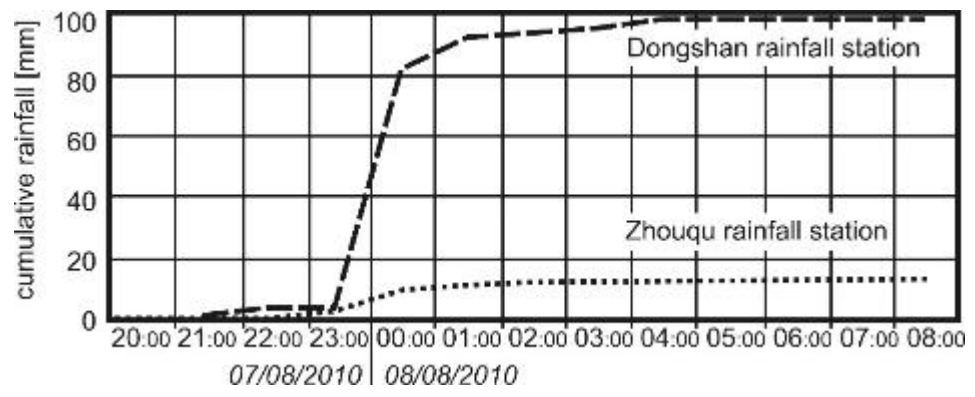
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Figure 3.

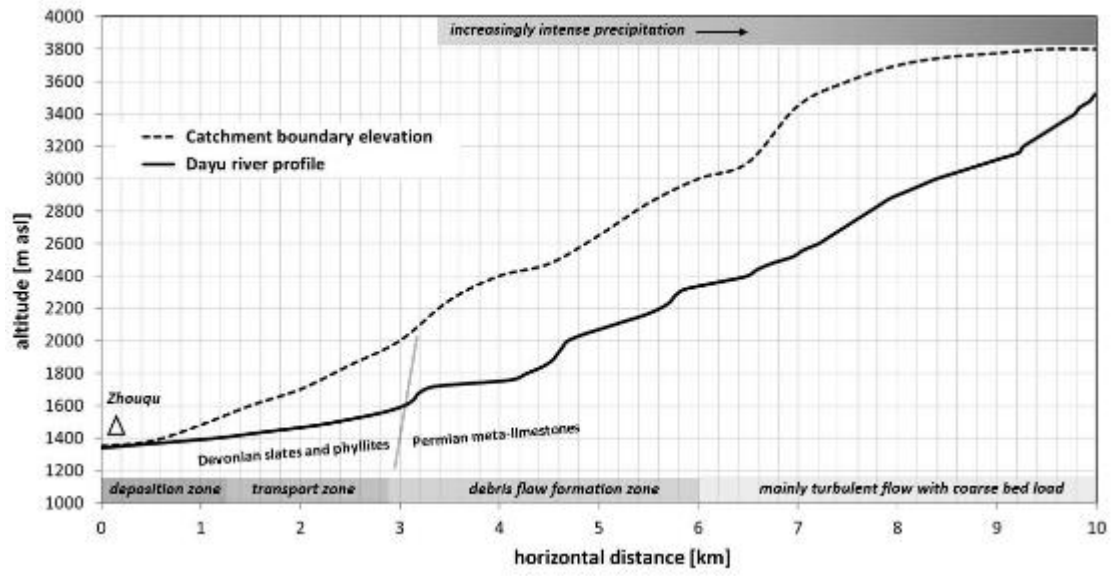
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Figure 4

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Figure 5

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Figure 6.

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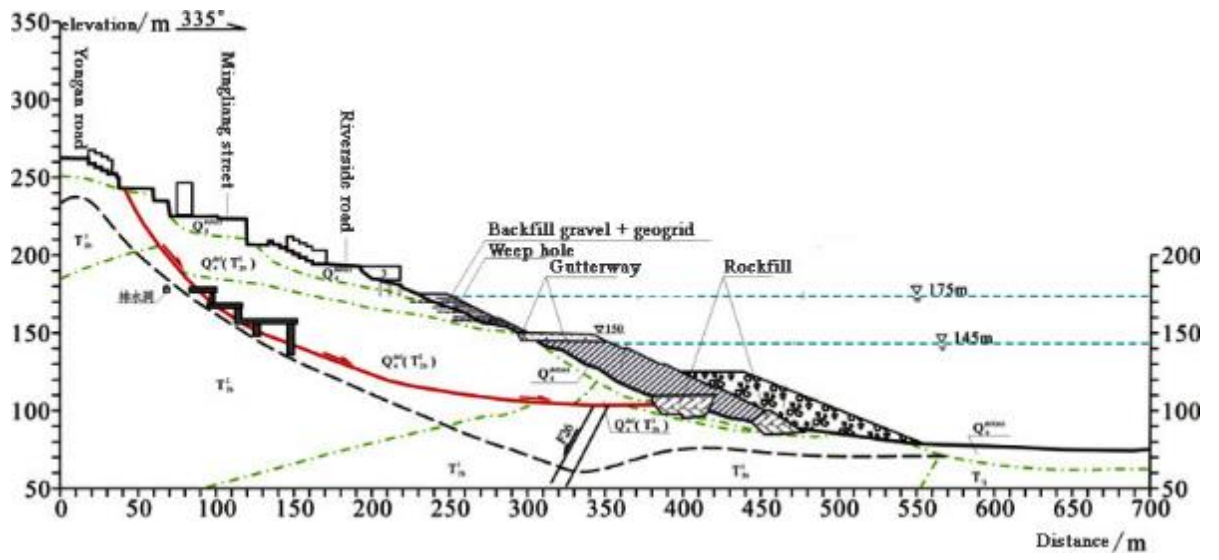
Figure 7

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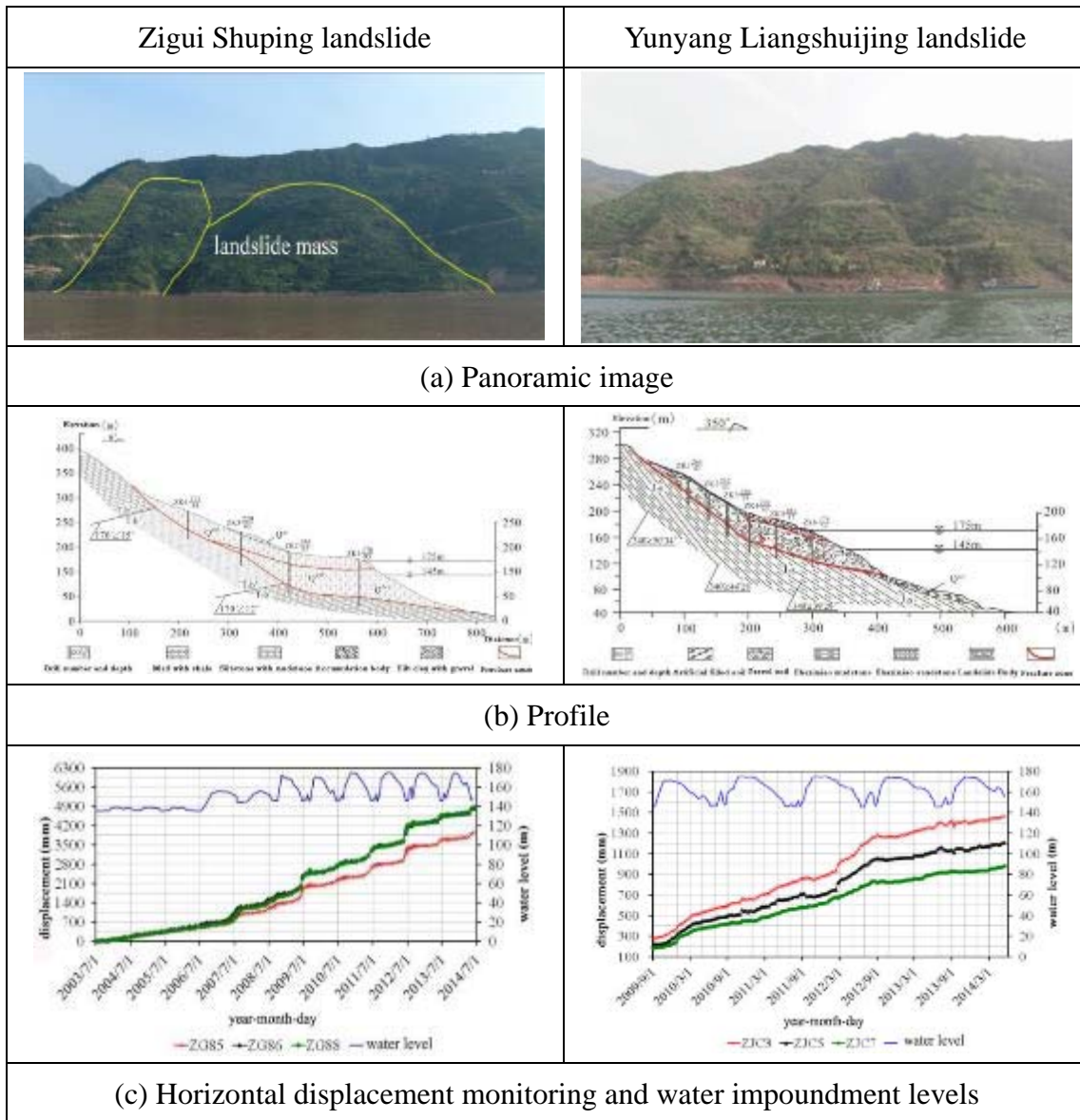
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Figure 8

Figure 9



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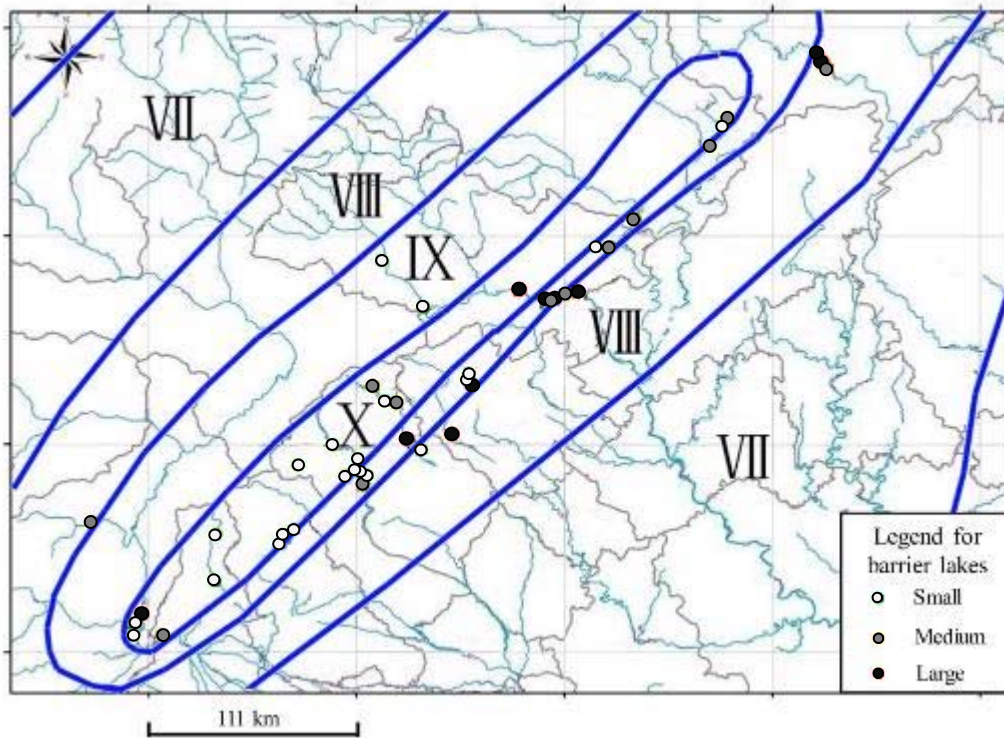
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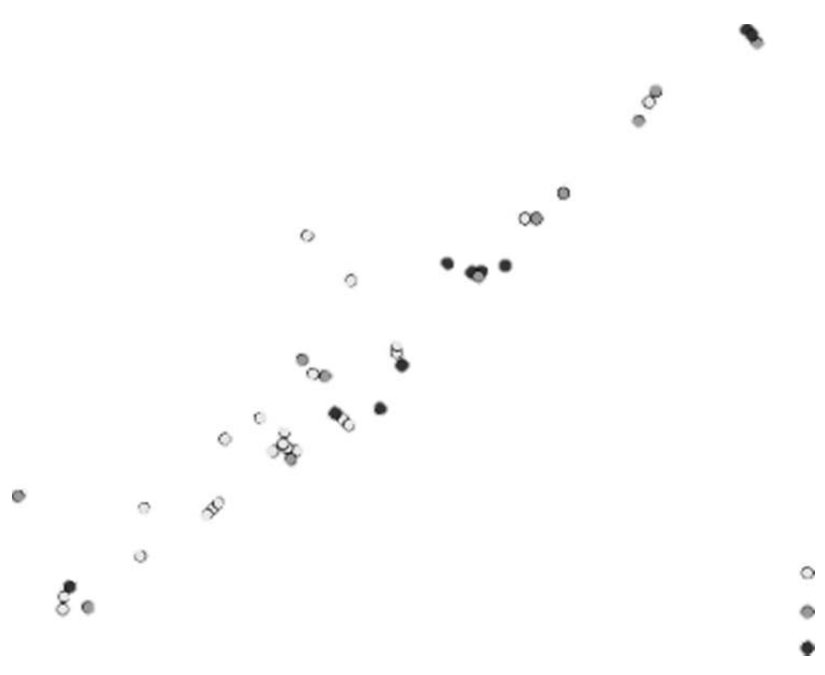


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Figure 10.



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Figure 11

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Figure 12