Landslide damming in Western Sichuan Province, China, with special reference to the 1786 Dadu River and 1933 Diexi events

by

Song Ling

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required revisions, as accepted by any examiners.

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Abstract

Landslides and landslide damming events can be triggered by various processes, and they can also cause catastrophic damage. With the help of historical documents and Geographic Information System (GIS), historical landslide damming events in Western Sichuan are investigated and reconstructed, in order to derive new data and knowledge.

This thesis contains four chapters. The first chapter presents a broad introduction to landslides and landslide-dammed lakes in China. Damage and distribution of these events are introduced, triggers to landslides, longevity of landslide dams are briefly illustrated; several large landslide damming events in Sichuan are discussed as examples, including the 1786 Dadu River, 1933 Diexi, 1967 Tanggudong, and 2008 Tangjiashan cases.

A detailed study of the 1786 Dadu River event is presented as the second chapter. Compared to the previous work, new information to this historical event is discovered. A new landslide site that is more consistent with most historical documents is proposed, and a dammed lake formed by the landslide is defined and measured. A maximum pool height of 1,300 m asl, and a volume of 1.15Gm^3 is derived. The estimated pre-breach dammed lake is one of the largest landslide-dammed lakes in Chinese history. Based on the 100,000 deaths the event caused, it is the most catastrophic landslide dam breaching event in world history.

The analysis of the 1933 Diexi event is presented as the third chapter. Precise locations of earthquake-triggered landslides are determined. Area and volume of the three lakes that formed in the Min River are calculated based on previous work and ArcGIS, and the surface area as well as volume of the lakes in different time eras are calculated. Further calculations and estimations of the initial source of the landslides, cross-section profiles, volume of water released, and outburst flood discharge are also presented in the chapter. The results shown that volume of the Diexi Lake before failure reached 450Mm^3,

and approximately half of the volume (200Mm^3) breached during the 1933 flood. The peak flood discharge of the dam breach was estimated to be 20,000m^3/s.

The research on the Diexi event shows its scientific significance: 1) Diexi Lake was one of the largest landslide lakes in China, and its failure was one of the most catastrophic that occurred in high population density areas throughout Chinese history; 2) the Diexi landslide dams show a combination of landslide dam failure as well as long-term dam stabilization; 3) no surveying data can be found in the Diexi area from the 1930s, which means that estimation has to be made based on research in the Min River valley before the 1933 earthquake, and observation of the Diexi Lake before its failure.

A study of the relationship between magnitude and frequency of natural hazard event is presented as the fourth chapter. Since the magnitude and frequency relationship of natural hazards can be expressed as a robust power law regression, which can be used in quantitative risk assessment, a brief investigation is carried out on M&F correlation of historical earthquakes in the different areas, landslides that caused damming, and dammed lakes in China. Results found in this research are compared to previous work by others, and characteristics of the natural hazard frequencies are illustrated. The study shows that the magnitude of damming landslides in China has a similar trend compared to the worldwide dataset. Also, China is prone to more small dammed lakes than the world average, reflecting its rugged tectonically-active geomorphology.

Acknowledgements

Firstly, I thank my advisor Dr. Stephen G. Evans for his guidance, patience and encouragement.

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In addition, I thank the State Key Laboratory of Geohazard Prevention and Geoenvironment Protection (SKLGP), Dr. Runqiu Huang and Dr. Yunsheng Wang for the Open Fund Financial Support and their kindly help during the 2014 field investigation.

Lastly, I thank Dr. Keith Delaney for his kind help and guidance in ArcGIS and Remote Sensing.

Dedication

This is dedicated to my parents, Zina Bao and Yaxi Ling, for their patience and support.

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Chapter 1

Landslide dams and landslide lakes in China

1.1 Context

Landslide has been long been regarded as one of the most devastating natural hazard processes in the world (Huang, 2008). Landslide shows its wide distribution in every mountainous area throughout the world, causing huge casualties and damage to the communities-infrastructure. As the global climate is changing, as well as artificial perturbation to the environment is increasing, the frequency of landslides is also increased (Huang, 2008).

China is one of the countries that experience most damage by landslides (Nadim et al., 2006). Catastrophic landslides are observed in every province other than Shandong (Huang, 2008). Due to tectonic and geomorphologic complexity, mountainous areas occur mainly in western China. This area is located on the boundary of the Tibetan Plateau and including the regions of eastern Tibet, Sichuan, Yunnan, Guizhou, Chongqing and western Hubei. As summarized in Table 1.1, all major historical landslide dam/lake events discussed in this chapter occurred within this area. The reasons why this area has a noticeably higher frequency of landslide damming events are: high earthquake frequency, large elevation drop caused by the Indian plate collision and subduction, and steep valleys cut by numerous major rivers.

Landslide hazard consists not only of distribution of occurrence, but also the potential for catastrophic and destructive behavior. It has been reported that previous to 2000, approximately 41,000 landslides were documented, with a total effected area of 1.74Mkm^2 (18.1% of Chinese territory); annual fatalities caused by landslides are over 1,000 every single year since 1995 (Huang, 2008). Along with earthquakes, severe casualties and huge economic losses make landslides one of the most destructive natural hazards in China.

Landslides can be deadly not just because they can engulf towns in a blink of an eye, but also because they cause secondary disasters or continuous threats. When landslides occur along rivers and block channels, dammed lakes are formed. Rising water level in the upstream area submerges the valley-bottom areas, and the lake may breach when the landslide (the natural dam) loses its stability. Thus, a breaching flood can cause much additional damage to the downstream area. The flood caused by the breach of the Dadu River landslide dam in 1786 killed approximately 100,000 people and is probably the most destructive single-event landslide disaster in the world (Figure 1.1). The 1933 Diexi event is also one of the most severe landslide dam breach events in recent Chinese history, for it killed over 2,000 people, causing significant loss of lives (Chang, 1934). The 2000 Yigong Lake was formed due to a snowmelt landslide along the Yigong Tsangbo River on April 9. Evans and Delaney (2015) measured the possible scale of the Yigong Lake before its failure on June 10, and massive volume of 2.015Gm^3 is revealed. The outburst flood damaged several roads and bridges in China, and caused casualties along the Brahmaputra River in India.

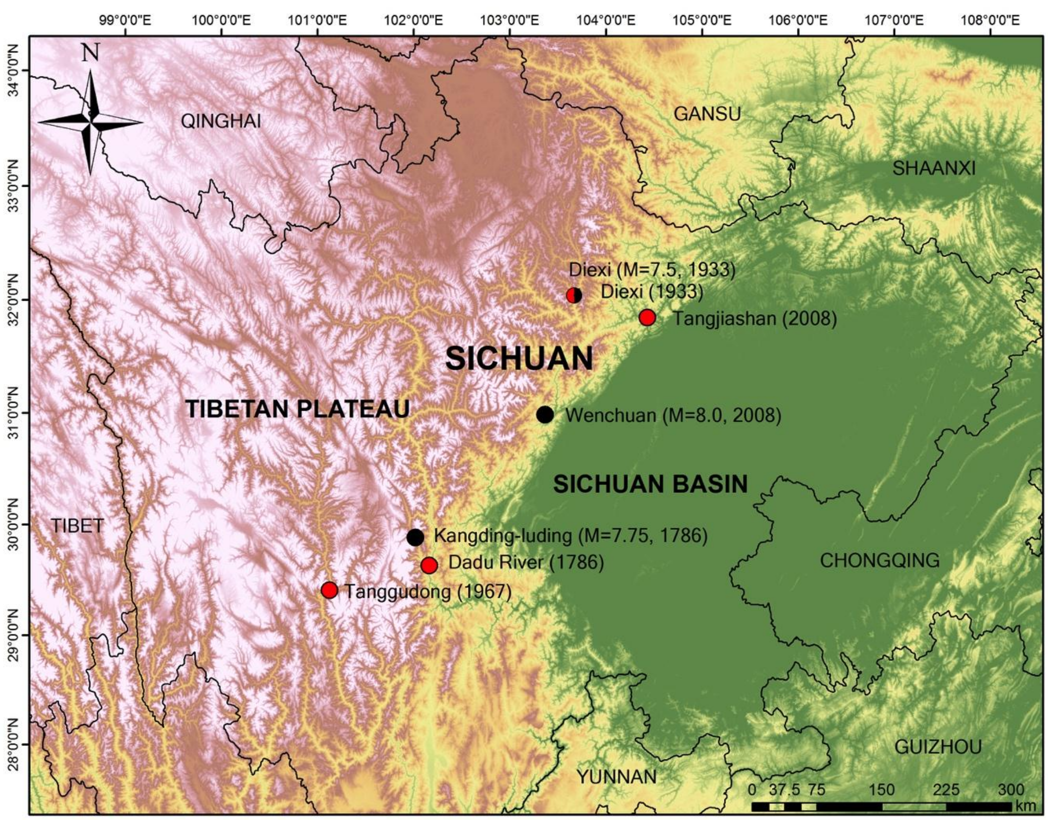

Figure 1.1 Locations of the landslide damming events in western Sichuan, China discussed in this thesis. Major earthquakes that triggered these events are labeled on the map. All events are located in the boundary zone between the Sichuan Basin and the Tibetan Plateau.

Huge casualties caused by landslide dam breaches reflect the significant potential impacts that these natural hazards may exert on society. Previous to 1950 the lack of natural disaster knowledge and communication tools led to little awareness by local authorities, which led to a failure to evacuate downstream areas. As the awareness of civil authorities to the potential breaching landslide dams was raised after the 1950s, large-scale downstream evacuations are implemented when any sign of a dam breach occurs. As a result, casualties caused by landslide dam breaches has been reduced significantly. Mitigation work, which includes constructing spillways and diversion tunnels, can control the maximum flood discharge and water level of the dammed lake effectively. This type of mitigation was carried out to the landslide dams that have the possibility to fail, such as the Tanggudong, Yigong, and Tangjiashan events. For example, 32 landslide dammed lakes larger than 10,000m^3 were formed during the 2008 Wenchuan Earthquake (Xu et al., 2009). With proper excavation, catastrophic dam breaches and outburst floods were avoided, and damage to downstream areas was reduced to a minimum.

1.2 Objectives

This thesis focuses on landslide dams and landslide lakes in China. The overall purpose of this thesis is to analyze landslide damming in Western Sichuan Province, China, with special reference to two historical events that breached and caused catastrophic damage to downstream areas: the 1786 Dadu River and 1933 Diexi landslide dams. Five specific research objectives were formulated in pursuit of this goal:

1. Introduce an overview of landslides and landslide dams in China, with some of their key characteristics.
2. Review several major landslide damming events in western Sichuan (Tanggudong, Tangjiashan), with brief chronology and event processes, major landslide dam and lake parameters.
3. Review and analyze the 1786 Dadu River event. A major part of this objective is to re-examine the evidence presented and conclusions drawn by Dai et al. (2005), on the 1786 Dadu River event,

and to attempt to correct parts of the paper (landslide location, lake area and lake volume), by adding new information that fits better the historical documents.

4. Review and analyze the 1933 Diexi events. Apply Geographic Information System (GIS) to historical events, where pre-event data is missing, in order to derive new data and knowledge about the complex events.
5. Apply the Magnitude and Frequency research from Evans (2006a, b) to landslide damming in western Sichuan, using events in China to verify and expand its credibility and reliability.

1.3 Methodology

1.3.1 Chapter 2&3

The purposes of Chapter 2 and 3 are to investigate and reconstruct major landslide damming events in Western Sichuan by using ArcGIS, thus the methodology of the two chapters are similar. Data used for the study includes a SRTM-3 digital elevation model (DEM) of the studied area obtained from http://srtm.csi.cgiar.org, and data (photographs, GPS coordinates) recorded in field investigations in 2013 and 2014. Moreover, for the Dadu case, additional information has been provided by the State Key Laboratory of Geohazard Prevention and Geoenvironment Protection (SKLGP), including a geological map, a geological cross-section, and a landslide engineering geology report as part of collaborative work on the Sichuan landslide dams.

ArcGIS is the main tool used for the study. Firstly, the maximum pool elevations of the landslide-dammed lakes are obtained from a literature review and historical documents. Then, lake areas are calculated by measuring the contour area in GIS at the pool elevations. Verification estimation is applied by georeferencing a historical map (where available) into ArcGIS. Next, volumes of the existing lakes are estimated by regression analysis. Multiple equations are introduced in order to minimize the error of the estimation, and error bars are applied to show the standard deviation. For the breached lakes, volume are calculated by the “Surface Volume” function of ArcGIS, which measures the volume of a raster dataset surface above or below a given reference plane. In this case, the volume above the DEM but below the pool elevation is derived. Finally, outburst flood discharges are estimated by well-known regression equations in the literature.

1.3.2 Chapter 4

The purpose of Chapter 4 is to study magnitude and frequency relations of earthquakes, landslides and dammed lakes in China. For this study, historical earthquake data is from the China Seismic Information website (www. csi.ac.cn), and data on landslides and dammed lakes are from a detailed catalog by Chai et al. (1995).

Tools used for data analysis are Microsoft Excel and GoldenSoft Grapher. Events are first sorted by their magnitudes (for earthquakes Richter magnitude scale; for landslides and lakes volume) from largest to smallest. Then, these events are ranked according to magnitude. Events with the same magnitude are numbered as the lower rank (e.g., if the 2^{nd} and 3^{rd} events have the same magnitude, they are ranked as 3). Next, the rank is divided by the time span of the record (measured in years), deriving the annual frequency. Thus, a magnitude-frequency plot can be made on a log-log scale. After generating a power function trendline, the “slope”, which refers to the power, is calculated and analyzed. The slope reflects the distribution of hazard events at different orders of magnitude, and it can be used to make a quick estimation of the frequency of an event of a certain magnitude that may occur in the study area.

1.4 Landslide triggers

Landslides are mainly triggered by earthquake, heavy precipitation, weathering, rapid erosion, snowmelt, and artificial perturbation. For China, earthquake takes a large proportion (Wen et al., 2004), that can also be appreciated in Table 1.1. Wen et al. (2004) found that around 75% of the landslides are triggered by rainfall, and 20% of those are induced by earthquakes, after researching 70 giant landslides in China since 1900. In addition, Evans et al. (2011) found that one third of the major landslide dams are caused by strong earthquakes.

1.5 Longevity of landslide lakes

Not every landslide lake fails. A large percentage form permanent lakes and become part of the local terrain. Permanent landslide lakes are widespread throughout the world, and also in western China. These lakes are called “Haizi” in Sichuan dialect, meaning “sea”. Evans et al. (2011) found that less than half (9 of 19, 47%) of the researched landslide lakes over 20Mm^3 have breached or partially breached since their formation. Further, among all breached lakes from 1841 to 2010, Evans et al. (2011) stated that half of lakes breached within 75 days; no more than 20% percent failed after one year; and only 6% of these failed two years after their formation. Figure 1.2 (Evans et al., 2011) shows the general trend of the relationship between days to failure and percent of dams lasting for longer, based on a dataset of 15 landslide / rockslide dams that finally breached between 1841 - 2010. The figure illustrates a fairly reasonable trend of longer longevity is associated with a smaller possibility to fail.

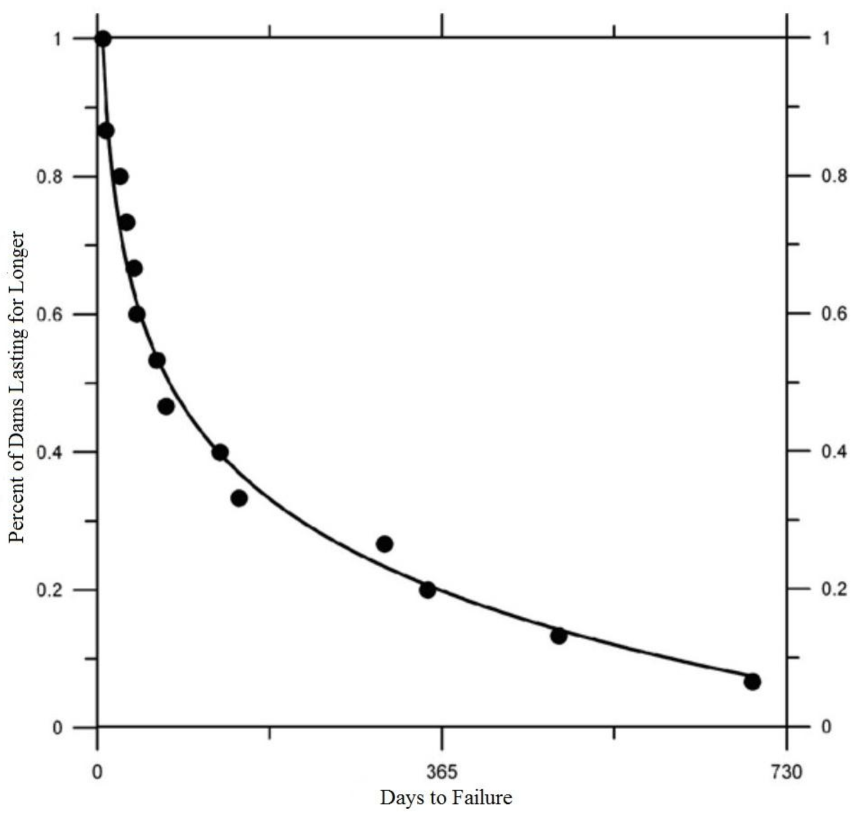

Figure 1.2. The longevity of 15 landslide dams for which the dates of formation and failure are known in the period 1841-2010 (after Evans et al., 2011)

1.6 Landslide dam breach and flood discharge

As the amount of water that forms a landslide-dammed lake may breach in very short period of time, the peak discharge that a landslide dam outburst could generate may be massive. Dams are mostly located in mountainous areas with narrow river channels, and restricted valley topography that also helps to increase maximum flood wave height as well as peak discharge. Therefore, peak discharge of a landslide dam breaching flood is larger than that of a normal flood caused by precipitation, by several orders of magnitudes (Evans et al., 2011).

Among all historical landslide dam breach events in China, the 2000 Yigong Lake created the largest flood, reaching a peak flood discharge of 120,000m^3/s (Shang et al., 2003). In comparison the maximum flood discharge of the 1998 Yangtze River flood, which is one of the heaviest floods in Chinese history, was 71,100m^3/s (Zong and Chen, 2000). Evans et al. (2011) also stated that the peak flood discharge of the 2000 Yigong outburst also exceeded that of the largest artificial dam breach ever recorded. Thus, landslide dam failure can potentially be one of the most devastating hydraulic processes (Evans, 2006b).

1.7 Typical landslide dam events in Western Sichuan

As shown in Table 1.1, some typical landslide damming events in Western Sichuan are introduced. Processes of forming, breaching and mitigation are discussed. Moreover, for the breached cases, downstream flood and damage are outlined.

Table 1.1. Major landslide dams in western Sichuan in the historical period (for location see Fig. 1.1).

Locality	Coordinates	Date	Triggered by	Breach Date
Dadu River[2]	29.6249N 102.1564E	01/06/1786	Earthquake	10/06/1786
Diexi[3]	32.0356N 103.6738E	25/081933	Earthquake	09/10/1933
Tanggudong[4]	29.4100N 101.1239E	08/06/1967	Weathering & erosion	17/06/1967
Tangjiashan[5]	31.8453N 104.4280E	12/05/2008	Earthquake	N/A[1]

1: N/A - Controlled breach by artificial spillway. 2: Dai et al., 2005. 3: Chang, 1934. 4: Chen et al., 1992. 5: Cui et al., 2011

1.7.1 Dadu River, Sichuan, 1786

The 1786 Dadu River natural dam breach cost the largest casualties in a landslide disaster in Chinese history. The landslide dam was caused by the Kangding - Luding Earthquake that occurred at noon, 01/06/1786, and the epicenter of the earthquake is 29.8833N, 102.0167E, with an estimated of magnitude M7.75 (Dai et al., 2005). Dai et al. (2005) investigated some of the potential locations and proposed a possible landslide site. The site consists of two landslides, with volume of 6Mm^3 and 5Mm^3, respectively. They estimated that the landslide-dammed lake formed by the landslides had a 6.8km length, a 1.7km^2 area, a pool elevation of 1,180 m asl, and a total volume of 50Mm^3.

However, it is doubtful whether the breach of a 50Mm^3 lake could have led to such damage as is documented downstream. Thus, the credibility of the landslide location suggested by Dai et al. (2005) is questioned. Thanks to the help of Dr. Y. S. Wang from the State Key Laboratory of Geohazard Prevention (SKLGP), some new information about this event is revealed. As detailed in Chapter 2, a new potential landslide site is proposed, which is adjacent to the one suggested by Dai et al. (2005). A new lake volume of 1.15Gm^3 is calculated based on our analysis of the newly proposed site, matching most of the description in historical documents.

1.7.2 Diexi, Min River, Sichuan, 1933

The Diexi landslides refer to a group of landslides induced by a M7.5 earthquake which occurred on 25/08/1933, near the Town of Diexi, Sichuan, China (coordinate of the town: 32.0419N, 103.6800E) (Chang, 1934). As described in Chapter 3, three landslide lakes were formed as several major landslides blocked the Min River. They are: Da Lake, Xiao Lake, and Diexi Lake, in order from upstream to downstream. At the same time, a series of minor landslide lakes were formed in the surrounding area, especially along the Songping Gully, one of the Min River's tributaries. Among all remaining lakes, the Da Lake is the largest, with an average depth of 81m, average width of 360m, 3500m in length, and total volume of 70Mm^3 (Chai et al. 1995). Because of alluvial deposition over 80 years, the original lake (before the dam breach) was much larger (based on Chang, 1934, maximum length of the lake once reached 12.5km). The Xiao Lake is 2,350m in length, 290m in average width, 42m in average depth, and 50Mm^3 in volume (Chai et al. 1995). The Diexi Lake, which breached 45 days after its formation, had an estimated volume of 80Mm^3 (Chai et al. 1995).

The Diexi Lake breached on 90/10/1933, 45 days after the initial earthquake. The dam breach was triggered by a convergence of factors, including M4.5 aftershock, minor dam failures in a tributary, and heavy precipitation in upstream areas. Based on the estimations of Chang et al. (1934), maximum flood wave height during the breach was 66m near the dam, 24m at Mao County, and 12m at Guan County (the present Dujiangyan). The flood affected over 250km of downstream areas (Li et al., 1986).

Due to the lack of geology knowledge of the local authorities, no risk assessment or pre-disaster evacuation were applied after the landslide lakes formed in 1933. As a result, one of the lakes breached in a situation completely out of control, and caused devastating damage downstream. Based on the survey of Longqing Chang (1934), the earthquake killed over 6,000 people, and the Diexi Lake outburst flood killed another 2,428 people, making the 1933 event the most devastating landslide dam breaching disaster in China in the 20th Century.

1.7.3 Tanggudong, Yalong River, Sichuan, 1967

The Tanggudong landslide occurred at 9:00, 08/06/1967, on the west bank of the Yalong River, approximately 80km downstream of the County of Yajiang (coordinates: 29.4100N 101.1239E). A landslide lake formed by the blockade overtopped the dam at 9:00 17/06/1967, some 9 days later; and the dam breached on the same day, at about 14:00. Although nearly 50 years have passed, the 1967 landslide boundary can still be clearly seen from a satellite image, mainly because of the steep 45 ° slope (Figure 1.3). The landslide is located near the Tibetan Plateau, where it is hard for vegetation to recover; the bedrock mainly consists of granite and quartz veins, which resist weathering (Huang, 2008).

It has been estimated that 68Mm^3 of landslide material rushed into the Yalong River (flowing N to S), forming a dam whose east side was 335m high, and 175m high of the west side (Chen et al., 1992). Thus, it is estimated that the height of the landslide dam was 175m (Figure 1.4). The landslide dam formed a lake which was 53km in length, with a total volume of 680Mm^3(Chen et al., 1992).

The landslide lake did not breach at its maximum volume. Based on data from hydrologic stations both upstream and downstream, Chen et al. (1992) calculated the breached volume was 640Mm^3, which was 94% of the total volume. Due to dam failure and water erosion, the dam height was dropped to 87m (Li et al., 1986). As the river depth decreases dramatically when the water level approach the remnant dam, flow velocity was reduced. Therefore, sediments started to fill the lake. A "line-like" landslide lake can still be observed at the site, with a total length of over 10km, 25 - 300m in width, and 15 - 20m in depth (Huang, 2008). Rapids have formed by water passing directly over the landslide debris, due to sudden increase in river gradient (1:40, figure 1.4) at the dam.

Huang (2008) reported the peak flood discharge to be 57,000m^3/s, while Chen et al. (1992) and Li et al. (1986) stated that the peak discharge recorded in the event was 53,000m^3/s, which was recorded at Mahe hydrologic station, 6km downstream of the landslide site. The flood had a significant influence on the Yalong River, as well as the Yangtze River, which the Yalong River flows into. A water level rise of 1.54m was measured in Chongqing, 1,730km downstream (Huang, 2008). Table 1.2 shows a summary of the measured maximum wave height during the outburst flood versus distance from the landslide dam (Chen et al., 1992).

Table 1.2. Outburst flood from Tanggudong rockslide dam 1967: maximum wave height versus distance from the dam (data from Chen et al., 1992).

Hydrologic station	Distance from dam (km)	Maximum wave height (m)
Mahe	6	50.4
Wali	214	29.6
Luning	310	20.4
Deshi	551	16.5

No deaths resulted from the outburst due to proper evacuation actions by authorities. However, property losses were inevitable: 435 houses, 2.33km^2 farmland, 131 livestock, 79 tons of harvested crops, 51km of roads, 8 bridges, 47 tunnels, and three hydrologic stations (Mahe, Wali, Luning) were destroyed by the outburst flood (Chen et al, 1992, Li et al., 1986).

The Tanggudong landslide can be classified as a landslide that does not have an obvious trigger (e.g. earthquake, rain, snowmelt, artificial perturbation). Based on Huang's analysis (Huang, 2008), it is triggered by long-term weathering and river erosion.

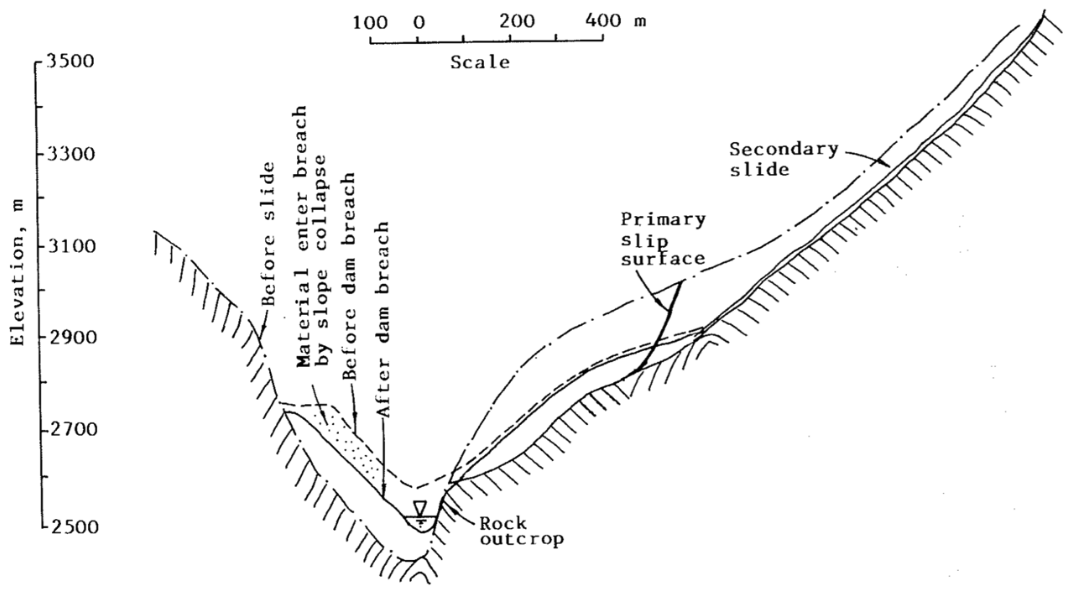

Figure 1.3. Cross section through the Tanggudong landslide dam on the Yalong River facing downstream (Figure 3 from Chen et al., 1992, p. 814).

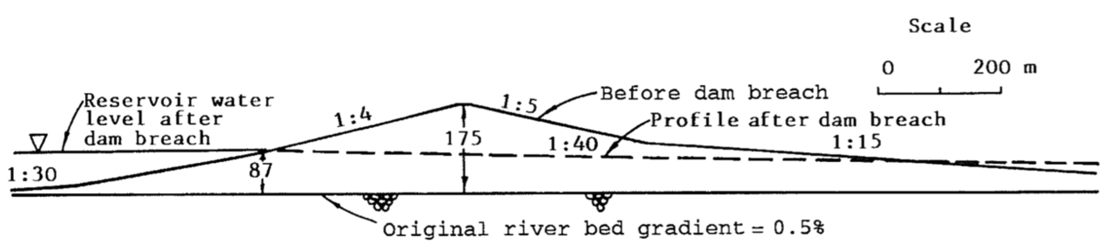

Figure 1.4. Longitudinal cross section of the Tanggudong dam (Figure 4 from Chen et al., 1992, p. 814).

1.7.4 Tangjiashan, Sichuan, 2008

Tangjiashan Lake was the largest landslide lake induced by the M8 2008 Wenchuan earthquake

(Cui et al., 2011). It is located at 31°51’N 104°26’E, along the Tongkou River, 6km upstream from Beichuan City. The original landslide dam was 803.4m along the river profile, 611.8m across the river, and 82.65m in height, with a total volume of 20.37Mm^3 (Huang, 2008). The highest and lowest point of the dam were at 793.9 m asl and 669.5 m asl, respectively. Before the artificial breach was initiated, the lake reached a highest water level of 740 m asl, and a volume of 315Mm^3 (Cui et al., 2011).

As the Chinese government realized the potential threat they were facing, evacuation actions were applied (Cui et al., 2011). After risk assessment, including a breach simulation to the dam, over 70,000 people living in potential submerged areas were moved to higher ground (Cui et al., 2011). Meanwhile, an artificial spillway was designed to lower the water level of the dammed lake. The spillway was designed to be 695m long and 8m wide at the bottom; its entrance elevation was 742 m asl, and exit elevation was 740 m asl (Cui et al., 2011). The construction of the spillway was accomplished on 31/05/2008. The spillway was slightly different from the design plan, with a shorter length (475m), and lower elevation (740 m asl at entrance, 739 m asl at exit) (Cui et al., 2011).

A controlled breach was initiated when water level reached 743m at 13:30, 07/06/2008. A peak flood discharge of 6,500m^3/s was recorded at 11:30, 10/06/2008 (Cui et al., 2011). As shown in Figure 1.4, the breach process lasted for approximately two and half days. During this process, water level of the lake was reduced by 30m (743 m asl to 713 m asl).

The breached water did obvious erosion to the artificial spillway. After the flood, the spillway was enlarged to 890m in length, 200m in width; the entrance width was 145 - 225m wide and the elevation is 713.5 m asl, while 100-145m in width and 704.2 m asl at the exit (Cui et al., 2011). Approximately 5Mm^3 of landslide materials were eroded during the breach process, which meant that the volume of the remaining landslide dam was about 15Mm^3 (Cui et al., 2011). By 12/06/2008, the breaching process was essentially complete. At that time, flood discharge passing through the spillway was already reduced to 78m^3/s, and the total volume of the lake was decreased to 80Mm^3 (Huang, 2008).

The Tangjiashan event is the largest landslide dam event in China in recent years, and it is also an excellent example of prevention and reduction in natural disaster potential. Although the initial landslide buried 84 people, no casualties were caused during the whole excavation and breaching process. Wise planning, rapid response and relatively precise construction are the keys as to why the Tangjiashan Lake mitigation turned out to be a great success. These are good lessons that should be learned for the future.

Figure 1.5. Tangjiashan landslide-dammed lake during controlled breach on June 10, 2008. Note the enlarged spillway caused by water incision over the landslide body (Photographed by Prof. Liu Ning. Figure 10.14 from Cui et al. 2011).

Chapter 2

The 1786 Dadu River Event

2.1 Introduction

The 1786 landslide-damming event is located along the Dadu River, western Sichuan, China. The landslide dam was caused by the Kangding - Luding Earthquake that occurred at noon, 01/06/1786; the epicenter of the earthquake is 29.8833N, 102.0167E, with an estimated magnitude of M7.75 (Dai et al., 2005). Seismic waves spread along the Moxi fault and reached the landslide site, approximately 30km SE of the epicenter, with an intensity of IX (Dai et al., 2005). The Dadu River area is geologically complicated and highly seismic. As three major fault zones intersect in this region, historical and pre-historical landslide damming events can be found along the Dadu River valley. Ouimet et al. (2007) and Wu et al. (2013) made detailed inventories of these events, and analyzed landslide mechanisms and river morphology of the area. Dai et al. (2005) published a detailed account of the 1786 landslide along the Dadu River and the subsequent dam breach and outburst flood. This paper is a highly detailed summary to this historical event, mainly because its comprehensive collection of historical data from original documents (Dai et al., 2005), and represents the major reference work on the 1786 Dadu event.

As the earthquake happened over 220 years ago, and the landslide lake breached with all its volume, few historical records can be found indicating the precise landslide location and the extend of the landslide dammed lake. Dai et al. (2005) investigated some of the potential locations and proposed a possible landslide site, which is shown on Figure 2.1. As Dai et al. (2005) did not mention the coordinates of the site, it has to be found on satellite images using the map and photographs they provided. The estimated coordinates of the remaining landslide bodies are believed to be 29.6314N, 102.1608E.

As shown in Figure 2.1 (Figure 6 in Dai et al., 2005), two sub-landslides can be discerned from the site; slide 1 is located to the north and slide 2 lies to the south. Based on the estimation of Dai et al.

(2005), the slope angle is 35 °- 40 °, and volume of slide 1 and 2 are approximately 6Mm^3 and 5Mm^3, respectively. Dai et al. (2005) also indicated that slide 2 was the landslide that entirely blocked the Dadu River, for its remaining landslide debris can still be found on the other side of the river along the sliding direction. Moreover, the height of the dam was calculated as approximately 70 meters by Dai et al. (2005). As a result, landslide lake data can be obtained from a DEM (Digital Elevation Model), showing the highest water level was 1,180 m asl, lake length was 6.8km, lake area was 1.7km^2, and total volume was 50Mm^3 (Dai et al., 2005).

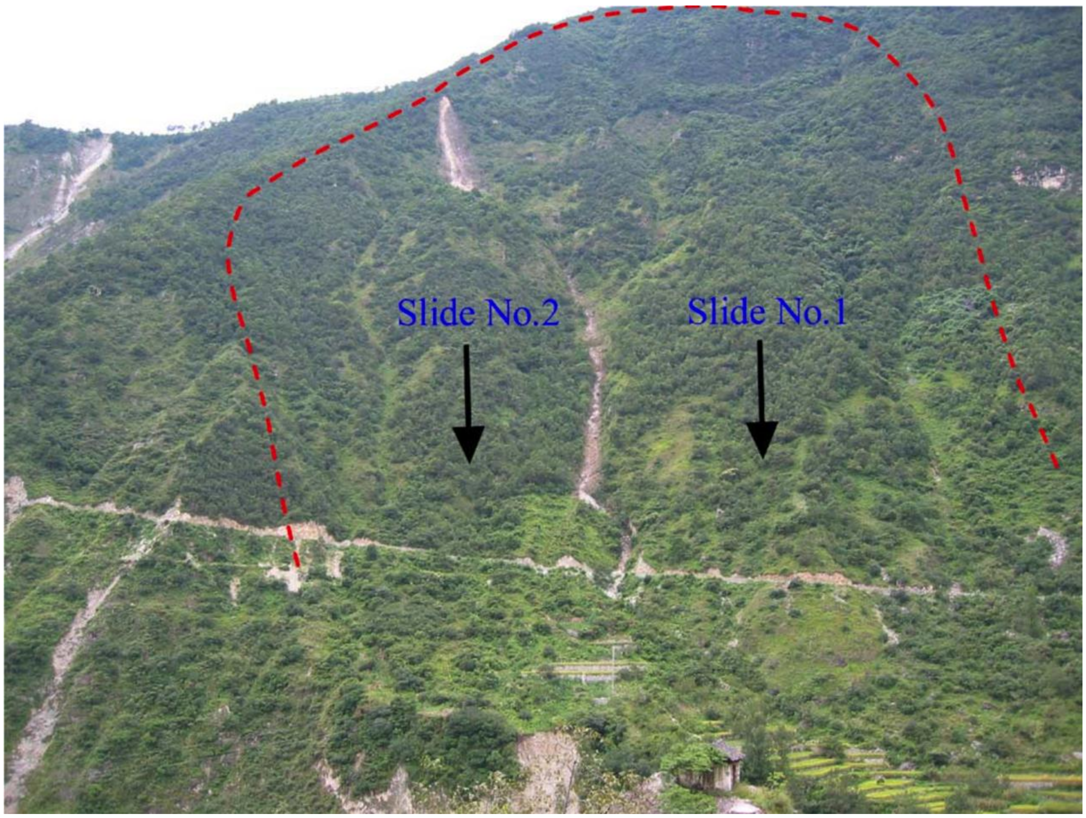

Figure 2.1. Landslide that formed the 1786 lake, located on the right bank of the Dadu River (coordinates: 29.6314N, 102.1608E) according to Dai et al. (2005). The red dashed line indicates the landslide boundary. (Figure 6 from Dai et al. 2005, photograph facing west)

According to historical document, the landslide dam overtopped on 09/06/1786, and breached the next day, causing a destructive downstream fold that killed about 100,000 people downstream. Dai et al. (2005) estimated some parameters of the flood by using various regression equations. The result shown the mean velocity was 3.5m/s, and the peak flood discharge was 37,345m^3/s (Dai et al., 2005).

Compared with normal flood parameters and annual hydraulic data, the peak flood discharge was 6.8 times larger than the largest flood discharge recorded in the Dadu River (5,500m^3/s, in 1992), and about 25 times of the average flow (100 - 1,500m^3/s) (Dai et al., 2005).

However, the killing of approximately 100,000 people in one of the most severe dam breach events recorded in world history, suggest a significant and very large landslide dammed lake. However as rated above, Dai et al. (2005) estimated the breached dammed lake that caused the flood to be only 50Mm^3 in volume. We consider this too small in volume to have caused the well-documented outburst flood catastrophe downstream. With help from Dr. Y. S. Wang, from the State Key Laboratory of Geohazard Prevention (SKLGP), some new information on this historical event is discovered. A new site of the 1786 landslide is proposed, and the volume of the dammed lake formed by the landslide is calculated for the first time. Moreover, earthquake magnitude and frequency of the Dadu River area is also briefly studied (see Chapter 4).

2.2 The 1786 Dadu landslide dam – the suggestions of Dai et al. (2005)

Dai et al. (2005) proposed two adjacent landslides, with volumes of 6Mm^3 and 5Mm^3, respectively (Figure 2.1). Based on the estimation of Dai et al. (2005), the dammed lake caused by the landslides reached an elevation of 1,180 m asl. At this pool elevation, the lake was 6.8km in length, 1.7km^2 in area, and 50Mm^3 in volume. It is doubtful a dam breach of this limited scale could cause such catastrophic damage downstream. Meanwhile, the reservoir proposed by Dai et al. (2005) cannot match most of the historical descriptions. Moreover, it is found that the total volume of water that is impounded by the dam in 9 days is far larger than the proposed reservoir volume, which means that in Dai's case, the dam would have no reason to hold such a long time. Therefore, it is considered that the landslides and its dammed reservoir proposed by Dai et al. (2005) are unlikely to have caused the 1786 dammed impoundment or the volume necessary for the documented downstream catastrophe.

2.3 A more probable landslide dam – the Mogangling landslide

Wang and Pei (1987) suggested that the landslide that caused the disaster is located in the "Shenbian Administrative Zone", which refers to the Lengqi (29.7869N, 102.2299E) – Tianwan (29.4354N, 102.1717E) section of the Dadu River. By searching possible landslides in the nearby locations, another landslide site that possibly caused the Dadu River damming is proposed as the Mogangling Landslide (Figure 2.2 and 2.3). It is suggested that compared to the landslides of Dai et al. (2005), the Mogangling Landslide is more likely to have caused the 1786 disaster, largely because it can match most of the historical documents and data: 1) the landslide dam height reached 1,300 m asl (Figure 2.4), making a large enough reservoir to reach the City of Luding, which is 34km upstream; 2) the calculated reservoir volume (using GIS as detailed below) can match the total volume of water that flowed into the lake during the 9 day blockage period. This rationale is developed in more detail in the following paragraphs.

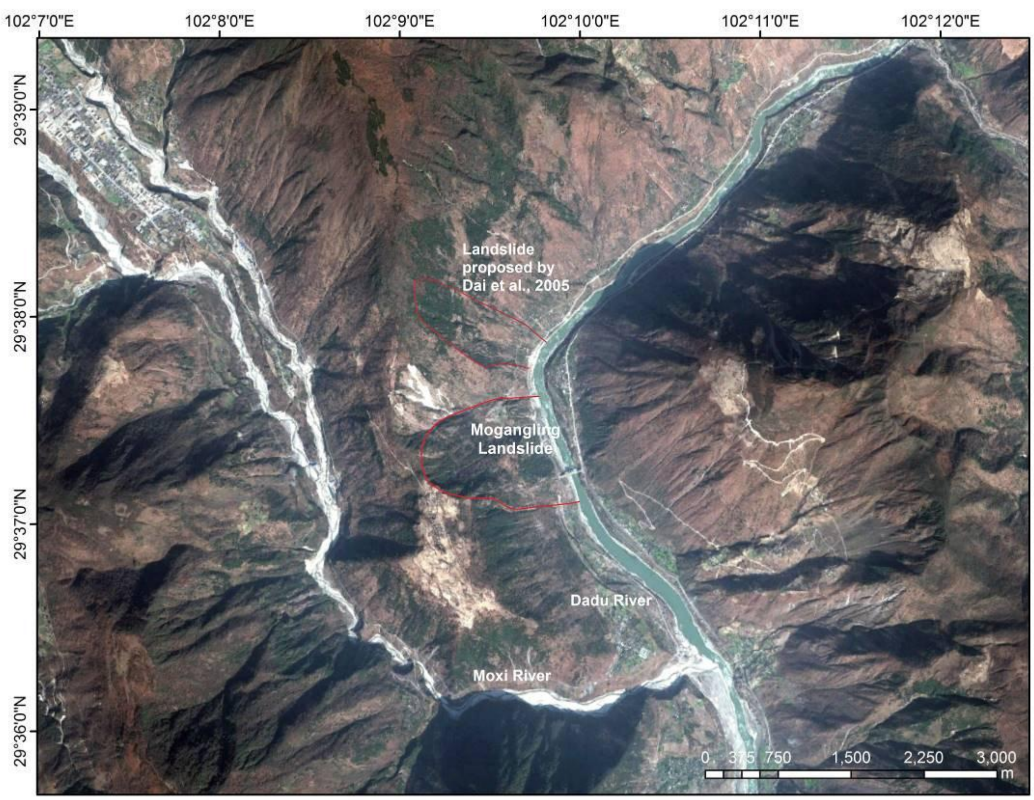

Figure 2.2. Satellite image of the Mogangling Landslide in relation to the landslides proposed by Dai et al., (2005). Red lines represent the landslide boundaries. Dadu River flows from N to S.

Figure 2.3. Photograph of the Mogangling Landslide, located on the right bank of the Dadu River (coordinates: 29.6237N, 102.1578E). Photograph taken on 18/07/2014, on the left bank, facing west.

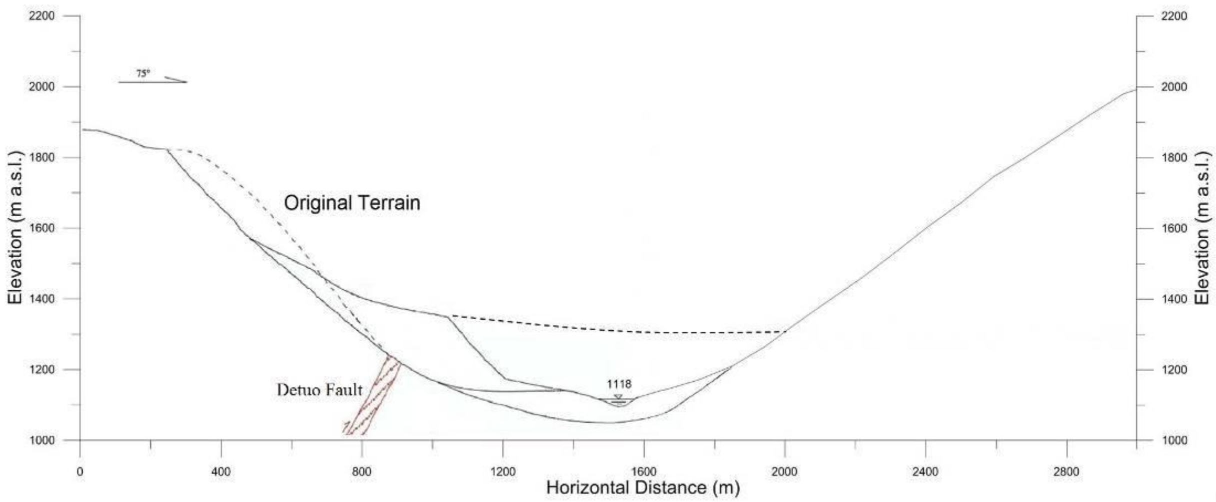

Figure 2.4. Cross section of the Mogangling Landslide (modified from Figure 5 of Wu et al., 2013, no vertical exaggeration). The Blue dashed line indicates the estimated landslide body before breaching. Note the minimum elevation of slightly over 1,300 m asl, suggesting a maximum pool elevation of about that elevation.

The Mogangling (Mogang Ridge / Crest) is more or less adjacent to the landslide proposed by Dai et al. (2005), and is located 500m further downstream on the west bank of the Dadu River, 2.5km upstream north from the Moxi River. The Mogangling Landslide is on the east slope of the Mogangling, with a coordinate of 29.6237N, 102.1578E. Wu et al. (2013) drilled several boreholes on the landslide body, thus, very detailed sub-surface information is known. The main sliding direction of the landslide is 75 °N. The landslide body is 450m long, 1000m wide along the river thalweg, and has a total volume of approximately 45Mm^3 (Wang et al., 2013) According to the cross section map of the landslide, which is shown as Figure 2.4, it can be seen that foothill start at 1,120 m asl; from 1,180 – 1,350 m asl is the frontal edge, which has a slope of 50 °; a landslide platform is located from 1,350 – 1,400 m asl, with a slope of 5 - 12 °; the landslide rear edge is from 1,400 – 1,890 m asl, while its slope is 35 ° from 1,400 – 1,580 m asl, and 57 ° from 1,580 m asl to the top (Figure 2.4).

2.4 Geological setting of the Mogangling landslide

Lithology of the area mainly consists of granite and diorite, with diabase in some parts (Wu et al., 2013). Quaternary colluvial deposits can be found on the rear edge of the landslide. Alluvial deposits are also found near the river channel, which is shown on Figure 2.5.

As it can be seen from Figure 2.6, three major fault zones intersect in this area. The Longmenshan Fault Zone stats from the Luding – Lengqi area and stretches northeastward; the Xianshuihe Fault Zone starts from southwestern Kangding and goes towards northwest; while the Anninghe Fault Zone starts south of Detuo and stretches southward. Meanwhile, the Moxi fault, along with the Detuo Fault which is not labeled on the map, pass through the intersection.

Figure 2.5. Alluvial deposits on left bank of the Dadu River, photo taken on 18/07/2014.

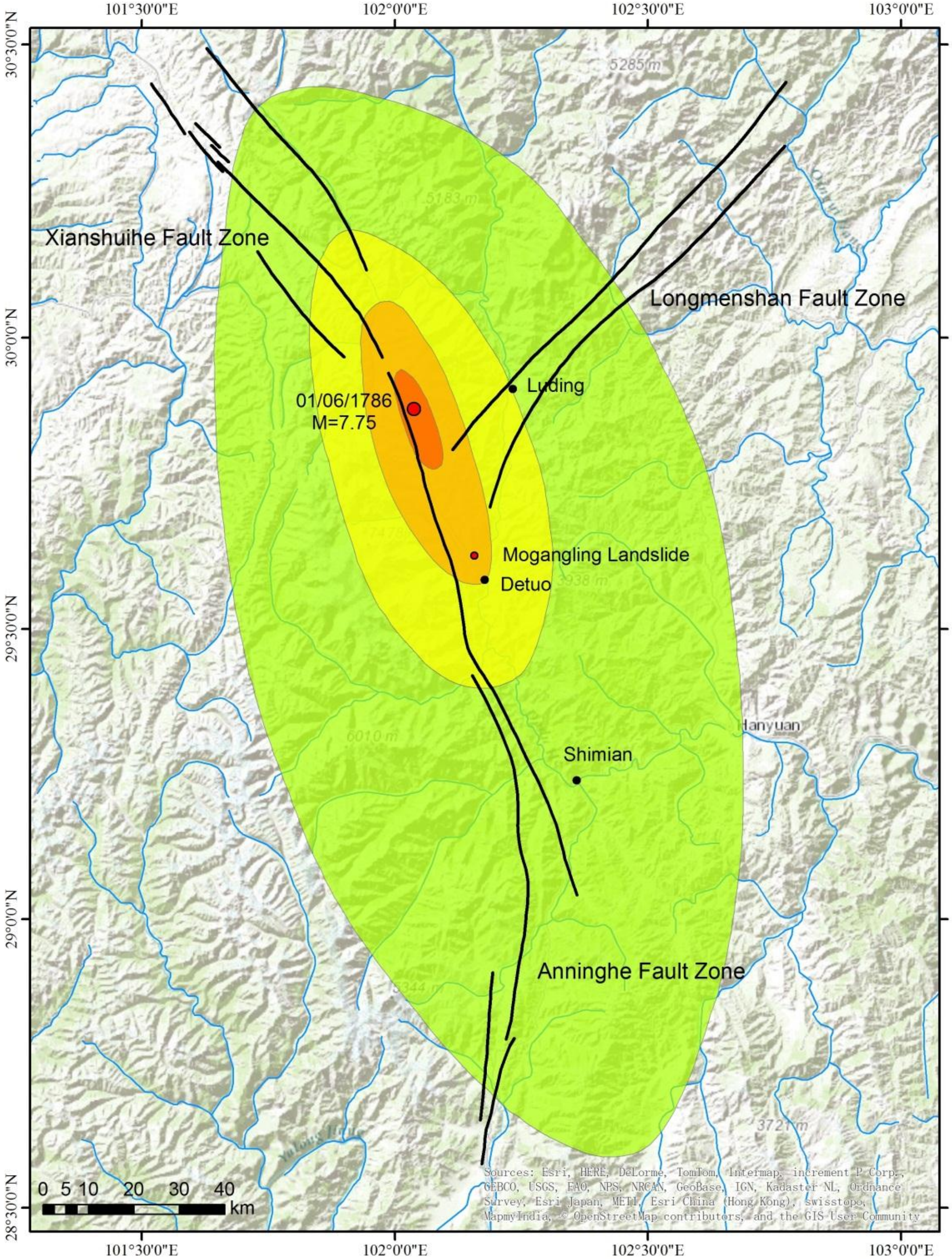

Figure 2.6. Fault zone and earthquake intensity map of 1786 earthquake (georeferenced from Dai et al., 2005, base map from ESRI).

Figure 2.7 shows the geological map of the landslide area. It is noticed that the Detuo fault passes underneath the Mogangling Landslide. The Detuo Fault stretches southward where it breaks into two branches along each bank of the Dadu River. The Detuo Fault merges with the eastern branch after passing Mogangling at further downstream, with a total length of approximately 60km. The fault planes dip west at steep dip angles, which vary from 45 ° to 80 °. Moreover, the Moxi fault also passes this area, with a distance west to the landslide of no more than 3km. The attitude of the fault is 250 °∠ 70 °. The Moxi fault is considered to be the trigger fault of the 1786 earthquake, and that earthquake is the largest one recorded within the fault. The nearest recorded modern earthquake within the fault happened on Sept 30, 1972, with a magnitude of 5.5.

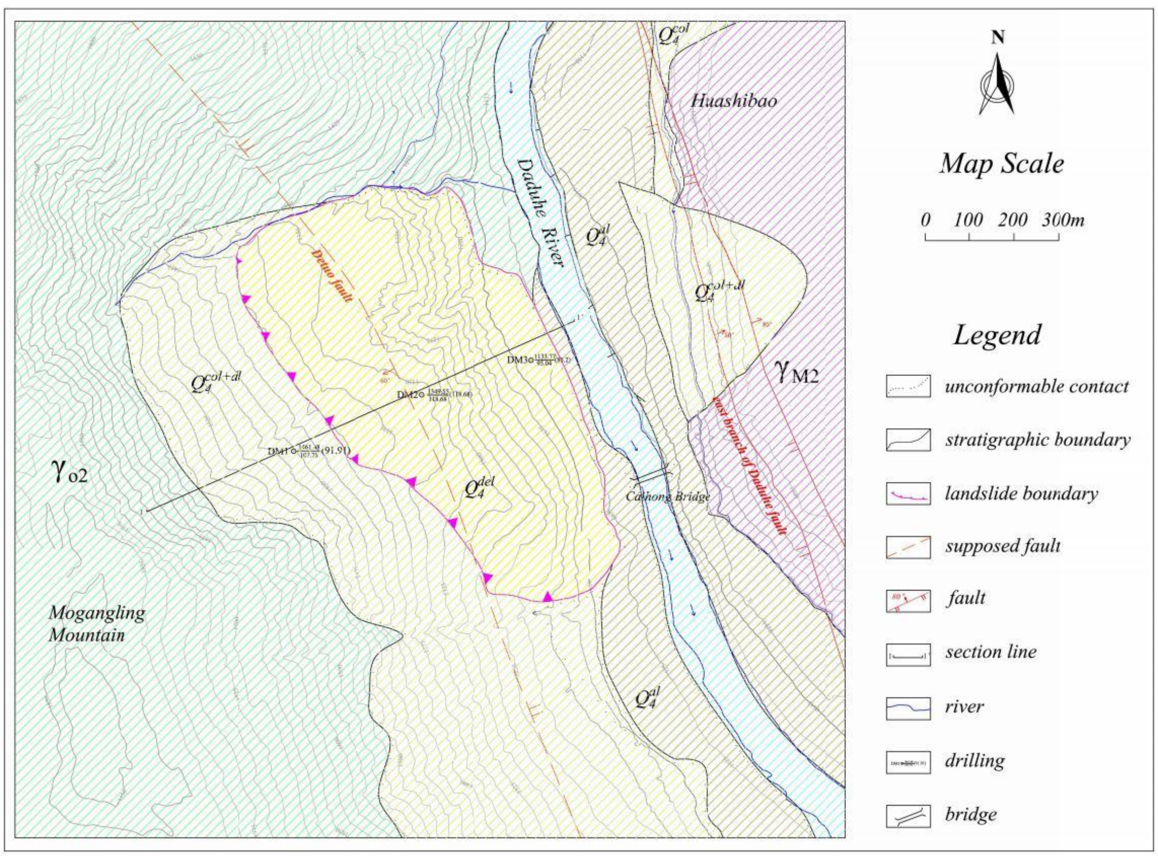

Figure 2.7. Geological Map of the Mogangling Landslide (Figure 3 from Wu et al., 2013). The bed rocks are granite and diorite, colluvial deposits can be found on the landslide head, and alluvial sediment at the valley bottom (Wu et al., 2013). Two faults can be observed on each side of the river.

2.5 Historical earthquakes

Mogangling Landslide is located in a seismically active area. By sorting all earthquake data from 1216, within an area bounded by the coordinates 28-31 °N, 101-104 °E, nine earthquakes larger than M7 are recorded. There are 21 earthquakes from M6.0-6.9; while 83 from M5.0-5.9. The largest earthquake recorded in this area is the 2008 Wenchuan earthquake, and the 1786 earthquake is the second. The seismic intensity zones are labeled on Figure 2.6, the Mogangling Landslide is located within the Intensity = IX zone.

2.6 Maximum pool elevation of the 1786 landslide dammed lake

Determining the maximum pool height of a breached reservoir is the key step of any historic landslide-dammed lake studies. Since the 1786 landslide only blocked the Dadu River for 9 days, no geological evidence of the lake can be found within the surrounding area. However, several descriptions from various historical documents are examined to help us estimate the 1786 pool height. As some of these descriptions may contradict each other, a literature review is needed to determine which one is most credible.

1. As it can be seen from the Mogangling Landslide cross section (Figure 2.4; Wu et al. 2013), a trend line can be sketched in order to infer the shape of the landslide body that blocked the Dadu River before the breach (Figure 2.4). It can be seen that the minimum height of the landslide mass is at the most 1,300 m asl. Moreover, the height of the landslide dam above the river channel is known to have been 167m (Annuals Committee of Luding County, 1999). If this height is added to the elevation of the river channel (~1,130 m asl from the SRTM-3 DEM) at the dam site, a pool elevation of 1,297 m asl is derived, which matches quite well the 1,300 m asl estimation.

2. Based on Wu et al. (2013), "*people could touch the river water by feet from the Luding Rope Bridge*". As we know the elevation of water at the Luding Bridge is 1,309 m asl, indicating that the water level before breaching was definitely over 1,300 m asl. However, evidence shows that the so

called "Luding Rope Bridge" is not exactly the same bridge as it is today. The bridge was reconstructed several times from 1786 to present day at the same location. One of the reasons is that the frequent debris flows near Chuba Village downstream, have resulted in the riverbed being raised at Luding. Chuba is 4-5km downstream from Luding city, and its elevation at the river bank is 1,274 m asl. Assuming the river gradient is 0.3-0.5%, elevation at Luding can be estimated to be 1,298 m asl, which is fairly close to the estimates calculated above.

3. Wu et al. (2013) stated that "*the only tall ginkgo tree in Lengqi Town* (coordinates: 29.7869N, 102.2299E) *was submerged till the top (1,245m)*". The ginkgo tree can still be found, but not at the elevation of 1,245 m asl. As the elevation of the Lengqi Town is 1,280 m asl, plus the height of the tree, 30m, showing that the highest water level should be less than 1310m, but not too much.

4. Dewei town. Again based on another statement by Wu et al. (2013), "according to local documents of Luding, the water level of the reservoir rose to an elevation of 1,240 m asl at the river mouth of Dewei Town", is considered to be incorrect. The elevation of Dewei is 1,207 m asl. If the water level at Dewei is 1,240 m asl as stated by Wu et al. (2013), there is no possibility for the tail of the reservoir to reach Luding, which means, this is contradictory to all other statements.

To sum up, most of the available evidence about the maximum pool height of the 1786 Dadu River landslide-dammed lake points to an elevation of 1,300m above sea level, as the estimations to the Luding Bridge, the gingko tree at Lengqi, as well as the damming landslide body leads to a match. However, estimation based on water level at Dewei shows too large a difference to the others, and is taken out of consideration.

2.7 Lake size and volume of the 1786 landslide-dammed lake

In order to reconstruct the landslide lake on the Dadu River that breached on June 9, 1786 to the maximum extent, we take the maximum pool height as 1,300 m asl. We also use the more recent 90m resolution SRTM DEM to map the maximum extent of the lake and its volume.

Although an elevation of 1,300 m asl is estimated as the most reasonable maximum pool elevation, we cannot directly determine the precise water level of the lake in June, 1786. We thus assume a range of pool heights. After deriving the lake volumes correlating to these heights, they are compared to the descriptions in historical documents. Lake water levels at every 10-meter interval between 1,200 m asl to 1,300 m asl are assumed in order to calculate the lake areas and lake volumes, which are shown as Table 2.1.

Table 2.1. Lake area and volume of the 1786 landslide-dammed lake at successive pool elevations (1,200 m asl to 1,300 m asl) measured in ArcGIS from topography derived from SRTM-3 DEM data.

Pool Height (m asl)	Lake Area (km^2)	Lake Volume (Mm^3)
1200	1.53	57.6
1210	2.50	90.5
1220	3.66	133.5
1230	4.87	190.5
1240	6.29	263.0
1250	7.84	353.4
1260	10.17	467.5
1270	12.48	603.3
1280	14.64	768.5
1290	16.59	949.3
1300	**18.54**	**1,150.4**

It can be seen (Table 2.1) that, based on the 1,300 m asl maximum pool elevation scenario, the volume of the dammed lake reaches 1.15Gm^3. This is considered to be one of the largest landslide-dammed reservoirs in recent history (Evans et al., 2011), and one of the largest dammed lakes recorded in Chinese history. The largest recorded dammed lake in China was the 2000 Yigong Lake along the Yigong Tsangbo River, Tibet, which had a volume of 2.015Gm^3 (Evans and Delaney, 2015). These two lakes are the only landslide-dammed lakes that have reached 1Gm^3 volume in China. As a comparison, volume of the well-known 2008 Tangjianshan Lake is 302Mm^3, which is only one-fourth of the 1786 lake volume estimate. Our calculated volume of the 1786 lake can be compared to some of the largest dammed lakes outside China, such as Lake Indus (6.5Gm^3, Pakistan, 1841), Lake Sarez (17Gm^3, Tajikistan, 1911), and Lake Rio Barrancos (1.55Gm^3 outburst, Argentina, 1914) (Evans et al., 2011).

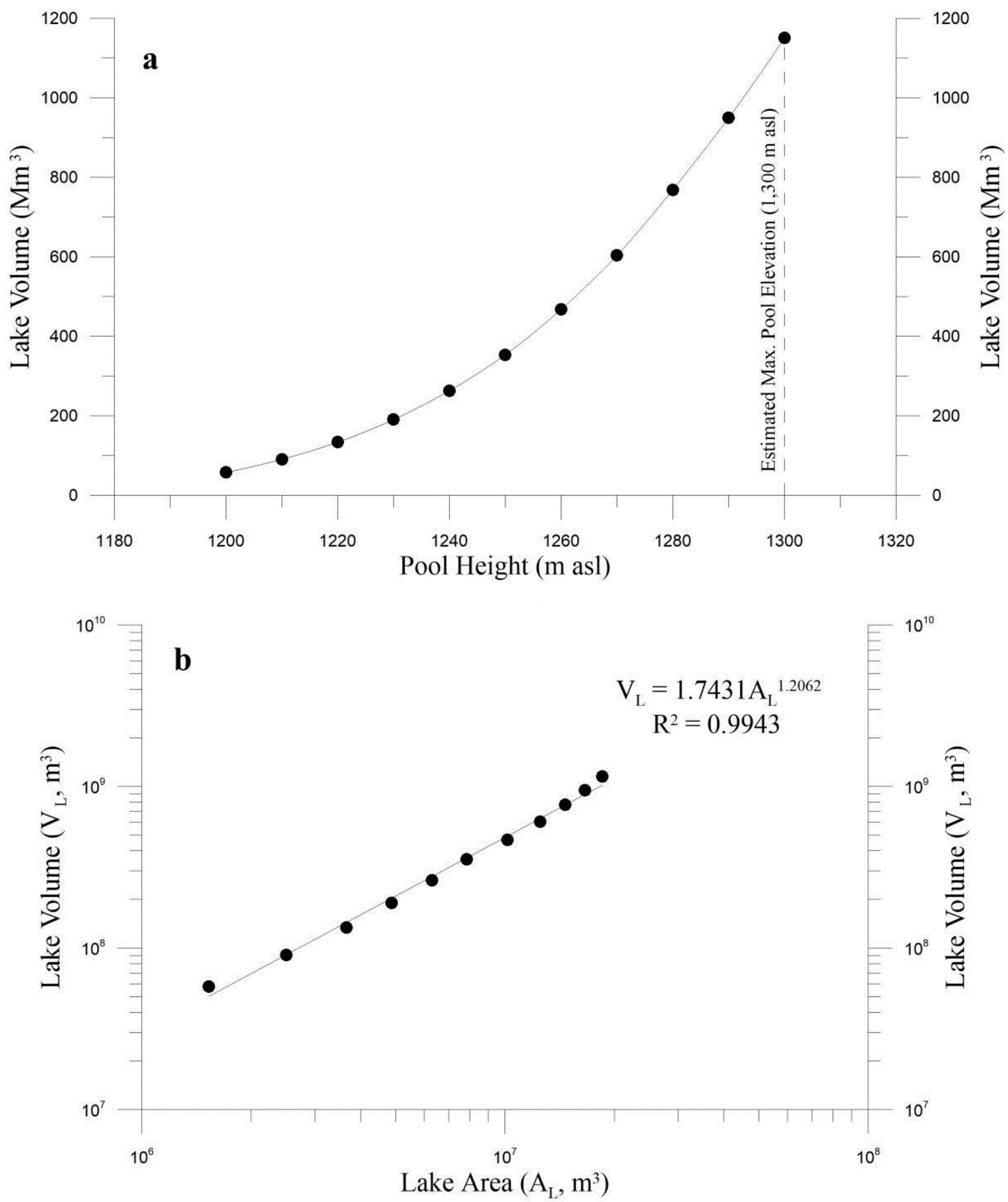

Figure 2.8. Upper plot: dammed lake volume calculated from SRTM-3 DEM at different assumed pool heights. Note that volume is 1.15Gm^3 at 1,300 m asl. Lower plot: dammed lake volume at different lake areas, power law relation is found as shown in the plot.

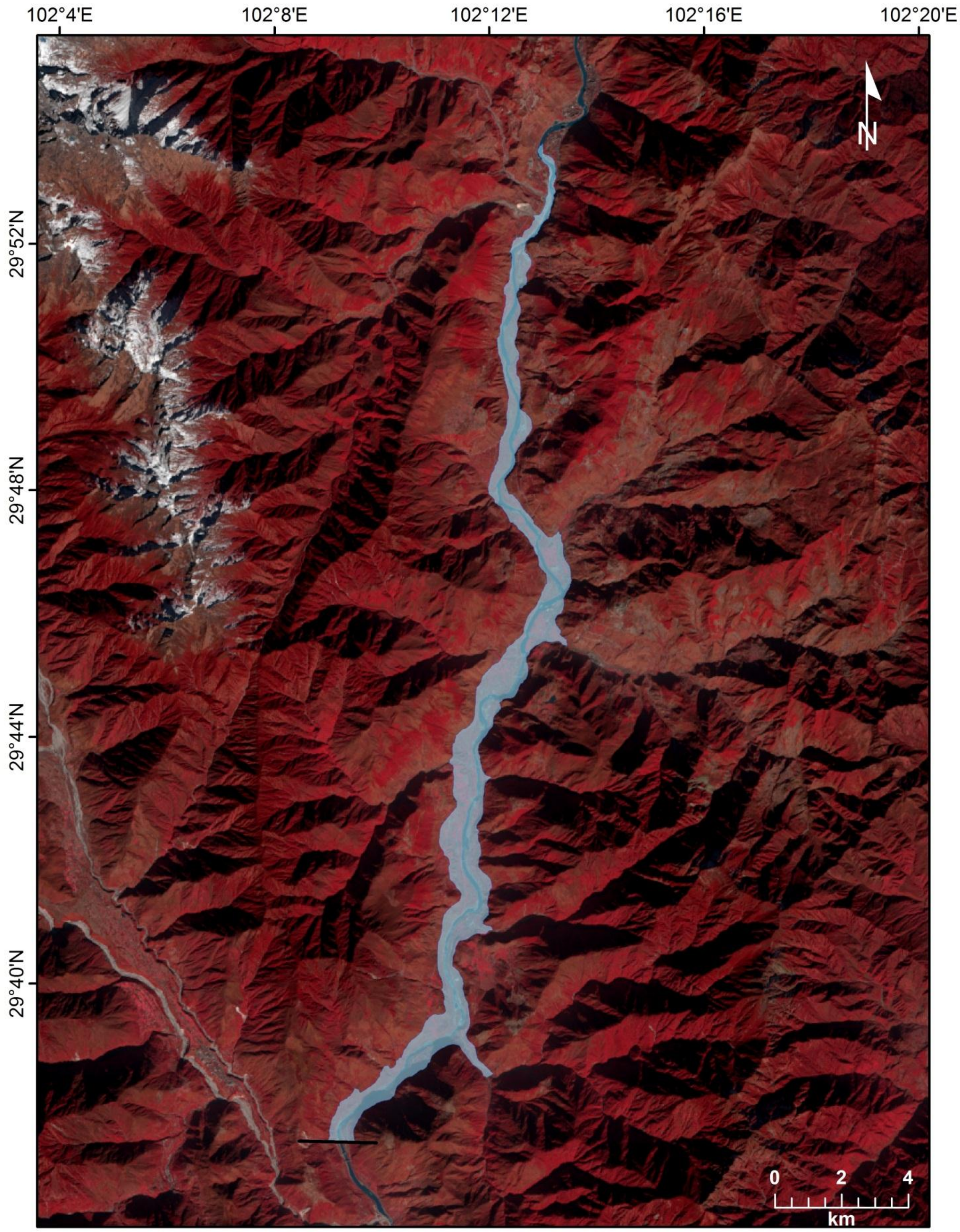

Figure 2.9. Full extent (submerged area) of the 1786 landslide-dammed lake on the Dadu River at the maximum pool elevation of 1,300 m asl. Base map from false color Landsat 8, taken in December 7, 2013

Reservoir volume calculated from SRTM-3 DEM can be compared with the volume calculated from the monthly discharge of the Dadu River. A discharge table is shown in Table 2.2, which is measured at the Luding Hydrological Station, near the tail of the 1786 reservoir, 34km upstream of the landslide dam. It can be seen that the mean monthly discharge of the Dadu River in June is 1,670m^3/s. We multiply this by the duration of the dammed period (9 days), and we obtain a volume of 1.30Gm^3. By taking evaporation and runoff into consideration, it is thought to be a reasonable correspondence to the volume.

The profile of the Dadu River calculated in ArcGIS is shown in Figure 2.10. Based on previous work of Wang (2014, a) and Ouimet et al. (2007), historical and pre-historical landslides near Luding on the Dadu River were labeled on the plot. Names of these landslides are according to Wang (2014, a), and two other landslides which Wang did not include but were mentioned by Ouimet et al. (2007) were labeled as landslide O1 and O2. It can be seen that this section of the river is highly affected by landslides. Moreover, landslides often appear in pairs on each side of the rivers, such Jiajun Landslide and Shangkuiwu Landslide. Due to China's high demand for electricity, several hydroelectricity dams are planned in this section of the Dadu River. Construction of these dams are at different stages, only the Luding dam is completed by now. However, due to the fact that the data of the SRTM-3 DEM was obtained in 2000 (before construction work), these dams cannot be shown on the plot. It can be seen that some of the dams are planned to be constructed close to landslides.

Table 2.2. Average monthly discharge (m^3/s) of the Dadu River measured at Luding Hydrological Station from 04/1952 to 12/2001 (Wang, 2014, b).

	Month											
	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan.	Feb	Mar	Apr
Mean discharge	810	1670	1960	1440	1620	1160	587	354	257	226	239	366
Percentage of runoff	7.7	15.4	18.6	13.6	14.9	11.0	5.40	3.37	2.44	1.94	2.27	3.37

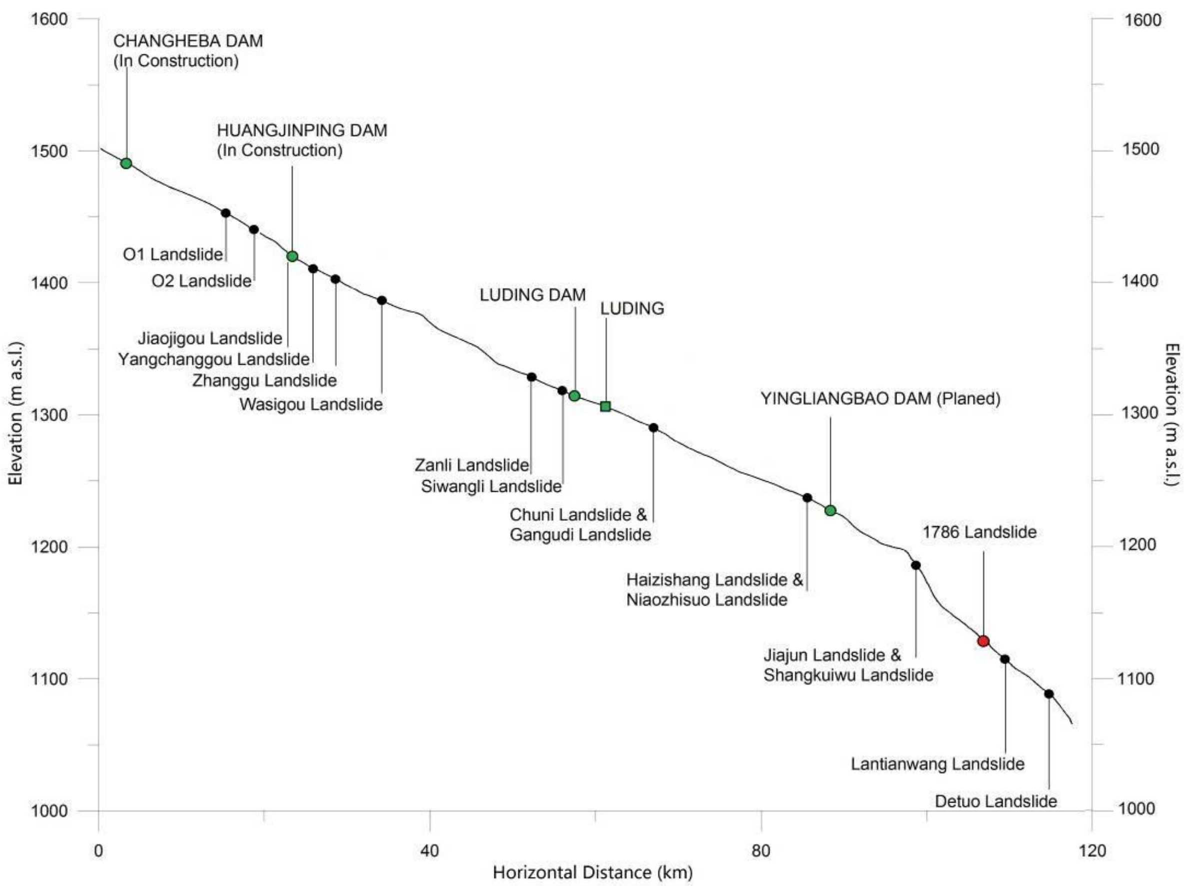

Figure 2.10. Profile of the Dadu River near Luding. Green dots refer to HEP dams (including completed, in construction, and planned structures) (Vertical exaggeration: 6270x).

2.8 The 1786 downstream flood

Since the Dadu event happened over two centuries ago, it is impractical to get detailed flood data (e.g. maximum wave height, peak discharge) for the outburst flood. Thus, only historical descriptions in local chorography can help us understand the general nature of the 1786 flood. After obtaining several papers about this event (e.g. Dai et al., 2005, Jiang, 2006, Xie, 1991), we translated and paraphrased these historical descriptions as in the following:

1. The Tianquan chorography written in the Xianfeng Period, Qing Dynasty (1850-1861) recorded that "mountains at Moxi collapsed, blocking the Dadu River for 9 days, and the reservoir tail approached the Luding Bridge"; "June 9, another large earthquake occurred. The reservoir at Lengqi (coordinates: 29.7869N, 102.2299E) suddenly broke, with a scale similar to falling mountains,

sweeping all civilians on both banks. The flood reached Leshan (Figure 2.11) after one day. At 7am June 10, people observed a huge flood at the eastern gate. People were crowded there to watch the flood. Then the city wall broke down suddenly, and the number of people fall into the river is countless" (Dai et al., 2005).

2. According to the Leshan chorography written during the ROC period, "the flood arrived at Leshan on June 10. The height of waves was tens of meters, just like a moving mountain. Tens of thousands of civilians were drowned. The maximum water level at Leshan in a previous flood was carved on a temple wall, and this time it got doubled" (Dai et al., 2005).

3. Jiang (2006) stated the flood scene as the following: "Flood came to Leshan city from southwest, and breached its city wall for hundreds of meters. An Iron cast bull to symbolize blocking the water, which is around 4 meters high, also was submerged and nowhere to be found. The flood intruded into every gullies, streams and ports along the river, and it also intruded the Min River along upstream for 5 kilometers. The flood waves became subdued at Yichang, Hubei Province. Every boat that came across them got sunk. River surface downstream Luzhou and Yibin was covered by house materials, just like bamboo rafts."

4. Rongchang chorography states that "people in Leshan, Luzhou, and Yibin that are drowned are over 100,000" (Dai et al., 2005).

From these few isolated descriptions about the flood, the following obsevations can be made:

1. The dammed reservoir is huge. It started from the Mogangling Landslide (the dam), across the Lengqi town, and all the way up to the Luding Bridge (~40km upstream). This is one of the main lines of evidence for a massive landslide-dammed lake.

2. Was the dam breach caused by an earthquake? This is considered to be possible, because based on the acquired historical landslide dataset, an M5 earthquake occurred on June 9 only a few kilometers south of the dam.

3. The flood reached Leshan (~320km downstream from the dam) approximately one day after the dam breach. The flood destroyed parts of the city wall and drowned many civilians who came to

watch the flood. The city also experienced a severe flood, as Xiande Xie (1991) estimated the maximum water level using the elevation of the temple, and obtained a result of 375.06 m asl at the temple and 376.90 m asl at the famous Leshan Buddha. This is considered to be 14.88m higher than the maximum water level ever recorded at Leshan (362.02 m asl, July 13, 1981). Compared with the elevation of Leshan City (approx. 360 m asl), the highest flood level is nearly 17m higher.

4. Leshan is the first large city on the flood path, but still received devastating damage. This shows that the flood damage to the counties / towns upstream from Leshan can only have been more catastrophic. However, no casualty information can be found about these towns. As these towns are not far from the river banks or near the flood water level, civilians living in these towns had no chance to escape from a flood of this scale. As a result, the scene after the flood had past these towns (e.g. Shimian, Hanyuan) can be called catastrophic.

5. Historical documents emphasized the damage at Leshan, but other descriptions can be found of damage to other cities downstream of Leshan, such as Luzhou and Yibin. As previously stated, the flood vanished at Yichang, Hubei Province. It can be estimated from this evidence that the flood traveled for approximately 1,190km (160km from Leshan to Yibin, 1,033km Yibin to Yichang) below the Dadu landslide dam, and the flood wave at Yichang is zero. In order to illustrate the scale of the flood, a flood extent map and profile of the Dadu River are shown as Figure 2.11 and 2.12.

6. As the precise statistics of civilian fatalities after the flood is unavailable, only an estimation can be made. Based on the Leshan Chorography, tens of thousands of people were killed in the flood. It is probably the fatality (confirmed death plus missing) number just within the Leshan administrative area. If it is only for Leshan, the total fatality can be easily rise to over 100,000, because the fatalities in cities upstream (Shimian, Hanyuan) and downstream (Yibin, Luzhou, Chongqing, and Yichang) have to be counted. As Leshan city is the largest city of that time in the flood path, it should have experienced higher fatalities compared to other cities downstream. As a result, the estimation of 100,000 people killed by the 1786 flood made by the Rongchang chorography appears reasonable.

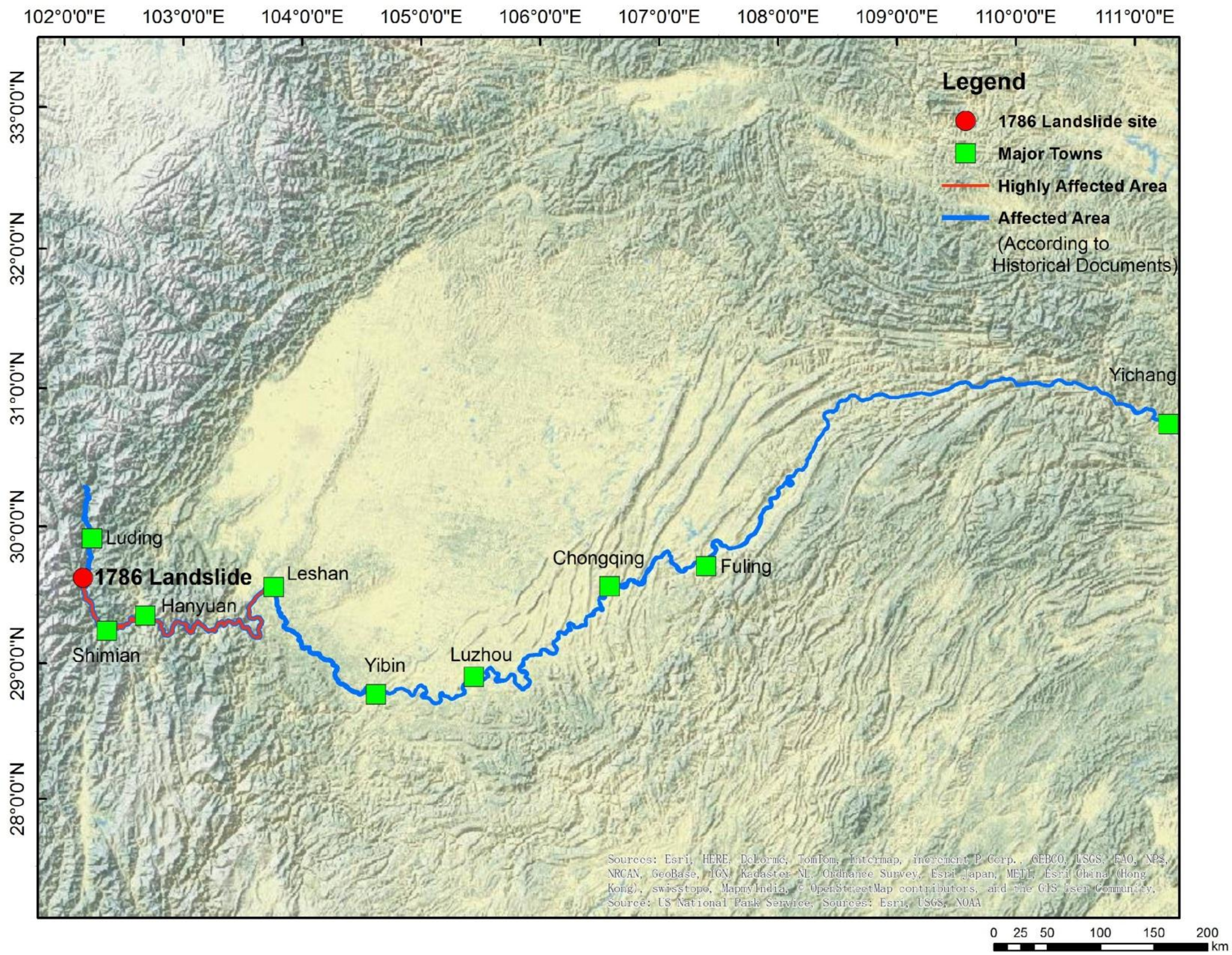

Figure 2.11. Profile of the 1786 flood extent downstream from the breached Mogangling landslide dam. Green squares are major cities along the Dadu River affected by the flood. The flood had dissipated by Yichang (approximately1,510km downstream from the Dadu dam). Base map from ESRI.

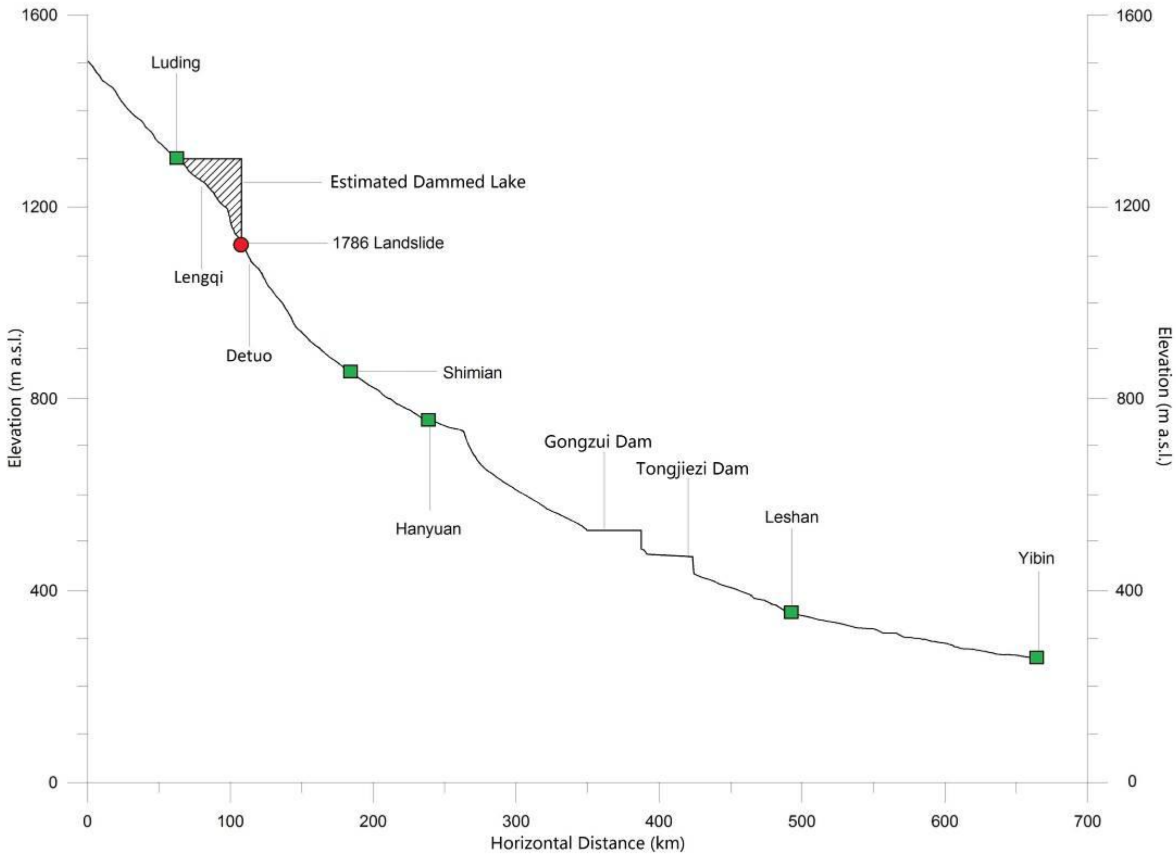

Figure 2.12. Profile along the Dadu River from Luding to Yibin. Note comparison of man-made reservoirs and the 1786 landslide-dammed lake (Vertical exaggeration: 2970x). The distance from the 1786 landslide dam to Yibin is approximately 480km.

2.9 Conclusion

This paper presents a detailed review of the 1786 Dadu River event. A new possible site for the landslide is suggested, i.e. the Mogangling Landslide. Measurements and estimations are made based on the newly proposed site, and a maximum pool height of 1,300 m asl, as well as a volume of 1.15Gm^3 is derived. The estimated dammed lake was one of the largest landslide-dammed lakes in Chinese history. Because of the 100,000 deaths the event caused, the 1786 Dadu River event is regarded as the most catastrophic landslide-dam breaching event globally.

Chapter 3

Landslide dams and landslide lakes generated by the 1933 Diexi Earthquake

3.1 Introduction

This Chapter focuses on the landslide damming events of Diexi on the Min River in 1933. Induced by an M7.5 earthquake, three landslide masses blocked the Min River to form three landslide-dammed lakes, which are, the Da Lake, Xiao Lake, and Diexi Lake. The Diexi Lake breached on 09/10/1933, 45 days after the triggering earthquake. The dam breach of Diexi Lake was caused by a combination of factors, including an M4.5 aftershock, minor dam failures in a tributary causing flooding into the lake, and precipitation in upstream areas. Based on the estimations of Chang (1934), maximum flood wave height downstream from the breached dam was 60m at the Town of Shidaguan, 18km downstream, and 12m at Guan County (nowadays Dujiangyan, 175km downstream). The flood influenced over 250km of downstream areas (Li et al., 1986). Based on the investigation by Chang (1934), the earthquake killed over 6,000 people, and the outburst flood killed at least 2,428 additional persons, making the Diexi event the most devastating natural dam breaching disaster in China in the 20th Century. This chapter aims at deriving new data about the 1933 Diexi event (lake volume, volume released, flood discharge) by literature review and applying GIS to the study of historic landslide damming events.

3.1.1 Geography and geology

The 1933 Diexi Event occurred near the Town of Diexi (Figure 3.1, 32.0425N, 103.6793E), in the upstream part of the Min River. Min River is a major tributary of the Yangtze River, and it starts from the southern slope of Mt. Min. The river is called as “Min” after two of its original branches converge at the Town of Chuanzhusi (Chuanzhu Temple) by the Panzhou River on the west, and Zhangla River on the east (Figure 3.1). The Min River flows across the Songpan County, Mao County, and the Wenchuan County before it runs into the Chengdu Basin at the City of Dujiangyan (Figure

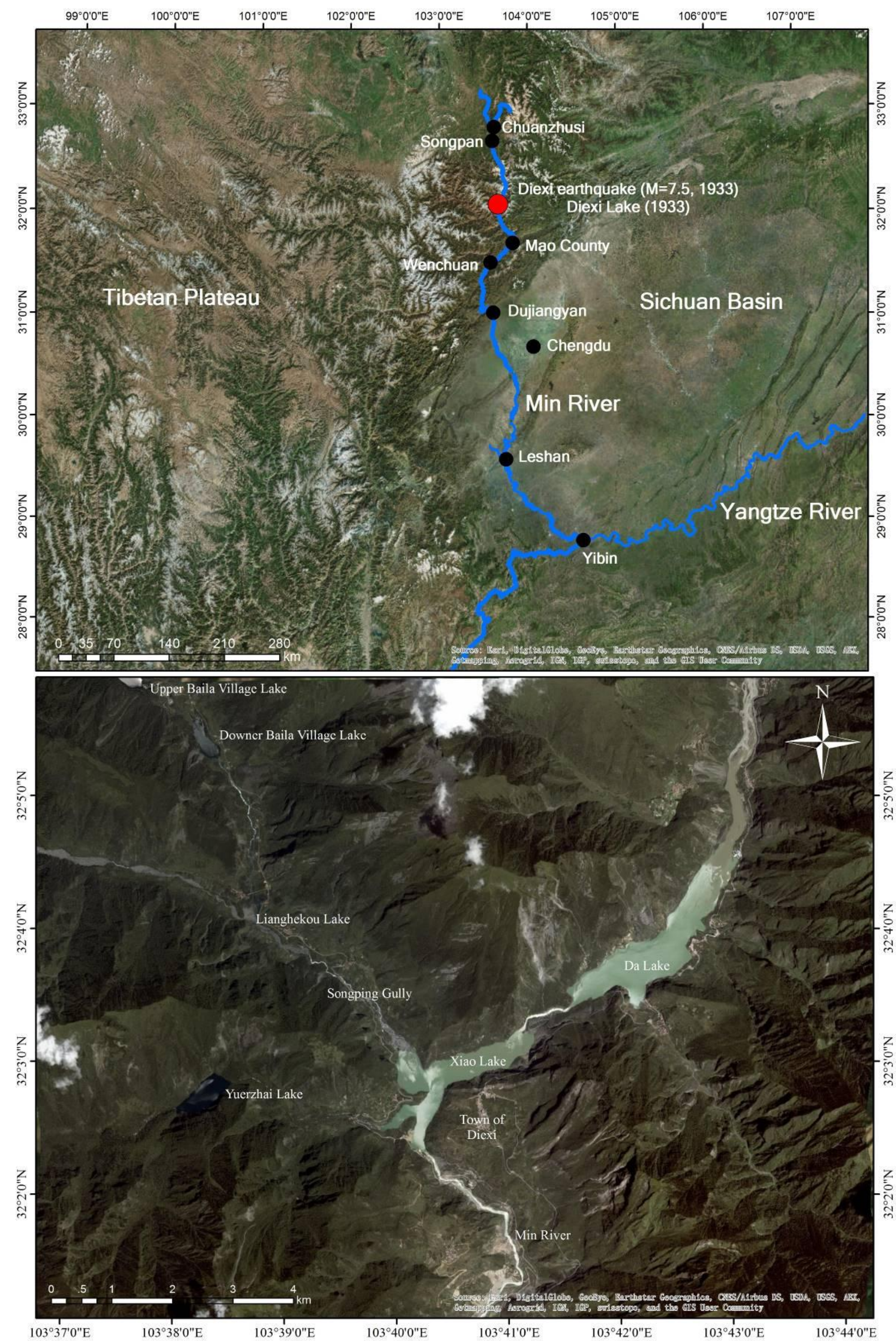

Figure 3.1. Location of Diexi. The upper map shows the general location of Min River and major cities along the river. The lower map shows the location of Town of Diexi, and major landslide-dammed lakes. Base map from ESRI.

3.1). It flows southward in the basin, the Dadu River joins the Min at Leshan, and flows into the Yangtze River at the city of Yibin (Figure 3.1). The total length of the river is 1,279km, with an elevation drop of 3,560m. The section from the origin to Dujiangyan is called the upstream part of Min River. It is located in the transition zone between Chengdu Basin and Tibetan Plateau. Dramatic uplift and long-term incision has formed the present deeply cut valleys. Most of the mountains along the river are high, and reach 4,000 m asl. As the distance from Songpan to Dujiangyan is 384km, and the elevation drop between two cities is 2,050m, the average gradient of the upstream Min River is 5.34‰ (Chang, 1934).

The Town of Diexi lies on a gravel terrace on the east bank of the Min River, with a distance south to Mao County of 60km, and north to Songpan of 120km. The terrace is 2km long in the north-south direction, and 800m wide in the east-west direction. The town was located in the south of the terrace, and close to the river bank (cliff), with an elevation of 2,290 m asl. Jiaochangba is the flat area that lies in the north terrace, which is 1.5km north to the town, with an elevation of 2,345 m asl.

It can be observed that the terrace is formed by river deposition. Gravels and boulders found on the terrace vary in size, from 20cm in diameter, up to over 1m, but most of the particles are around 20cm (Chang, 1934). These gravels are sub-rounded and coarse angular particles can also be found, indicating a short water erosion time or limited transporting distance. Gravels formed the entire terrace, and by Chang's estimation in 1934 based on average river gradient, it was 270m higher than the river surface before the 1933 earthquake. The Min River bypasses the terrace by flowing westward when coming from north. After accepting the stream from the Songping Gully on its right bank, the river turns southeast. The river flows again to the south after passing the Diexi terrace.

As Diexi is located on the boundary of the Tibetan Plateau, this region is highly affected by the collision of the Eurasia Plate and the Indian Plate. As a result, faults and folds are highly concentrated in the Diexi area. Bedrock exposed in the region are Devonian to Jurassic in age. Most of the bedrock is metamorphic in different stages, such as metamorphic limestone & sandstone, schist, and phyllite. Mountains and cliffs around Diexi mainly consist of quartz and mica schist, dark grayish or green in colors. Orientation of these rock layers are mainly 170 °in dip direction and 30 °in dip angle (Chang, 1934).

3.1.2 The ancient dammed lake of Diexi

A set of ancient sedimentary deposits can be found near Diexi. Wang et al. (2008) investigated the deposit Diexi in 1999, and they found that these are “classical” landslide lacustrine deposits (Wang et al., 2008). The lake is named as the “Ancient Dammed Lake of Diexi”. The total thickness of the sediments is over 200m, and ^{14}C dating indicates that the lake was formed 22,000 years BP and disappeared 10,000 years BP (Wang et al., 2008). Field investigations were carried out in Diexi in the summer 2013 and 2014, and obvious outcrops of lacustrine deposits can be found on roadsides, an example of which is shown as figure 3.2. The landslide lacustrine deposits illustrate the long landslide-damming history of the Diexi area.

Figure 3.2. Lacustrine deposits of the “Ancient landslide-dammed lake of Diexi”. Photo was taken near the reservoir tail of the present Da Lake (taken on 12/07/2014).

3.1.3 Historical earthquakes near Diexi

Diexi is located in area of active seismicity (Wang et al., 2008). By collating all earthquake data starting from 1216A.D. (data from the China Seismic Information website, www.csi.ac.cn), within the coordinate of 30.5°-33.5°N, 102-105°E, a total of 6 earthquakes larger than M7 are recorded. Moreover, 16 earthquakes are recorded from M6.0-6.9, while 72 are recorded from M5.0-5.9. The largest earthquakes recorded in this area are the 2008 Wenchuan earthquake (M8), the 1879 Wudu earthquake in Gansu Province (M8), and the 1933 Diexi earthquake is the third largest (Appendix C).

3.2 The 1933 Diexi event; process and chronology

3.2.1 The 1933 Diexi earthquake

The M7.5 Diexi earthquake is considered to be the most destructive earthquake in the upper stream area of the Min River in recent times. The earthquake occurred at 15:50:30, August 25, 1933, near the Town of Diexi, Mao County, Sichuan Province, approximately 160 kilometers from the provincial capital, Chengdu (Figure 3.3). The magnitude of the Diexi earthquake was M7.5, and the epicenter was located at Diexi village, with a depth of 15km (Chai et al., 1995). The largest intensity of the earthquake was X (modified Mercalli scale), with an epicentral area of 290km^2 (Chai et al., 1995). A large number of earth fractures, large-scale rockslides and landslide-damming can be found in the intensity X epicentral area. The intensity IX area is 1,080km^2 in size (Wang et al., 2008), with minor fractures and rockfalls. Based on incomplete statistics, the 1933 earthquake directly caused 6,865 dead, 1,925 injured, and 5,180 houses destroyed (Chai et al., 1995).

3.2.2 Landslide damming

The M7.5 Diexi earthquake is extraordinary because of its severe secondary disasters related to river damming by earthquake-triggered landslides. Numerous landslides were triggered by the earthquake in the area. Three of them blocked the main channel of the Min River and formed three major dammed lakes along the valley. They are:

i) Da Lake: formed by Yinpingya landslide;

ii) Xiao Lake: formed by Dachao landslide (or also Jiaochang landslide);

iii) Diexi Lake: formed by Diexi landslide & Ganhaizi landslide (Figure 3.4).

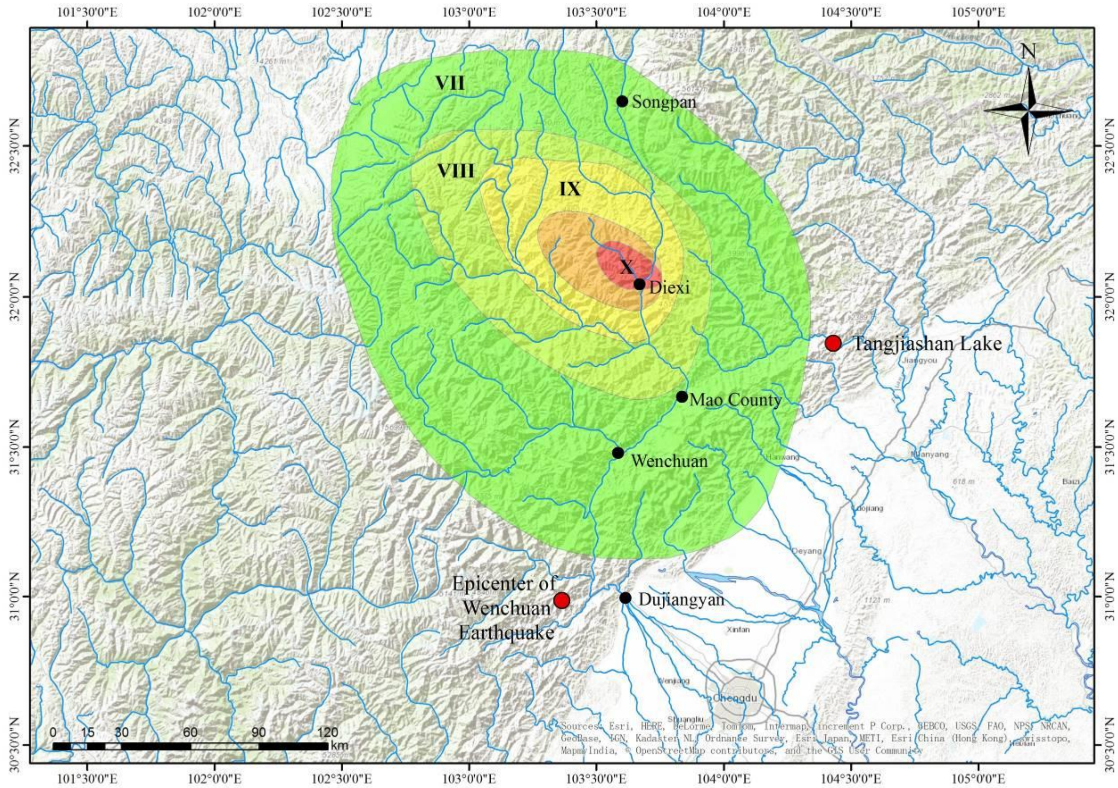

Figure 3.3. Intensity map of the 1933 Diexi earthquake (Georeferenced from Chai et al., 1995, base map from ESRI). Black dots refer to major cities in the area. Epicenter of the 2008 Wenchuan earthquake, and the earthquake-triggered Tangjiashan Lake are labeled as red dots.

Due to almost complete absence of geology work in China in the 1930s, no risk evaluations or controlled spillway excavations were done at these landslides. This led to the failure of Diexi Lake on 09/10/1933, 45 days after the earthquake. An approximate additional 2,500 people were killed by the outburst flood, which is over one third of the total death in the earthquake itself.

Major events from the occurrence of the earthquake to the final breaching of the Diexi Lake in 1933 are summarized as follows: (mainly according to Wang et al., 2008)

1. 25/08/1933: Earthquake occurred, and three landslides blocked the Min River. The river was cut off from the Yinpingya landslide to the next tributary, which is 28 kilometers downstream. The

dammed lake area exceeded a length of 10 kilometers within one hour (from the Diexi landslide to the tail of the Da Lake).

2. 06/09/1933: Da Lake approached its maximum size, 12.5km in length and 2km in width.
3. 14/09/1933: Water level overtopped the Yinpingya landslide, which was 156m in height, 800m in length (across-river), and 1700m in width (along-river) (Li et al., 1986). Water and debris submerged some remaining infrastructure between Yinpingya and Jiaochang landslide dams. Then water filled this area, forming the Xiao Lake.
4. 30/09/1933: Water level overtopped the Jiaochang landslide, and gradually formed the Diexi Lake. Due to the fact that the elevation of the Diexi landslide dam was higher than the previous two dams, three dammed lakes were connected together when water overtopped the Diexi landslide. The combined lake was estimated to be 13 kilometers long, and had a total volume of over 400 Mm^3, which is shown in Figure 3.4a (Li, 1978).
5. 07/10/1933: Water overtopped the Diexi landslide. The cutoff Min River flowed again.
6. 09/10/1933: The Diexi Lake breached at 7pm, causing a destructive outburst flood. Three factors are considered to have contributed to the dam failure: i) occurrence of a M=4.5 aftershock; ii) failure of several minor dammed lakes in the Songping Gully, releasing water and debris that flowed into the Diexi lake; iii) continuous precipitation and rapid rise of water level upstream in Songpan area. The maximum outburst flood level was 60m at Diexi, 24m at Mao County (48km downstream), 12m at Guan County (Dujiangyan, 175km downstream). Incomplete statistics showed that the flood killed approximately 2,500 people (Chang, 1934). After the landslide dam failure, the lakebed of the former Diexi Lake was silted-up with deposits of approximately 100 meters in depth. Water level of the Xiao Lake decreased 50m, to 2,200 m asl (Figure 3.4b).
7. Since the breach of Diexi Lake in 1933, the remaining lakes and landslide dams have undergone morphological changes. On 21/08/1936, struck by a flood, water level of the Xiao Lake decreased by 20 meters, and washed-out deposit made the Jiaochang and Diexi landslide completely merged. A 2-3 kilometer long spillway is formed and still exists.

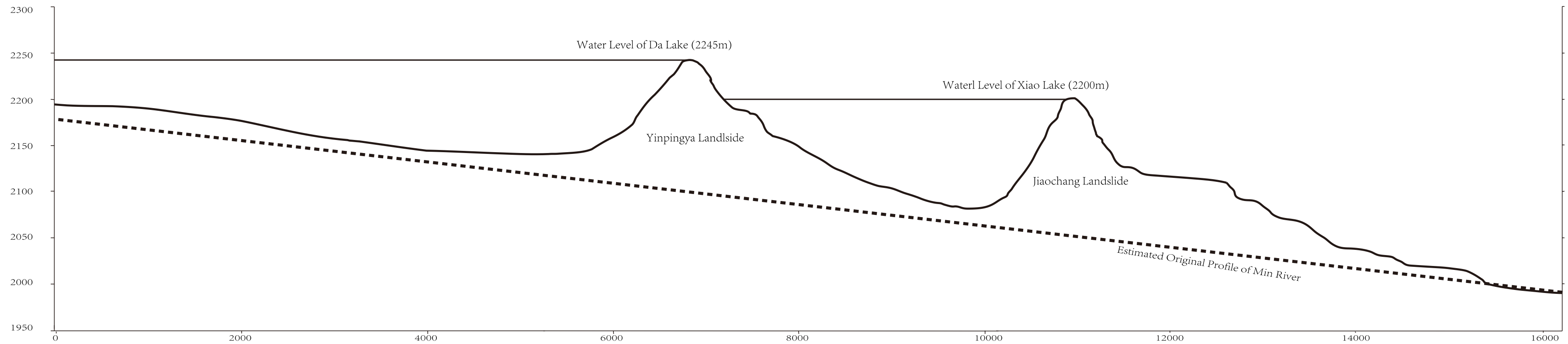

Figure 3.4a. Cross-section of Min River before dam failure, 1933 (topographic data from SRTM-3 DEM, vertical exaggeration 10:1). A combined lake (Diexi Lake) was formed at the elevation of 2,250 m asl.

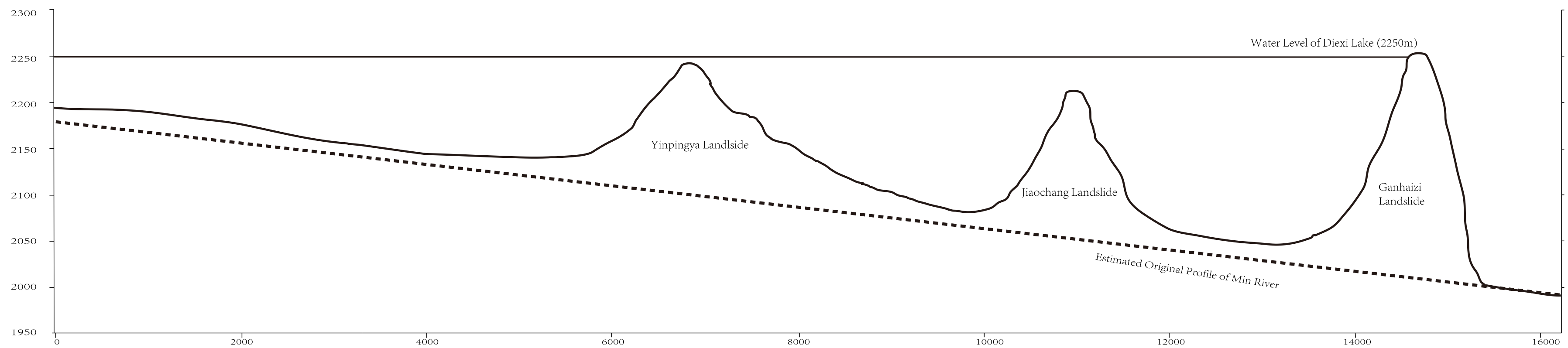

Figure 3.4b. Cross-section of Min River after dam failure, 1933 (topographic data from SRTM-3 DEM, vertical exaggeration 10:1). Lakebed of the former Diexi Lake was silted-up with deposits.

8. An additional 20-30m depth at the exit of the Xiao Lake was eroded downward, due to several floods in the 1980s and early 1990s.

3.1 Landslide geometry

3.3.1 Landslide locations

The development and distribution of landslides in the Diexi area is heavily influenced by local geological structure and active fault location (Wang et al., 2008). The description of landslide source areas of this study is mainly based on the work of Wang et al. (2008), with some re-interpretation based on two field investigations in 2013 and 2014. Landslides in the Diexi region can be divided into the five following areas: (Figure 3.5)

i) Yinpingya rockfall area;

ii) Jiaochang landslide area;

iii) Ganhaizi landslide area;

iv) Diexi (ancient town) rockfall area;

v) Songpinggou landslide area.

Figure 3.5 shows the location of each major landslide together with their boundaries. Each of these 5 landslide / rockfall areas will be described in the following sections. In addition, due to the fact that no previous work has identified the precise location of the breach of Diexi Lake, field surveys focused on finding the dam breach site. A highly probable location was found 2.5km downstream from the Xiao Lake, which is shown in Figure 3.6.

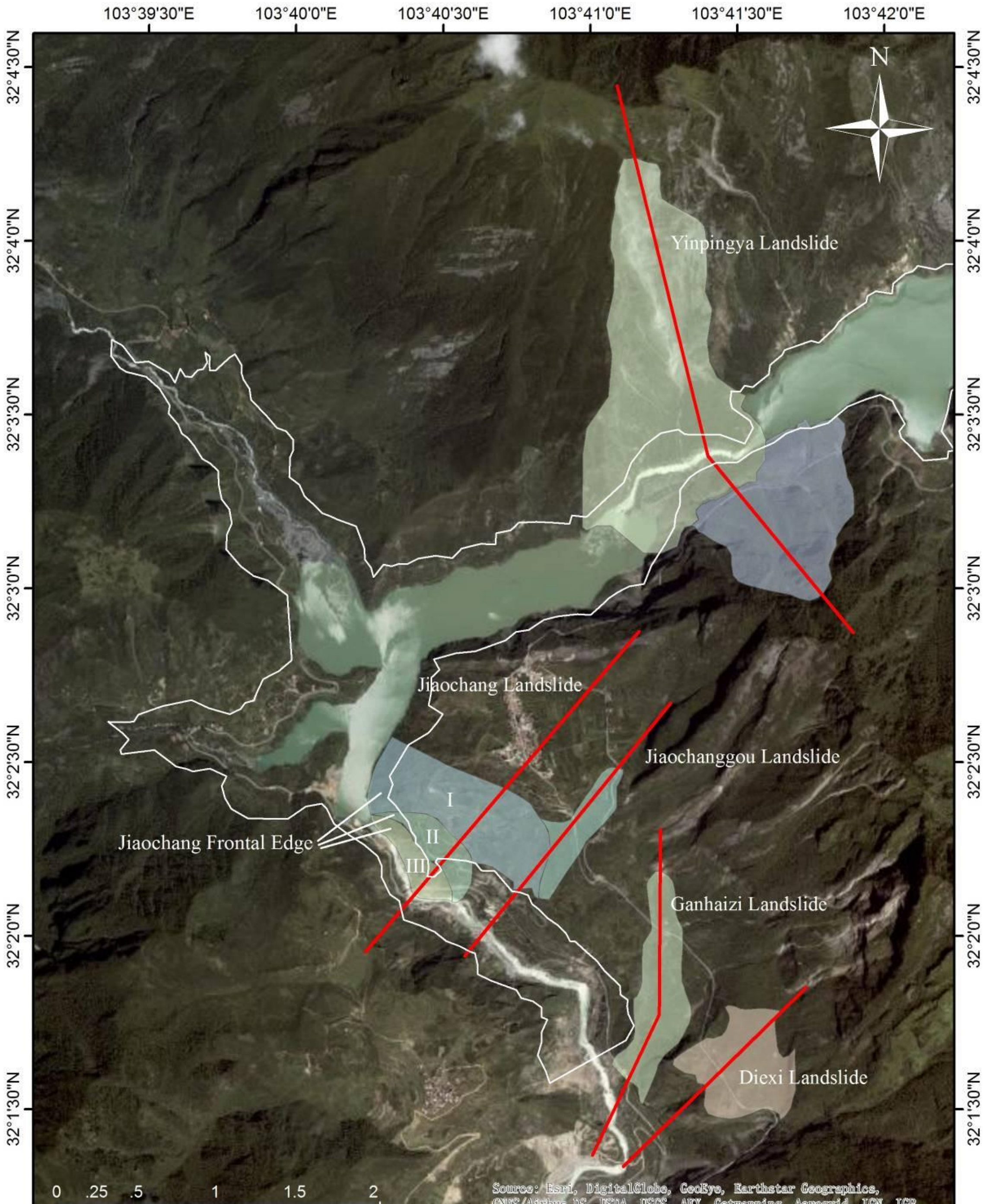

Figure 3.5. Locations of major landslides in the vicinity of Diexi (satellite imagery from ESRI). This map is modified from the landslide map of Wang et al. (2008). Lines crossing landslide areas indicate the directions of cross sections in Figure 3.7 to Figure 3.11.

Figure 3.6. Photograph of the remnant dam of Diexi Lake, which was formed by the Ganhaizi landslide and the Diexi landslide (taken on 17/08/2013).

3.3.2 1933 earthquake-triggered landslides in the Diexi area

3.3.2.1 Yinpingya rockfall dam

Yinpingya rockfall area is the most upstream landslide area in the vicinity of Diexi (Figure 3.5). Materials that formed this rockfall originated on both sides of the Min River. Slopes of both valley sides are steep, sloping at an angle of about 40°-50°. Lithology of this area is mainly metamorphic rocks, with the rockfall dam consisting of coarse metamorphic rock debris as well as giant boulders (Li et al., 1986). Average of rock diameter is 0.8 – 1 meter, and the largest boulder can be up to 5 meters in diameter (Li et al., 1986).

A cross section of the Yinpingya rockfall is shown as Figure 3.7. The original height of the dam was 156m, 1700m in length (along stream), and 800m in width (across stream) (Li et al., 1986). The landslide materials form a dam that completely blocked the Min River, and as a consequence, Da Lake was formed. As the original elevation of the dam crest, 2,229 m asl, is lower than the water level of the Diexi Lake formed downstream, it was partly submerged by the water of Diexi Lake. The remnant dam did not undergo severe erosion during the dam breach. In late 1933 and early 1934, a spillway was formed by river erosion over the top of the dam, which is about 20m in width, and 12m in depth (Li et al., 1986).

Water level of the Da Lake has not experienced a large drop since it formed in 1933 (2,229 m asl in 1933, and 2,221 m asl measured in 2013). However, the water area of the Da Lake has noticeably decreased during the last 80 years. Compared to its original length of over 12.5km in 1933, Da Lake only has a total length of 3.5km as measured in 2004 (Duan et al., 2004). It is estimated that deposition at the tail of the reservoir is the main reason to decrease the lake area.

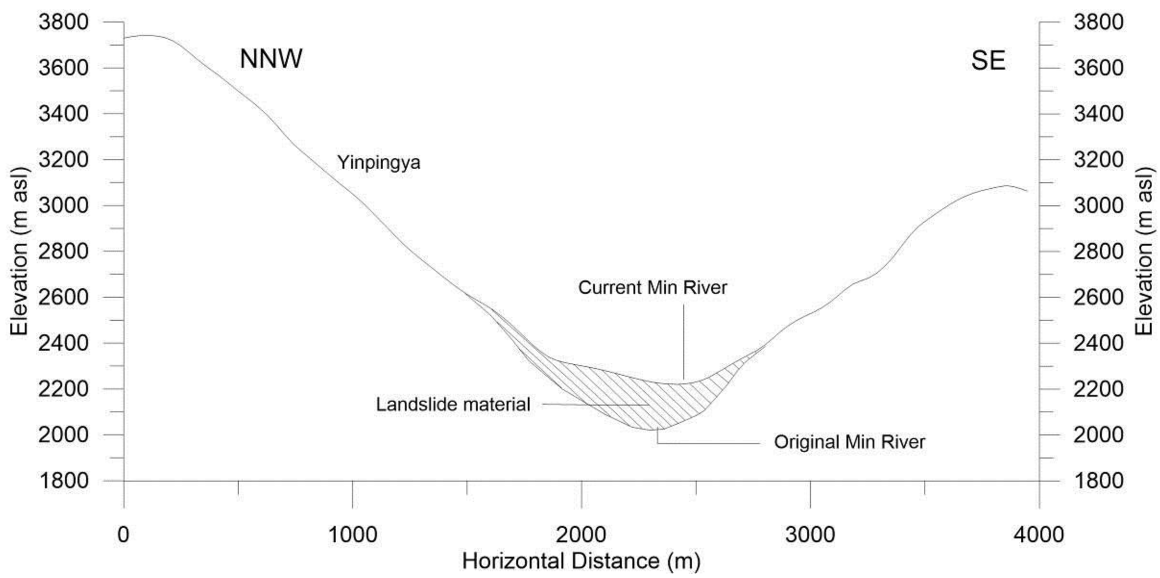

Figure 3.7. Present cross-section of the Yinpingya rockfall (modified from Wang et al., 2008, facing downstream, data from a SRTM-3 DEM). No vertical exaggeration.

3.3.2.2 Jiaochang landslide

Jiaochang landslide is the main debris source forming the Xiao Lake dam, and is also the most complicated landslide area in the vicinity of Diexi. Jiaochang refers to a terrace that lies on the southern side of the present Xiao Lake, which is 1.5km^2 in area, and the elevation of the terrace is 2,345 m asl. Drilling results show that 60 to 80 meters of lacustrine deposits are found at Jiaochang, which proved the existence of the pre-historical dammed lake, the above mentioned Ancient Dammed Lake of Diexi.

Jiaochang landslide area shows its complexity by combining four different landslides within its boundary. Areas covered by lacustrine sediments are named “Jiaochangba” (Jiaochang dam, Figure 3.8). Meanwhile, a small area within Jiaochangba not covered by lake sediments is named “Liduishan” (Mt. Lidui, Figure 3.8). At the southwestern edge of Jiaochang, the frontal edge of Jiaochang dips into the Xiao Lake with an angle of approximately 40 °. In addition, a rectangle-shape landslide named as “Jiaochanggou” (Jiaochang gully) occurred south of Jiaochang, which is close to its southern boundary (Figure 3.9). Locations of these areas are shown in Figure 3.5.

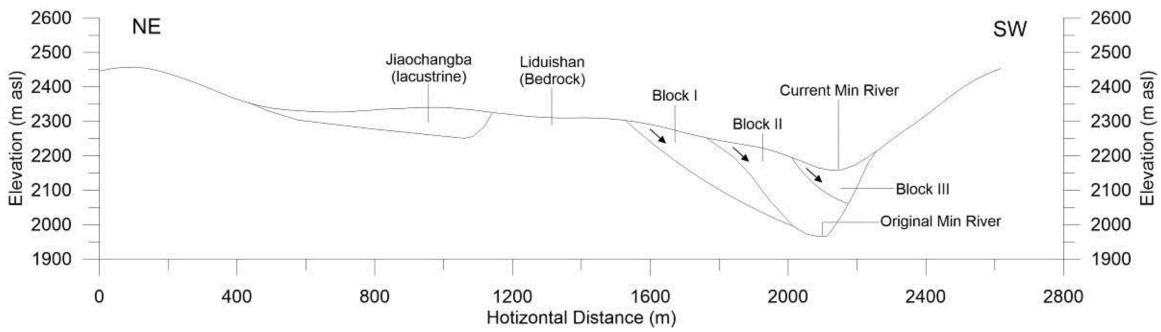

Figure 3.8. Cross-section of Jiaochang landslide area (modified from Wang et al., 2008, looking downstream). Deposits from the terrace slid down and blocked the river valley (Block I, II and III) in 1933 (topographic data from SRTM-3 DEM, no vertical exaggeration).

Jiaochangba; Jiaochangba is a flat area covered by 60-80m of lacustrine sediments in thickness. Ground fracturing in this area was observed during the 1933 earthquake (Chang, 1934). Two sets of fractures crossed at Jiaochangba, orientated in north-south and west-east. These ground fractures, as well as earthquake-generated faults, resulted in ground sinking and deformation at Jiaochangba.

Liduishan; Liduishan is located at the southwestern of Jiaochangba, and consists of metamorphosed sandstone and crystallized limestone. Although obvious displacements can be found here, Wang et al. (2008) regard Liduishan as resulting from local co-seismic surface deformation, not due to landslide movement. Bedding can still be observed, even though they have been strongly deformed and sheared. Rock layers consist of metamorphosed sandstone and phyllite dip at an angle of 20 °-30 ° towards SE (200 °).

Jiaochang Frontal Edge; frontal edge of southwestern Jiaochang is the largest landslide mass in

Diexi, with a total volume of approximately 36Mm^3. Lacustrine deposits overtopped have a dip angle of 10 ° towards the northeast (away from the river). Sliding direction of the landslide is 220 °, and three major landslide blocks can be observed (in sequence from upslope to river Blocks I to III), which are shown in Figure 3.8. Block I is the largest among the three blocks, which is about 22Mm^3 (Wang et al., 2008). The block stretched down to the original Min riverbed and dammed the river. Block II has a volume of 11Mm^3 (Wang et al., 2008). Block III can be partly observed from the Jiaochang frontal edge outcrop, and partly submerged by the Xiao Lake. This block is highly cracked and loose, and has a volume of 3.1Mm^3 (Wang et al., 2008). As the sliding blocks were compressed during the landslide motion (sudden brake when hitting the other bank), Xiao Lake dam is considered to be stable (Wang et al., 2008).

Jiaochanggou; The Jiaochanggou landslide area is approximately 1km in length, 160m in average width, and has a total volume of 17Mm^3 (Wang et al., 2008). Movement direction of the Jiaochanggou landslide is 220 °. Jiaochanggou is also covered by lacustrine deposit, and it forms the down-stream part of the Jiaochangba landslide area (Wang et al., 2008). Cross-section of the Jiaochanggou landslide area is shown in Figure 3.9.

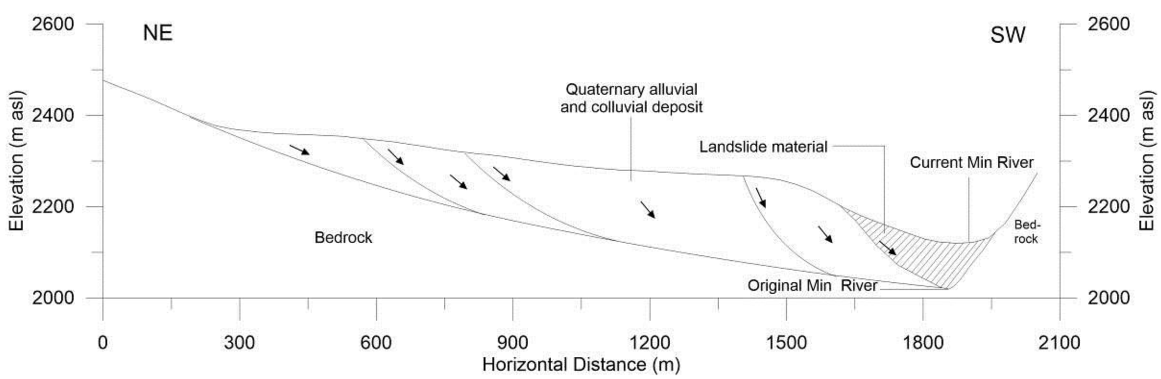

Figure 3.9. Cross-section of Jiaochanggou landslide area (modified from Wang et al., 2008, looking downstream, topographic data from SRTM-3 DEM, no vertical exaggeration).

3.3.2.3 Ganhaizi Landslide Area

Ganhaizi landslide area is located on the eastern (left) bank of the Min River, south of the Jiaochang area (Figure 3.5). Ganhaizi landslide is 1,250 meters in length, and 250 meters in width

(Wang et al., 2008). Three depressions can be found on the landslide, with the largest one at the top of the landslide. This area used to be a lake that dried up, so the landslide got its name (Ganhaizi means “dried lake” in local dialect). It is considered that the total volume of landslide materials is about 20Mm^3 (Wang et al., 2008). These materials are the major source that formed the Diexi dam, the largest lake formed in 1933. The dam is approximately 255 meter high (Chang, 1934), which is estimated to be 2,250 m asl at the top; the dam breached on 09/10/1933, causing a destructive outburst flood in the Min River.

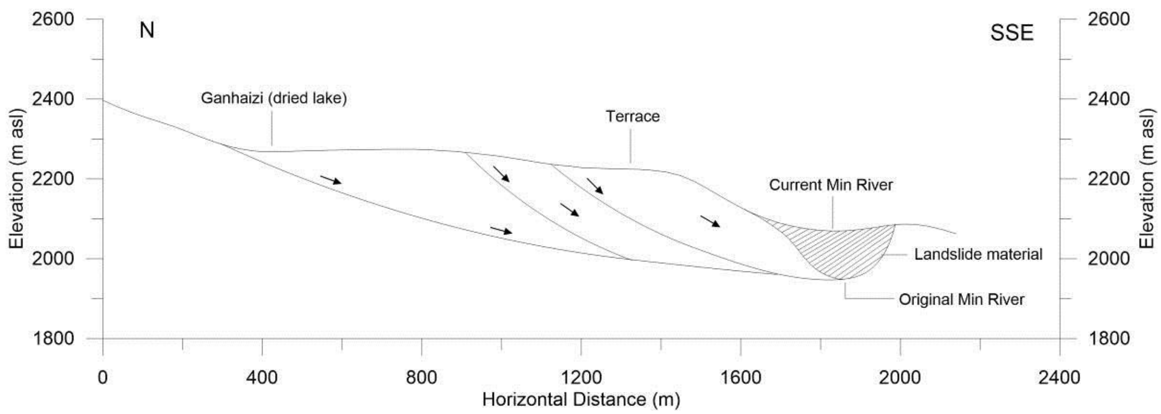

Figure 3.10. Cross-section of Ganhaizi landslide area (modified from Wang et al., 2008, facing downstream, topographic data from SRTM-3 DEM, no vertical exaggeration).

3.3.2.4 Diexi (ancient town) Rockfall Area

Diexi (ancient town) rockfall area is located in the southernmost part of the Diexi region (Figure 3.5). This area got its name because it is the location of the ancient Diexi town, which used to be the highest populated place among the surrounding areas before the 1933 earthquake. The town was located on a landslide debris-alluvial fan, which consists of sand and gravel, well bedded, and slopes towards the river at an angle of 10°-15°. The ancient Diexi town had 278 houses and more than 500 residents before the 1933 earthquake. It was totally destroyed by an earthquake-triggered rockfall, killing everyone in the town except for 15 survivors (Chang, 1934). The topography of the area (alluvial fan) has not obviously changed since the 1933 earthquake. Wreckage of the ancient town, including part of the perimeter wall and one of its gates, can still be found at their original position.

The source of the rockfall that destroyed the town was the mountain slope behind the town, which is nearly 50 ° in steepness. Large rocks disintegrated into smaller pieces while falling down towards the town, and accelerated to a high speed. After destroying the town, the remaining landslide materials rolled down into the Min River valley and formed part of the Diexi Lake dam together with the Ganhaizi landslide.

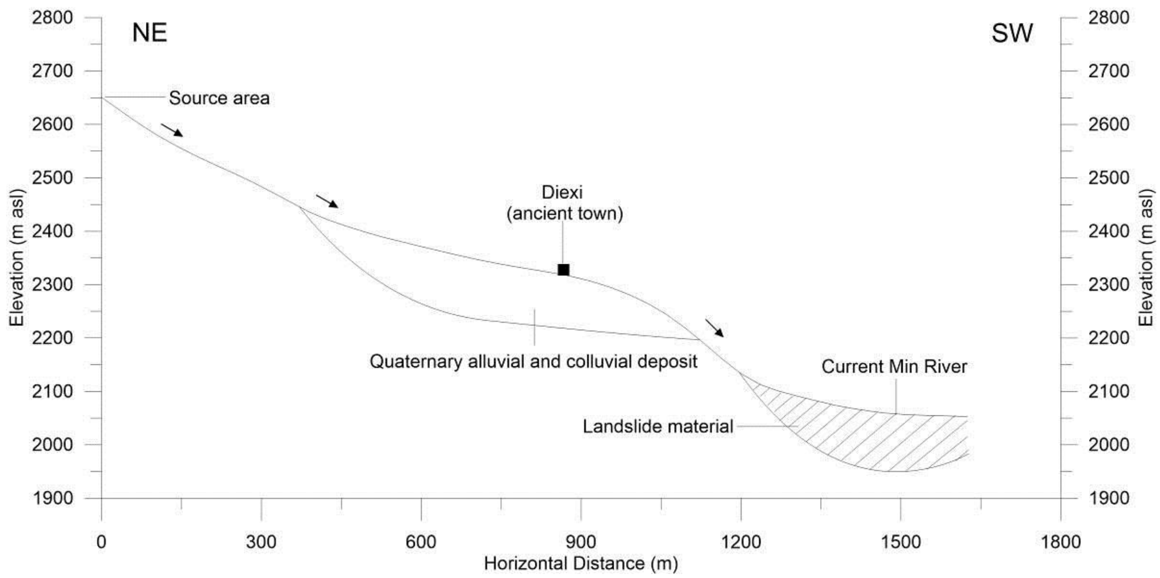

Figure 3.11. Cross-section of Diexi rockfall area (modified from Wang et al., 2008, facing downstream, topographic data from SRTM-3 DEM, no vertical exaggeration).

3.3.2.5 Songpinggou landslide area

Songpinggou (Songping Gully) is located on the northern (right) bank of the Min River (Figure 3.1). Songpinggou landslide area contains 13 landslides along the Songpinggou Gully. These landslides, rockfalls, and rock avalanches triggered by the 1933 earthquake blocked the stream and formed a string-of-pearls like chain of dammed lakes. These lakes are named as Lianghekou Lake (cross-section of two streams), Gongpeng Lake, Upper / Downer Baila Village Lake (Figure 3.1). Landslide materials that formed the Upper Baila Village Lake are mainly phyllite, coming from slopes dipping 35 °-70 °, and with a moving distance of 800 meters. The total volume of the landslide material is about 100,000m^3 (Wang et al., 2008). The Upper Baila Village Lake is 400 meters in length, and 100 meters in width. Lake water infiltrated the landslide body and runs into the Downer Baila Village

Lake. As the magnitudes of landslides within Songpinggou Gully are relatively small, they did not cause a large impact on the local environment.

3.4 Lake area and lake volume

3.4.1 Literature research on precise lake elevation

The elevation of two existing dams, which are, Da Lake and Xiao Lake, had already changed, due to the Diexi Lake failure on 09/10/1933 and erosion has taken place since 1933 of the two remaining dams. Neither precise surveys nor geology field investigations were carried out after the earthquake. All first-hand data of the earthquake-triggered landslides that can be found today are descriptive articles or reports. There are few data on the initial dams, thus they have to be estimated retrospectively. The major description and source of first-hand data of the Diexi earthquake are from The Investigation of the Diexi Earthquakes, Sichuan, written by Longqing Chang (Chang, 1934), who was the first geoscience professional to arrive in the Diexi area following the earthquake.

Precise surveying data on the dammed lakes varies by a large amount between different sources; since these data are derived from various time eras, i.e. from 1930s (estimated) to 2000s (precisely surveyed). These data are as the followings:

i) Surveyed data of Da Lake and Xiao Lake in 1980s, (Li et al., 1986);

ii) Surveyed data of Da Lake and Xiao Lake in 1990s, and estimated data of Diexi Lake (Chai et al, 1995);

iii) Surveyed data of Da Lake in 2000s (Duan et al, 2004);

iv) Estimated data of Diexi Lake before failure, according to Wang et al. (2008).

v) My field investigation data in 2013 and 2014.

Data on the three landslide-dammed lakes are summarized as follows:

Da Lake:

i) 1933 after dam breach: 12.5 km long, 2 km wide, water level estimated 2,245 m asl from topographic maps (Chang, 1934).

ii) 1986: water level 2,229 m asl, average depth 80m, volume 73Mm^3 (Li et al., 1986).

iii) 1995: average depth 81m, maximum depth 98m, average length 3,600m, average width 360m, surface area 1,800,000m^2, volume 75Mm^3 (Chai et al., 1995).

iv) 2004: water level 2,221.5 m asl, maximum depth 57m, volume 25Mm^3 (Duan et al., 2004).

v) 2013: water level 2,222 m asl (Ling, 2013 field investigation).

Xiao Lake:

i) 1933 after dam breach: water level estimated 2,195 m asl – 2,200 m asl from topographic maps (Chang, 1933).

ii) 1986: water level 2,180 m asl, length 2.5km (Li et al., 1986).

iii) 1995: average depth 42m, maximum depth 80, average length 2,350 m asl, average width 290m, volume 50Mm^3 (Chai et al., 1995).

iv) 2013: water level 2,146 m asl (Ling, 2013 field investigation).

Diexi Lake:

Water level 2,250 m asl, average depth 160m, average length 2,000m, average width 300m, and volume 80Mm^3, breached on 09/10/1933. Water level is calculated based on the elevation of Xiao Lake in 1980s (Li et al., 1986), plus the 20m that was eroded in the 1936 flood (Wang et al., 2008), and the 50m eroded during the 1933 dam breach.

Water level elevation of the lakes in different time eras are summarized in Table 3.1. Then water level of each lake in different time eras are used to measure the surface area as well as the volume of the three lakes in different times in ArcGIS.

Table 3.1. Water level elevations of Da Lake and Xiao Lake in different time eras (summarized from section 3.4.1, * indicates estimated water level, data from Chai et al., 1995, Chang, 1934, Duan et al., 2004, Li et al., 1986 and Wang et al., 2008).

	1933 before breach	1933 after breach	1986	2004	2013
Da Lake	2,250 m asl*	2,245 m asl*	2,229 m asl	2,221 m asl	2,222 m asl
Xiao Lake	2,250 m asl*	2,200 m asl*	2,180 m asl	2,148 m asl	2,146 m asl

3.4.2 Lake area

Methodology: Two methods are used in this chapter to measure the surface area of dammed lakes: DEM and georeferencing. The DEM method measures the area that corresponds to a certain elevation, within a valley. The area derived indicates the submerged area when the landslide-dammed lake water level was at that certain height. In georeferencing method, scanned maps from previous workers showing the boundary of the lake, and satellite images with correct coordinate information are imported to ArcGIS, then these two layers are merged by linking a number of the same locations on both layers. Each of these two methods has its own advantages and disadvantages. The DEM method is more coordinate correct than Georeferencing. Although both the DEM file and the satellite image are fairly accurate, matching between maps and satellite images could involve error. Matching between two layers can hardly be perfect especially for places without obvious landmarks. However, sometimes georeferencing can be more credible to estimate the submerged area. This is because the DEM data might not be obtained soon after the landslide happened. The topography of the study area could have been changed due to deposition and erosion.

The Diexi Lake was formed in 1933, and then breached in the same year. No detailed topographic map or photographic image can be found representing the 1933 Diexi Lake before failure, so the previous methods are applied to estimate the area of the 1933 Diexi Lake. The following data are used:

i) 90m resolution SRTM-3 DEM, derived from the SRTM official website: http://srtm.csi.cgiar.org/

ii) Base map provided by ArcGIS (coordinate corrected satellite image)

iii) Map of landslide blockages of the Min River (Figure 4 from Li et al., 1986)

Deriving area of Diexi Lake using DEM: As mentioned above, the maximum water level of the Diexi Lake was approximated at 2,250 m asl. Areas are equal to or that have elevation lower than 2,250 m asl are selected to represent the submerged area. Then a polygon shapefile was created by plotting along the 2,250 m asl contour upstream of the landslide dam to form an outline of the 1933 lake, which is shown as Figure 3.12.

The surface area of the 1933 lake was then calculated by using the “Calculate Area” tool in ArcGIS. The tool generates a new layer with the same area of the sketched layer with its area value in an attribute table. The result shows the area of the 1933 Diexi Lake is 9,864,800m^2, or 9.865km^2. However, due to deposition near the tail of the reservoir, the plotted outline generated from ArcGIS is probably smaller than the historical Diexi Lake. Moreover, 90m resolution SRTM-3 DEM has limitations in showing the detailed shape of valley, which influences the accuracy of deriving the lake outline.

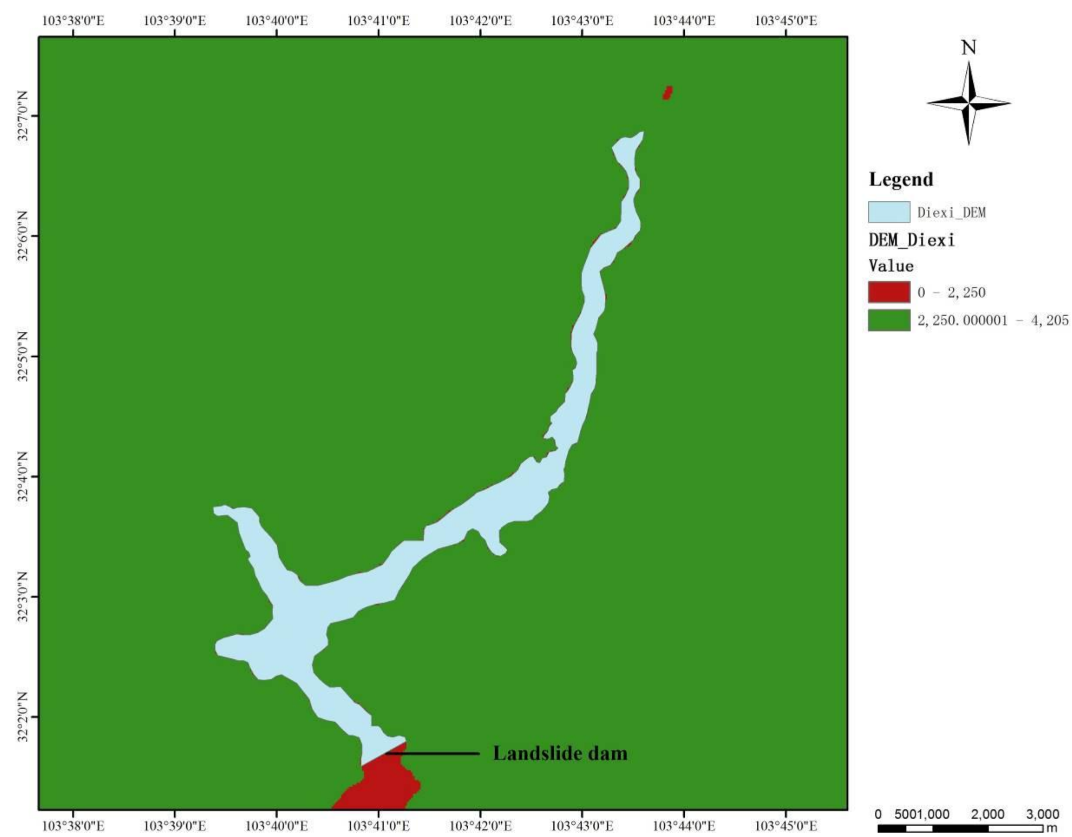

Figure 3.12. Plotted outline of 1933 Diexi Lake at the 2,250 m asl contour based on the DEM method (see text for discussion). This represents the full extent of Diexi Lake before breaching on 09/10/1933, 45 days after formation.

Deriving area of the Diexi Lake using georeferencing: A map (a scanned image, without spatial information) and a satellite image (with correct spatial information) are input into ArcGIS. Then georeferencing links between the map and the satellite image are created. Generally speaking, georeferencing is a process of giving a non-spatial file a map projection of a coordinate system. To do this, at least two links (more needed in rugged terrain) are made between two layers by linking same obvious landmarks. The following procedure is similar to the DEM method: a polygon is plotted along the estimated boundary of the Diexi Lake, and its area is calculated. Map showing the estimated Diexi Lake (Li et al., 1986) is shown as Figure 3.13, and the area of the polygon is 9,001,128m^2, which is approximately 9km^2. Georeferencing can measure lake area from previous maps when area value is not provided, but the precision of previous maps and georeferencing can highly influence the accuracy of the measurement.

It can be found that there exists a 9% difference between the two area values, which suggests that the derived areas have considerable credibility. Other than the limitations of the two methods (changed topography, inaccurate georeferencing), higher estimated water level can also contribute to the 9% difference.

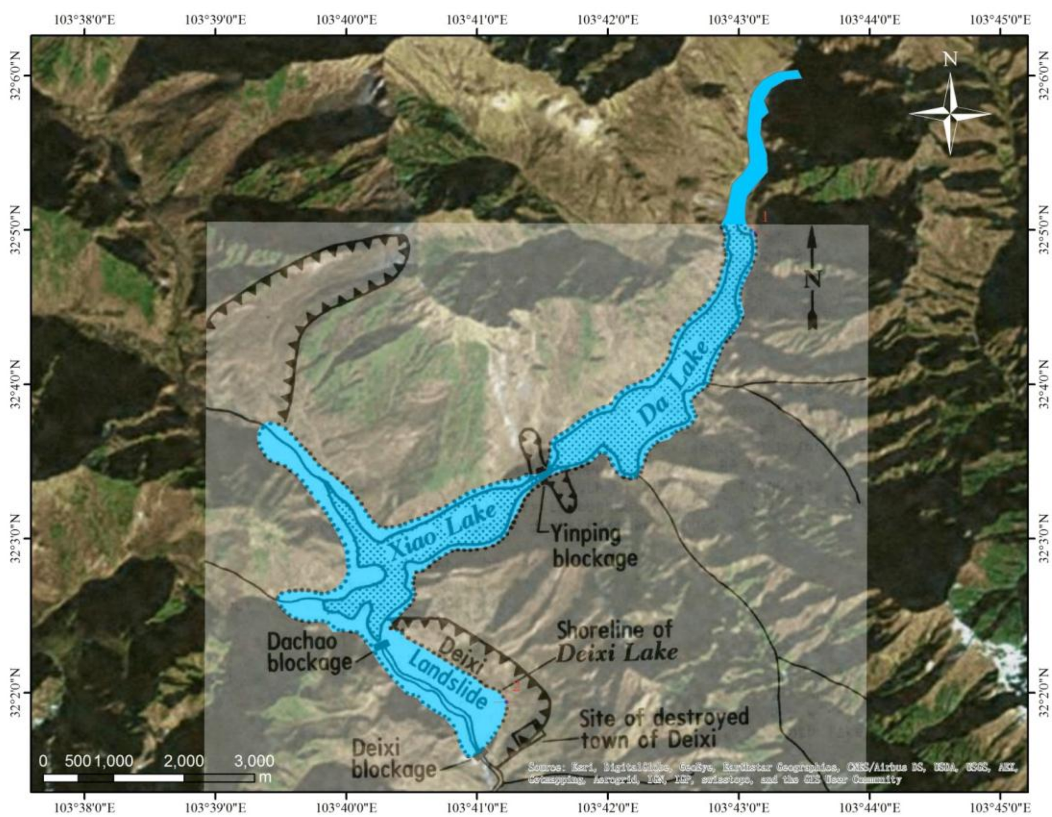

Figure 3.13. Sketched layer of 1933 Diexi Lake (overlay map from Figure 4, Li et al., 1986).

Area of Da Lake and Xiao Lake: Surface area of the present Da Lake and Xiao Lake are measured, using the DEM method. Based on previous surveying and field studies, water levels of the two lakes at different years are presented in the Table 3.1. It is obvious that over time, water level of the dammed lake decreased. This is mainly because water erosion to the landslide dam made the spillways deeper.

The same measuring procedure was done at Da Lake and Xiao Lake as the 1933 Diexi Lake. Polygons representing water level elevations in 1933, 1986, and 2004 are plotted, shown as figure 3.14. It can be seen that since the failure of the Diexi Lake in 1933, the sizes of both Da Lake and Xiao Lake have dramatically shrunk. Due to the deposition of upstream sediment, length of the Da Lake decreased from over 9 kilometers in 1933 to 5 kilometers at present. Meanwhile, the Xiao Lake also obviously shrunk in the Songping Gully direction, where there is stream flow into the Min River at Xiao Lake.

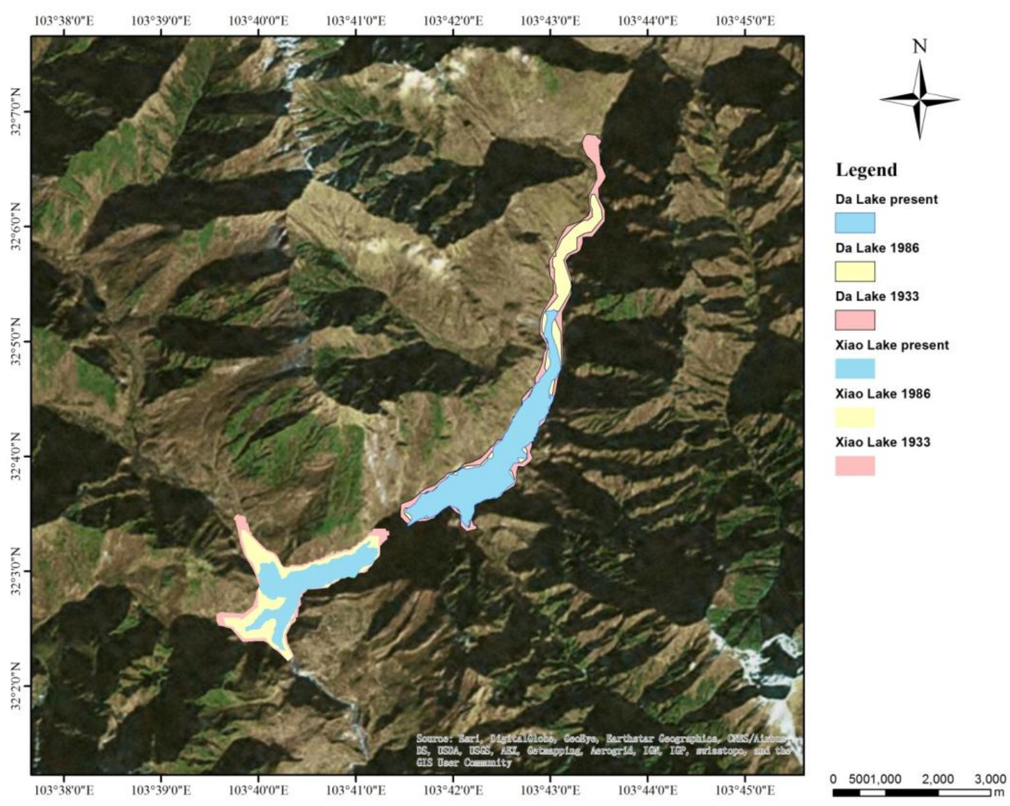

Figure 3.14. Area of Da Lake and Xiao Lake in 1933, 1986, and present (Base map from ESRI).

Areas of the two lakes are also calculated in ArcGIS, and the result is shown in the Table 3.2. It can be seen that both the Da Lake and the Xiao Lake shrunk rapidly in recent years. Especially for the Xiao Lake, approximately 40% of its area disappeared within 18 years.

Table 3.2. Area of Da Lake and Xiao Lake in 1933, 1986, and present day.

	1933 after breach	1986	2004
Da Lake	3,957,039m^2	2,513,992m^2	2,296,168m^2
	3.957km^2	2.514km^2	2.296km^2
Xiao Lake	2,816,658m^2	2,267,182m^2	1,367,662m^2
	2.817km^2	2.267km^2	1.368km^2

3.4.3 Lake volume

Two methods are used to measure the volume of the dammed lakes: DEM data and regression equations based on previous studies. The DEM method can calculate the lake volume by making a comparison between two different DEM surfaces (i.e. change detection). There are no maps showing the topography of the Min River valley before the 1933 earthquake and it is not therefore practical to find DEM file representing the form of the lake bottom. Therefore, it is also impractical to measure volume of the Diexi Lake by using a current DEM surface (e.g. SRTM-3).

Regression equations based on previous studies can be useful in this circumstance. They estimate dammed lake volume by inputting some key information on the dammed lake, for example, dam volume, or area of the lake. Equations are derived by finding the best-fit regression of numerous landslide dams of a certain study area. Previous studies on landslide-dammed lakes with similar terrain are chosen to estimate the volume of the 1933 Diexi Lake. Based on Chapter 2 of this thesis, after studying the 1786 Dadu River landslide dammed lake, which is located in a similar terrain to Diexi, the relationship between lake volume and area of the lake is summarized as a robust power law relation, which is $V_L = 1.7431A_L^{1.2062}$ ($R^{2=0.9943}$, Figure 2.8b of page 23). Similarly, after summarizing lake area and volume of the 2000 Yigong Lake (Table 22.2, Evans and Delaney, 2011), a power law relation is derived as $V_L = 9E\text{-}18A_L^{3.4246}$ ($R^{2=0.9991}$). Regression equation from the Dadu River case

(Chapter 2) is considered more appropriate because of its terrain similarity to Diexi. They are both located in western Sichuan, and valleys are both deeply cut. However, the Yigong dam site experienced another landslide damming event in 1900, and the valley was filled with deposits before the 2000 event occurred. This can explain why the Yigong regression will obtain relatively small lake volumes at large lake areas. Therefore, regression equation derived from the Yigong case is more suitable for estimating landslide-dammed lake volume where previous landslide damming had taken place, which is not the Diexi case.

Thus the volume of Da Lake, Xiao Lake, and Diexi Lake will be calculated using the Dadu regression ($V_L = 1.7431A_L^{1.2062}$). Calculated volume of each landslide-dammed lake is shown in the following tables (Table 3.3 – 3.5).

Application of summarized equations can show the uncertainty and limitation of the method, which is highly depend on the data source of the equation. Local topography varies dramatically between different valley areas. Using summarized equations that are not based on the geomorphology of the same area often make the estimation inaccurate. Despite this, the summary equations can still be useful as a first order approximation and the real values are still in the same order of magnitude.

Table 3.3. Estimated volume of the Da Lake.

Year	Lake Area (km^2)	Estimated Volume (Mm^3)
1933	3.957	158
1986	2.514	92
2004	2.296	82

Table 3.4. Estimated volume of the Xiao Lake.

Year	Lake Area (km^2)	Estimated Volume (Mm^3)
1933	2.816	105
1986	2.267	81
2004	1.367	44

Table 3.5. Estimated volume of the 1933 Diexi Lake.

	Lake Area (km^2)	Estimated Volume (Mm^3)
DEM	9.865	476
Georeferencing	9.001	426

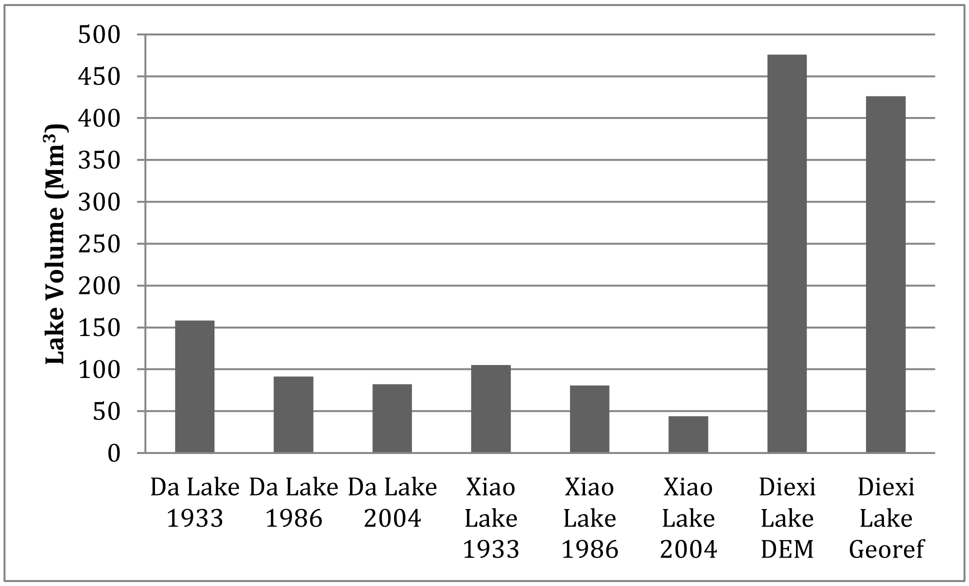

Figure 3.15. Mean lake volume of dammed lakes in different time periods.

An approximately 10% difference can be found between the volume of the 1933 Diexi Lake using DEM and Georeferencing. During 1933 to 2004, both Da Lake and Xiao Lake have shrunk 50% - 60% of their volume. However, Da Lake lost much of its volume during the 1933 – 1986 peroid, while Xiao Lake lost most of its volume during the recent 30 years. The cause of the atrophy of Da Lake is mainly due to the deposition of upstream sediments. As the Yinping landslide body mainly consists of erosion resistant materials (Li et al., 1986), the spillway connecting Da Lake and Xiao Lake has not been excavated much deeper since the lake was formed in 1933, which has reduced the shrinking rate of Da Lake (Figure 3.5). However, the spillway of Xiao Lake was cut by erosion much faster. During the 70 years since the earthquake, the elevation of the lake has dropped about 50 meters (2,200 m asl in 1933, and 2,150 m asl in 2004).

The difference in the calculation of lake volumes using the regression equation from Chapter 2 is, to some extent, acceptable. Chai et al. (1995) reported the volume of Da Lake and Xiao Lake in his paper in 1995, which are 70Mm^3 and 50Mm^3, respectively. The estimated values in 1986 using the equation from Chapter 2 are 91Mm^3 and 80Mm^3, which are larger than the value given by Chai et al. (1995). However, compare to the surveyed data of the Da Lake in 2004 (Duan et al., 2004), calculated 37Mm^3 volume is less than half the size of the regression estimated volume.

Fan et al. (2012) researched the lake area-volume relationship of the landslide-dammed lakes formed in the 2008 Wenchuan earthquake. It can be seen from Figure 3.16 (Fan et al., 2012) that a best-fit regression is calculated based on compiling 319 landslide-dammed lakes triggered by the Wenchuan earthquake. According to Fan et al. (2009), the results were "validated using field measurement data of 24 lakes that were surveyed by a Chinese expert team and the Chinese army directly after the earthquake" (Xu et al., 2009), and these lakes are labeled as the black dots in the plot. The 1933 Diexi Lake data point was plotted onto Figure 3.16; it is noted that the point is located within the 95% confidence interval (dashed line) calculated by Fan et al. (2012), indicating the volume estimation to the 1933 Diexi Lake is reasonable.

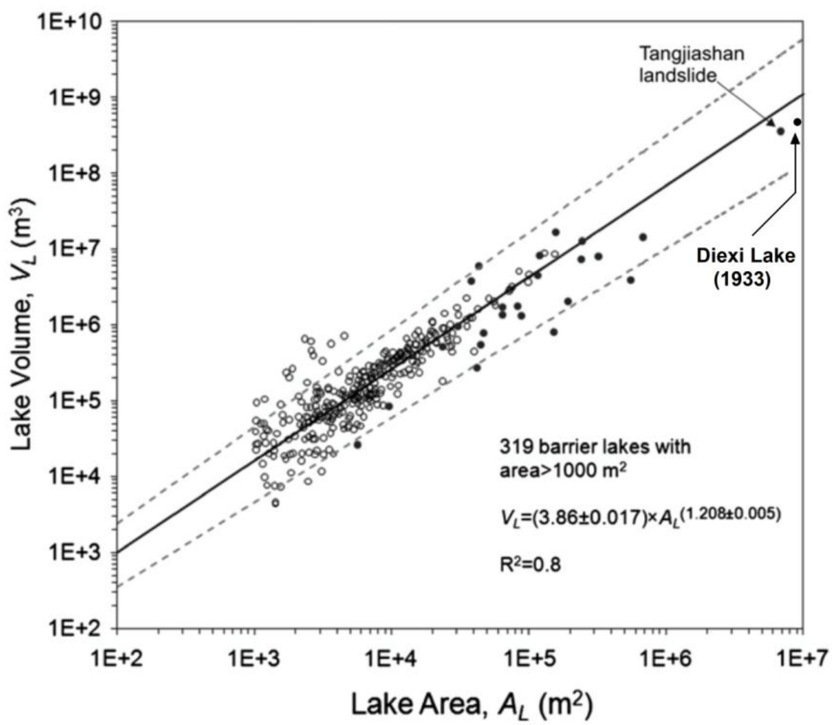

Figure 3.16. Power law regression between landslide-dammed lake volume and lake area (Figure. 11D from Fan et al., 2012). Dashed lines show 95% confidence interval. Note the newly-plotted 1933 Diexi Lake is also within the 95% confidence interval boundary calculated by Fan et al. (2012).

3.5 Water released in the 1933 outburst

The tool “Surface Volume” in ArcGIS is used to calculate the water volume released from the breached 1933 Diexi Lake. This tool calculates the area and volume of a raster dataset surface above or below a given reference plane. For the 1933 Diexi case, the volume of impounded water released can be regarded as the volume above the 1933 post-breaching water level (2,245 m asl for Da Lake, and 2,200 m asl for Xiao Lake, see Table 3.1), and beneath the pre-breaching maximum water level (2,250 m asl). As the water level of the two residual lakes kept decreasing since 1933, the volume difference between 1933 to present also has to consider Da Lake as well as Xiao Lake. As a result, the “Surface Volume” tool is applied to the three Lakes respectively, and the names of exported file are “SV DEM_Diexi”, ”SV DEM_Da” and, ”SV DEM_Xiao”. It should be noted that “SV_DEM_Diexi” is also the minimum volume from the DEM at the max. pool elevation. The water volume that released from the failed 1933 Diexi Lake can be calculated as the following equation:

Volume released = “SV_DEM_Diexi” – “SV DEM_Da” – “SV DEM_Xiao”

= 315,146,892 – 45,641,737 – 67,519,615

= 201,985,540 m^3 (201.9Mm^3)

Thus, approximately 200Mm^3 of water was released from the Diexi Lake due to the dam breach in 1933. It is nearly half of the maximum volume of the 1933 Diexi Lake, which is considered to be around 450Mm^3. Numerically, the 1933 Diexi event is not of the same magnitude as the top landslide dam flood cases in China. For example, the outburst volume of the 2000 Yigong landslide in Tibet was 2.015Gm^3 (Delaney and Evans, 2015), 10 times the volume of Diexi. However, the flood still caused severe damage and casualties, mainly because the areas in the Min River downstream from Diexi are relatively highly populated. Especially after Dujiangyan (175km downstream from Diexi, named as Guan County in 1933), the Min River runs into the Sichuan Basin, reduced water velocity makes the Min River become a meandering river under normal flow conditions. The sudden change in the valley environment at Dujiangyan and deep cut valley topography enhanced the impact of the flood to some extent. Observation show that the highest flood level was about 60m near Diexi (Chai et al., 1995), and a downstream area of 253km in length was affected (Li et al., 1986). The 1933 flood wave was still 12m in height when reaching at Dujiangyan, 175km downstream from Diexi, as shown in Figure 3.18 (Wang et al, 2008).

3.6 Flood discharge

Several regression equations developed for outburst floods are applied to estimate the peak flood discharge of the Diexi dam failure. Peak flood discharge is estimated by using parameters such as volume released and water level drop. Evans (1986) and Cenderelli (2000) provided well-cited regression equations based on known data, which are shown in Eq. (1) to (4):

$Q_p = 0.72V^{0.53}$ (Evans, 1986) (1)

$Q_p = 24d^{1.73}$ (Cenderelli, 2000) (2)

$Q_p = 3.4V^{0.46}$ (Cenderelli, 2000) (3)

$Q_p = 1.9(Vd)^{0.4}$ (Cenderelli, 2000) (4)

Where Q_p is for peak flood discharge (m^3/s), V is the volume of water that released from the lake (m^3), and d is the lake's water level drop due to the dam failure (m).

For the 1933 Diexi outburst we have estimated:

d = 2250 – 2200 = 50m (from Table 3.1)

V = 201,985,540m^3 (from section 3.5)

Therefore, peak flood discharge derived from Eq. (1) is 18,162m^3/s, Eq. (2) is 20,866 m^3/s, Eq. (3) is 22,486m^3/s, and Eq. (4) is 19,075m^3/s. It is clear that calculated peak discharge are in the same order of magnitude, and they also have considerable dispersion of about 20,000m^3/s.

Estimating peak flood discharge by applying Evans (1986) and Cenderelli (2000) regressions as a first-approximation shows fairly accurate magnitude. It is best applicable to those cases that have little information available, which occurred in the past when proper surveying methods were unavailable. However, its limitations are also obvious. Various estimations using different regressions are needed to ensure accuracy. This is essential because regressions may not fit the situation of the estimation, and multiple estimations can fairly reduce the probability of errors. In addition, regressions are set up based on summarizing various case histories of a certain study area, which means they have applicable restrictions. For example, Evans (1986) summarized the regression by collecting peak discharge data mainly from Northern America and Europe, which might not totally fit valley geometry of southwestern China.

3.7 Damage caused by 1933 flood

The Diexi landslide dam started breaching at around 7pm, 09/10/1933, 45 days after it formed in the Diexi earthquake. The flood wave reached Mao County (48km downstream) at 9pm, 12am at Wenchuan (98km downstream), and 3am at Dujiangyan (175km downstream, Chang, 1934). It is reported by Chang (1934) that flood wave height upstream of Town of Shidaguan (19km downstream) reached more than 60m. Although the Min River channel flattens and widens as it flows downstream, the wave height still reached more than 12m at Dujiangyan (Figure 3.17). Fortunately, the flood peak only lasted for an hour (Chang, 1934). As a large amount of debris also rushed downstream, villages and roads built near to the river suffered huge damage along the river. Chang (1934) reported that most villages were swept away by the flood, while towns were buried by debris, or were eroded downward by several meters.

After the flood reached the City of Dujiangyan (175km downstream), it flowed out of the narrow channel and entered the Sichuan Basin. When reaching the famous Dujiangyan Irrigation System, the flood partially destroyed the Feishayan (or Flying Sand Weir) and rushed into the urban area. Every place the flood passed became a gravel river bed, causing substantial damage.

Chang (1934) briefly investigated the damage by the flood. Because the statistics reported by the City of Dujiangyan were not complete, precise casualty numbers are not known. It is reported that the flood killed 340 people in Mao County, 488 people in Wenchuan, and at least 1,600 people in Dujiangyan. When summed up, more than 2,428 people were killed in the 1933 outburst flood catastrophe.

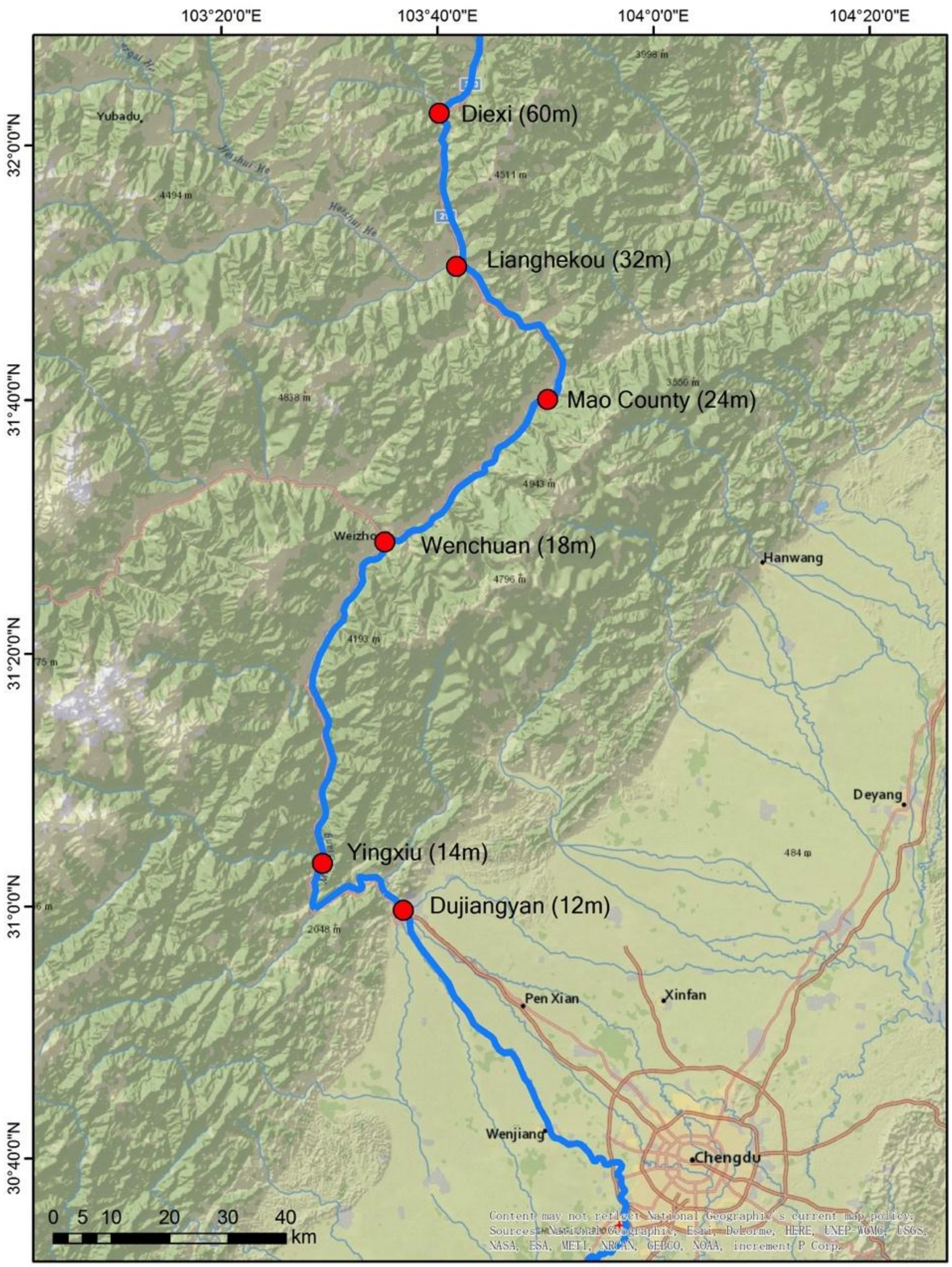

Figure 3.17. Map of the 1933 flood extent downstream from the breached Diexi Lake (09-10/10/1933). Red circles refer to major cities along the Min River affected by the flood. Height of the flood wave is labeled at each city (in brackets). Base map from ESRI.

An estimated peak flood discharge of about 20,000m^3/s is not one of the largest floods among Chinese landslide dam events. However, the flood still caused severe damage. The deeply cut valleys that drain the southeast Tibetan Plateau in southwestern China is probably the main reason that caused this. Narrow valleys forced the flood to concentrate, which would enormously enhance its power. It also caused the frontal wave height to have a low attenuation rate. The frontal flood wave had a height of 30 meters about 20km downstream of the dam, and was still over 10 meters high 175km downstream at Dujiangyan (Li et al., 1986).

3.8 Conclusion

This chapter reviewed and complied important information on the landslide damming and breaching flood of the 1933 Diexi event on the Min River. Landslide locations, lake area, lake volume before breaching, and volume breached have been investigated. By using GIS tools and SRTM-3 data, the volume of the pre-breach 1933 Diexi Lake was estimated to be in the order of 450Mm^3, of which 200Mm^3 breached in an outburst flood, 45 days after the formation of the lake. Although it was not one of the exceptional events in the world in terms of outburst volume magnitude, the Diexi case is still the most destructive natural dam outburst in China in the 20th Century. Due to lack of geological knowledge in the 1930s, few monitoring or warning of the event was carried out, which to some extent, enlarged the damage of the flood. It can be concluded that remote sensing data can be used to estimate the volume of a breaching flood or recently occurred landslide-dammed lake, when comparison before and after the breaching event can be made. However, this chapter shows its limitation to historical events, when no data is available before the event, and in cases where the topography has been severely modified. Moreover, risk assessments as well as fast-reacting forecasting, monitoring and warning are essential when facing potential natural disasters due to landslide-damming in order to reduce possible damage.

Chapter 4

Magnitude and frequency of historical earthquakes and landslide damming events

4.1 Introduction

Natural hazards can be viewed as a function of their magnitude versus annual frequency (Korup and Clague, 2009). Based on previous work from Evans (2006a, b), a basic method of quantitative risk assessment for both landslide dam formation and landslide dam failure is developed. After analyzing the magnitude and frequency relationship of massive rock slope failures, robust power law scaling relations with similar negative values of the exponent were derived (Evans, 2006b). As Evans (2006a) revealed the importance of studying the relation between magnitude and frequency of natural disasters, a brief analysis is carried out on M&F correlation of historical earthquakes in the different areas of western Sichuan, the magnitude of landslides that caused damming, and the volume of dammed lakes in China. Most of the researched events are located in geologically complex areas. Mountainous topography and a high density of active faults lead to frequent earthquakes and landslides in this collisional setting. Results found in the research are compared to previous work of Evans (2006a, b), and the characteristics of the natural hazard frequencies are illustrated. By studying historical natural hazard events, the probability of a potential natural hazard in a certain region can be estimated, thus, prevention and mitigation can be considered in advance to reduce the damage.

4.2 Magnitude and frequency of historical earthquakes near Mogangling

The coordinates of the Mogangling landslide are 29°37’25”N, 102°9’28”E. Therefore, a study area of 28°-31°N, 101°-104°E was chosen in order to make the landslide near the center. Historic earthquake data is provided by the China Seismic Information website (www.csi.ac.cn) and 85 earthquakes above M5 threshold are recorded from 01/01/1900 to 01/12/2014 (Appendix A). The threshold of M5 is chosen because it is large enough for historical documents to record, thus, fewer events can be missed. The M&F plot is shown in Figure 4.1. Because obvious gaps are observed in the dataset from the early 20th Century to the period 1962-1970, a second line is plotted showing the M&F relation of all events (M≥5) after 1970. It can be noticed that gaps do not have serious effect on the slope (-8.83 compared to -8.91). While the lower black dots on the plot represent the M≥7 earthquakes (13 in total) recorded after 1725 A.D., the slope is obviously steeper than the previous ones (-13.69 compared to -8.91). Two reasons can be suggested in order to explain this phenomenon. One is because the lack of data, especially for the relatively smaller earthquakes before the 20th Century. These minor earthquakes are more difficult to trace, and are sometimes missed in records. Another is the dramatic influence of recent large earthquakes, that is, the 2008 Wenchuan earthquake. The Wenchuan event is the largest earthquake in the dataset, and it unquestionably lifts the log-log trend line in the high-magnitude range thus reducing the slope. The shorter the sampling period is, the higher frequency of large earthquake will likely occur. Despite the limitations of the analysis, it can be estimated that the annual frequency of M≥6 earthquake occurring in the study area is about 0.2, which

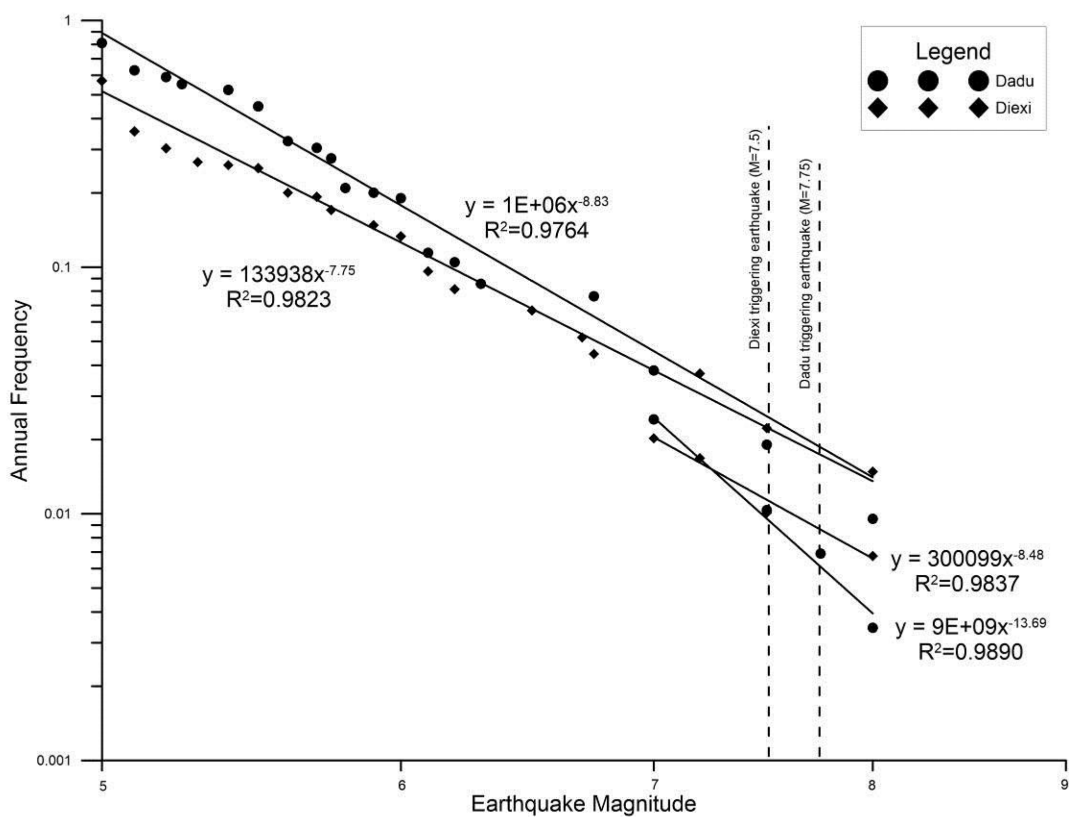

Figure 4.1. Magnitude vs. frequency plot of historical earthquakes near the 1786 Dadu River (n=85) and the 1933 Diexi (n=77). Data from the China Seismic Information website (www.csi.ac.cn).

means that it could occur every 5 years; the annual frequency of an M≥7 earthquake about is 0.04, indicating every 25 years. Annual frequency of a M≥7.75 (the same magnitude as the 1786 triggering event) earthquake varies from 6.02×10^{-3} to 2.40×10^{-2} by calculating the frequency on both slopes, which indicates 42 to 166 years. Using the equation from Evans (2006a), the annual frequency of generating a $V=1.15Gm^3$ rockslide dammed lake can be calculated as 0.02, showing that a lake of $1Gm^3$ scale might be formed around the world every 50 years.

4.3 Magnitude and frequency of historical earthquakes near Diexi

For the Diexi case, as the coordinate of the Town of Diexi is 32°2’37”N, 103°40’45”E, a study area of 30.5°-33.5°N, 102°-105°E was chosen. As a result, data provided by the China Seismic Information website (www.csi.ac.cn) shows, 77 earthquakes that exceeded the threshold of M5 are recorded from 01/01/1879 to 05/15/2010 (Appendix B). By calculating the frequency for this time period, an M&F plot for earthquakes in the Diexi area is shown in Figure 4.1. While the lower points in the plot represent M≥7 earthquakes (6 in total) recorded after 1713 A.D., the slope is nearly parallel to the previous one and only slightly steeper (-8.48 compared to -7.75). The reason that the two trend lines are more parallel compared to the Mogangling case is because two M8 earthquakes are recorded in the dataset, which are the 2008 Wenchuan earthquake, and the 1879 Wudu earthquake in southern Gansu Province (Appendix B). These two large earthquakes dramatically increased the frequency slope. Therefore, by calculating annual frequencies of M7 earthquake with both slopes, an interval of 0.02046~0.03816 can be derived, i.e. an interval of 26.2 to 48.9 years. Similarly, chances of an M7.75 or M8 earthquake occurring in the study areas are 57.6~115.9 years and 73.7~151.7 years, respectively. Incomplete historical data and the recent occurrence of large earthquakes dramatically influenced the geometry of the M&F plot, affecting its forecasting result. Despite this, the frequency of large earthquakes is still seen to be quite frequent.

4.4 Magnitude and frequency of landslides that caused damming

Further studies on the relationship between the frequency of landslides that caused damming and their magnitude is next considered. The dataset is from Chai et al. (1995), in which 147 landslide damming events in China from late Quaternary to 1994 are recorded. Among these events, 60 with known volume are chosen to calculate the frequency (Appendix C, and the magnitude-frequency relation in Figure 4.2). These events are selected after the beginning of the 20th Century, in order to avoid missing historical records, and a threshold volume of 1Mm^3 is selected. An obvious flattening trend (rollover) can be observed as the curve approaches V≤5Mm^3. The slope of the trend line is -0.63. Therefore, in order to avoid the influence from small events, a second trend line is plotted showing all events over the threshold of 5Mm^3 (Figure 4.2), deriving a slope of -0.84. As a comparison, Evans (2006a, b) obtained the relationship between magnitude (V) and frequency (F) of 37 rock avalanches larger than 20Mm^3 from 1900-2000 as $F=151384V^{-0.77}$. It is noted that the slope of the magnitude-frequency of damming landslides in China is nearly parallel to that of the global dataset from Evans (2006a).

Comparison with similar work done by Korup and Clague (2009), who used the frequency density of landslides. Frequency density refers to the annual probability of landslide to occur per unit volume. Korup and Clague (2009) researched the frequency density of 70 large landslides in China in the 20th Century, Holocene landslides in Southern Alps (New Zealand), and Holocene landslides in the Alps, and it is found that the slopes (α_v) of the Volume vs. Frequency density plot are: 1.95 ± 0.13 (China), 1.57 ± 0.57 (NZ), and 1.32 ± 0.06 (Alps), respectively. Therefore, it can be observed that the slopes in all cases are lower than 2, which indicates that "*fewer and larger landslides mobilise substantial fractions of the total debris volume, thus dominating the volumetric production rate of sediment*" (Korup and Clague, 2009). By using the data from Chai et al. (1995), plots of landslide volume vs. frequency density of landslides in China yielded value of α_v of 1.81 (5Mm^3 threshold) and 1.63 (1Mm^3 threshold). As the dataset used by Korup and Clague (2009) of landslides in China has a threshold of 10Mm^3, it is reasonable that the slope derived from the 5Mm^3 threshold reaches the lower bound of the one from Korup and Clague (2009).

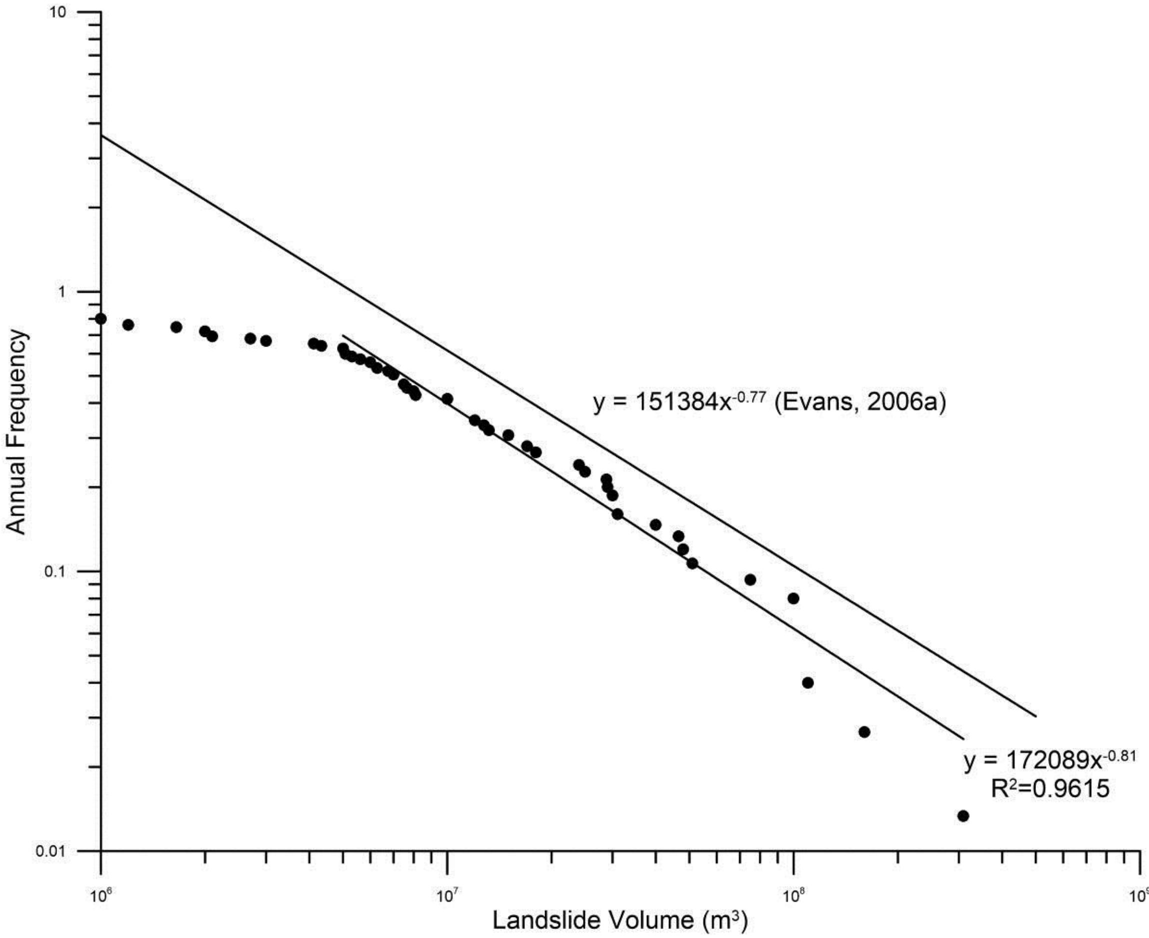

Figure 4.2. Magnitude vs. frequency plot of volume of landslides that caused landslide damming in China (1920 to 1994, n=60, from Chai et al., 1995). Also shown is magnitude-frequency plot of volume of large landslide that occurred globally (1900-2000, Evans, 2006a).

After comparing landslides that caused damming in China with the ones that occurred in other areas, as well as the globally, the following statements can be made:

(1): Landslides in China that caused damming have a similar trend compared to the world average, despite the threshold of China being smaller than that of the world dataset (5Mm^3 compared to 20Mm^3)

(2): According to data from Wen et al. (2004), China is more prone to have small landslides; while the frequencies of landslides that have larger magnitudes (larger than 15Mm^3) are relatively low. After comparing the frequency density of both datasets from Chai (1995) and Wen et al. (2004), few differences can be observed (10Mm^3 threshold: α_v=1.81 and 2.01; 20Mm^3 threshold: α_v=1.89 and 2.07, respectively).

4.5 Magnitude and frequency of landslide-dammed lakes

As Chai et al. (1995) did not show the volume of dammed lakes, other data has to be used to explore the relationship between landslide-dammed lake volume and frequency of landslide-dammed lakes in China. A total of 12 lakes with a threshold of 20Mm^3 are collated and used in the magnitude-frequency analysis (Appendix D: from: Huang 2008, Evans et al., 2011, Evans and Delaney, 2011, Chen et al., 1992, Figure 4.3). The power law relation is $F=1428.4V^{-0.53}$, steeper than the one from Evans (2006a), which is $F=103.4V^{-0.39}$ (with a threshold of 40Mm^3). It can be observed that dammed lakes smaller than the 140Mm^3 are more prone to occur in China than worldwide, while

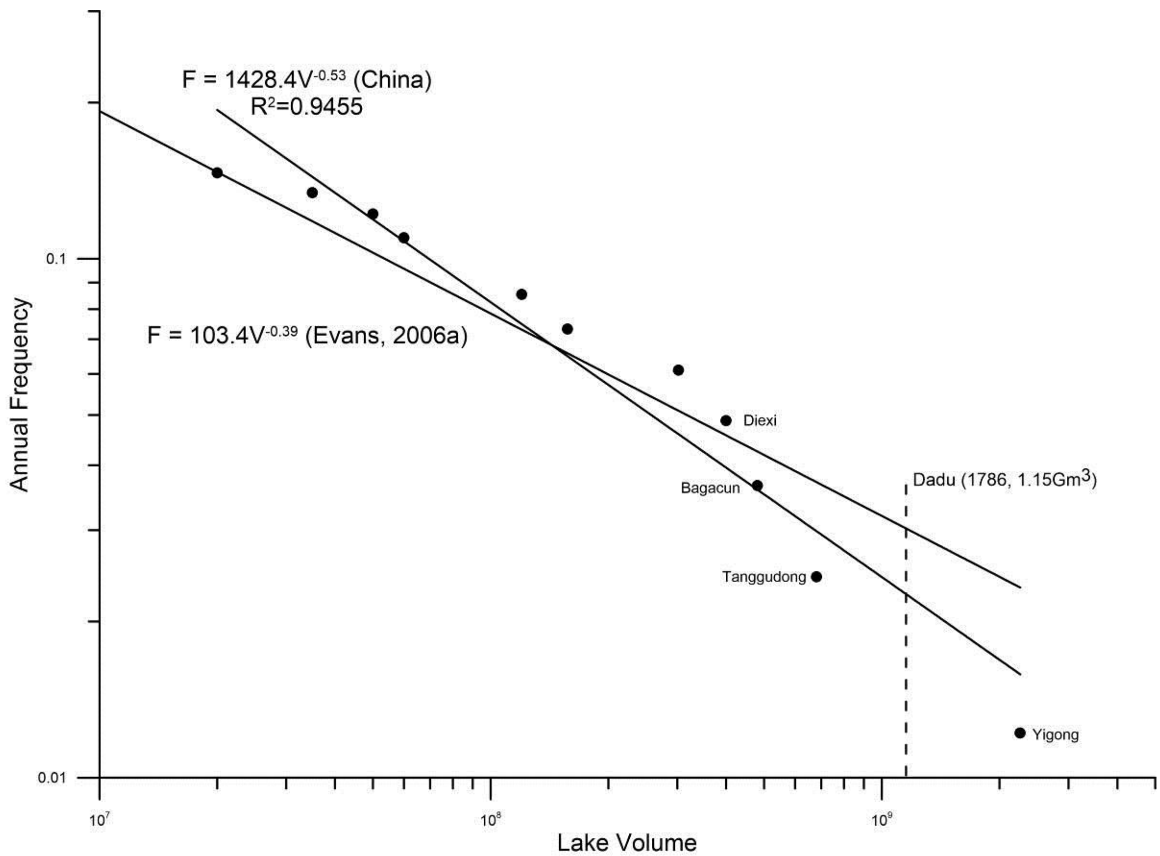

Figure 4.3. Magnitude vs. frequency plot of landslide-dammed lake volume (n=12; data from Huang 2008, Evans et al., 2011, Evans et al., 2011, Chen et al., 1992).

the lakes larger than this threshold are less likely to occur in China compared to other parts of the world. As the relatively high frequency of small events indicates most of the dammed lakes are the "small" ones. China is therefore more prone to have more but small landslide-dammed lakes than is suggested by the global dataset.

In order to verify these conclusions, another magnitude and frequency plot is made, showing all landslide-damming events in the 2008 Wenchuan earthquake (Xu et al., 2009). Wenchuan is taken as an example because all cases of landslide-dammed lakes are recorded without any missing. A total of 32 dammed lakes large than 10,000m^3 formed by the Wenchuan earthquake are collected (Appendix E, from Xu et al., 2009). The magnitude and frequency plot (Figure 4.4) represents how frequent a dammed lake of a certain volume occurred during the earthquake. It can be observed from the plot that most of the lakes are smaller than 20Mm^3, the previous threshold (in fact, only two were greater).

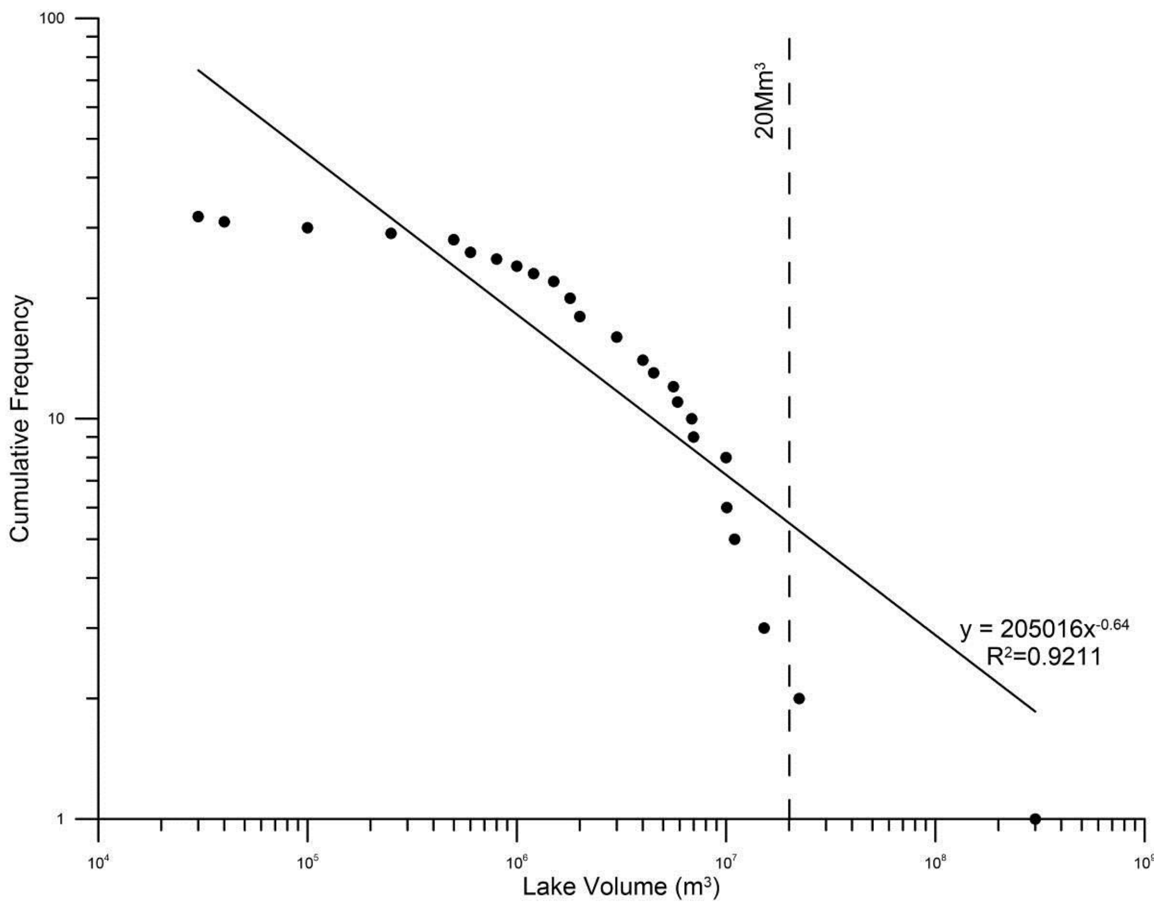

Figure 4.4. Magnitude vs. frequency plot of the volume of dammed lakes formed in the Wenchuan earthquake (n=32, data from Xu et al., 2009).

The slope of the trend line is -0.64, which is intermediate between those of the volume of all dammed lakes in China at different thresholds (-0.53 and 0.69; see Figure 4.3). This indicates that the estimation of the magnitude and frequency of landslide-dammed lakes in China is reasonable, and the conclusion that China is more prone to have smaller landslide-dammed lakes can be verified. A cause for this conclusion lies in the huge elevation change near the margin of the Tibetan Plateau, frequent earthquakes and deeply cut valleys that restrict the possibility of forming large landslide dammed lakes.

4.6 Conclusion

Magnitude and frequency relations of historical earthquakes in different areas of western Sichuan, landslides that caused landslide-damming, and dammed lakes in China are researched. By comparing to previous work from Evans (2006a, b), several conclusions can be made as follows:

1. Incomplete historic data and recent large magnitude earthquakes dramatically influenced the geometry of the M&F plot. For both study areas the frequency of catastrophic earthquakes is much larger than expected. This suggests that authorities should pay attention to natural disaster research, preparedness, as well as mitigation.

2. Landslides in China that caused damming have a similar trend. When compared to the global dataset. But landslides in China have relatively low frequencies, and the trend line has a slightly steeper slope, causing smaller frequencies at large magnitude.

3. China is more prone to smaller landslide-dammed lake than the global dataset suggest; the frequencies of large dammed lakes that occur in China are relatively low. This is proved by both historical records and the analysis of all dammed lakes in a single event (i.e. Wenchuan 2008).

Chapter 5

Summary and conclusions

Landslides have long been regarded as one of the most devastating natural hazards. Landslides show a wide distribution worldwide; they occur in every mountainous region. In this thesis a comprehensive investigation is made of landslides and landslide damming events in western Sichuan Province, China. Major characteristics of damming events (trigger, longevity) are analyzed. Several typical landslide-damming events are briefly discussed, including Tanggudong (1967) and Tangjiashan (2008). Special reference is made to two historical events; Dadu River (1786) and Diexi (1933), in Chapter 2 and 3, respectively. These two events are analyzed in detail, and some of the key parameters of the dammed lakes are estimated or measured for the first time. In Chapter 4 magnitude and frequency relations of natural hazards in China is studied, by applying a basic method of quantitative risk assessment suggested by Evans (2006a, b) to historical earthquakes, landslides, and landslide-dammed lakes in China. Major conclusions from each chapter are summarized in the following sections.

A detailed review to the 1786 Dadu River event is carried out in Chapter 2. We suggest that the current interpretation of the Dadu event is an unreasonable estimation of the scale of the 1786 landslide dam; a new landslide site that better fits the historical evidence is proposed. Measurements and estimations based on the proposed landslide dam site are carried out and show that the maximum pool height of the 1786 dammed lake is 1,300 m asl. This result shows a match to most of the details recorded in historical documents. Based on this scenario, the volume of the 1786 lake is calculated to be 1.15Gm^3. Verification is achieved by using the June average monthly discharge of the Dadu River measured at Luding to calculate the total volume of water blocked by the dam for 9 days, and the result is fairly close to the estimated reservoir volume. Therefore, for the first time we can know the large scale of the lake, and it was one of the largest landslide-dammed lakes in Chinese history. Because of the 100,000 deaths the event caused, the 1786 Dadu event is regarded as the most catastrophic landslide-dam breaching event globally.

A second detailed analysis is carried out of the 1933 damming event of Diexi along the Min River in Chapter 3. In this chapter important information on the landslide damming and breaching flood of the 1933 Diexi event is reviewed and investigated. Landslide locations, lake area, lake volume before breach, and volume breached have been investigated and calculated. By using modern GIS tools and SRTM-3 data, the volume of the Diexi Lake before its breach is calculated to be in the order of 450Mm^3, and nearly half (200Mm^3) breached in the outburst flood that occurred 45 days after formation. Moreover, peak flood discharge caused by the breaching is estimated by various regression equations, and the result shows that it reached a peak outburst flood discharge of 20,000m^3/s, which is unquestionably a huge discharge within the Min River channel. Although the 1933 Diexi breach event is not one of the exceptional events in the world, if compared to other gigantic landslide damming events, the Diexi case is still the most destructive natural dam outburst in China in the 20th Century in term of life loss. Due to lack of geological knowledge in the 1930s, no monitoring activities or warning of the event was carried out, which to some extent amplified the damage of the flood. It is concluded that remote sensing data can be used to estimate the volume of a breaching flood (or recently formed landslide-dammed lake), when comparison before and after the event can be made. However, research on the 1933 Diexi event shows its limitation when applied to older historical events, when no data exists for before the event and where the topography has been severely modified. Moreover, rapid risk assessments as well as fast-reacting forecast, monitoring and warning are essential when facing potential natural disasters due to landslide-damming in order to reduce possible downstream damage.

An analysis focusing on magnitude and frequency relations of historical earthquakes in different areas in western Sichuan, landslides that caused damming, and dammed lakes in China is presented in Chapter 4. By applying data from China to this basic method of quantitative risk assessment and comparing the results with worldwide data, characteristics of the natural hazard occurrences in China is discussed.

After comparing historical earthquakes near the Mogangling area and the Diexi area, it is found that incomplete historic data and the recent occurrences of large earthquakes dramatically influence the geometry of the M&F plot. However, both study areas show that the frequency of catastrophic earthquakes is much larger than expected, which suggests that authorities should pay more attention and put more effort into natural disaster research, forecast, as well as mitigation.

Moreover, it is found that landslides in China that caused damming have a similar magnitude-frequency relation compared to worldwide. In addition, compared to the world data, small damming events are more likely happen in China, and the frequency of large landslide-dammed lakes that may occur in China is relatively low.

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Appendix A

Historic Earthquakes Near Mogangling Landslide

Study Area: Latitude: 28N – 31N, Longitude: 101E – 104E

Source: www.csi.ac.cn

Part 1: Earthquakes larger than M=5 since1970 A. D.

Year	Month	Day	Long	Lat	Mag
1970	2	24	103.28	30.65	6.2
1970	7	31	103.73	28.63	5.4
1971	8	16	103.78	28.88	5.9
1971	8	17	103.78	28.9	5.7
1971	8	23	103.73	28.73	5.4
1971	8	17	103.62	28.83	5.4
1971	8	17	103.73	28.77	5.2
1971	8	18	103.62	28.8	5
1972	9	30	101.9	30.4	5.7
1972	9	27	101.7	30.4	5.6
1972	9	30	101.7	30.5	5.6
1972	4	8	101.8	29.6	5.2
1973	6	29	103.7	28.9	5.4
1973	6	30	103.8	28.9	5.2
1974	7	10	104	28.3	5.2
1975	1	15	101.9	29.4	6.2
1988	6	2	101.49	30.61	5
1989	6	9	102.38	29.34	5
1993	8	7	103.7	29	5
1994	12	30	103.6	28.9	5.7
1995	4	26	103.7	29	5.1
2001	2	23	101.19	29.4	6
2001	2	14	101.1	29.6	5
2008	5	12	103.4	30.95	8
2008	5	13	103.4	30.9	6.1
2008	5	12	103.5	31	6
2008	5	12	103.5	31	5.1
2008	6	11	103.4	30.9	5
2008	5	12	103.3	31	5
2008	5	12	103.5	31	5
2008	5	12	103.5	31	5

2008	5	12	103.8	31	5
2010	4	28	101.45	30.6	5
2013	4	20	102.99	30.3	7
2013	4	20	102.94	30.24	5.4
2013	4	20	102.92	30.32	5.4
2013	4	21	103	30.34	5.4
2013	4	21	103.05	30.36	5.4
2014	11	22	101.689	30.262	6.3
2014	11	25	101.727	30.182	5.8
2014	4	5	103.57	28.14	5.1
2014	8	17	103.5	28.1	5
2014	10	1	102.8	28.4	5

Part 2: Earthquakes larger than M=7 since 1725 A. D.

Year	Month	Day	Long	Lat	Mag
2008	5	12	103.4	30.95	8
1786	6	1	102	29.9	7.75
1955	4	14	101.8	30	7.5
1725	8	1	101.9	30	7
1893	8	29	101.5	30.6	7
1904	8	30	101.1	31	7
2013	4	20	102.99	30.3	7

Appendix B

Historic Earthquakes Near Diexi Landslide

Study Area: Latitude: 30.5N – 33.5N, Longitude: 102E – 105E

Source: www.csi.ac.cn

Part 1: Earthquakes larger than M=5 since 1879 A. D.

Year	Month	Day	Long	Lat	Mag
1879	7	1	104.7	33.2	8
2008	5	12	103.4	30.95	8
1933	8	25	103.4	31.9	7.5
1976	8	23	104.3	32.5	7.2
1976	8	16	104.1	32.6	7.2
1960	11	9	103.7	32.7	6.75
1976	8	22	104.4	32.6	6.7
1973	8	11	104.1	32.9	6.5
1989	9	22	102.51	31.58	6.5
1958	2	8	104	31.5	6.2
1970	2	24	103.28	30.65	6.2
2008	5	13	103.4	30.9	6.1
2008	8	1	104.7	32.1	6.1
1938	3	14	103.6	32.3	6
1941	10	8	102.3	31.7	6
2008	5	12	103.5	31	6
2008	5	12	103.6	31.4	6
2008	5	18	105	32.1	6
1976	8	19	104.3	32.9	5.9
2008	5	16	103.2	31.4	5.9
1879	6	29	105	33.2	5.75
1928	7	20	102.5	31.5	5.75
1933	10	15	104	31.8	5.75
1974	1	16	104.1	32.9	5.7
1974	11	17	104.11	33	5.7
2008	5	13	104	31.4	5.7
2008	5	14	103.4	31.3	5.6
1880	6	22	104.6	32.9	5.5
1934	6	9	103.7	32	5.5
1940	0	0	103.9	31.6	5.5
1952	11	4	103.5	32	5.5

1953	3	1	103.5	32.5	5.5
1961	3	30	103.7	32.8	5.5
2009	6	30	103.96	31.46	5.5
1978	7	13	102.95	31.93	5.4
2008	5	13	103.4	31.2	5.3
1976	9	21	104.2	32.8	5.2
1991	2	18	102.3	31.7	5.2
2008	5	12	104.1	31.3	5.2
2008	5	12	103.9	31.5	5.2
2008	5	13	104.5	31.7	5.2
1973	5	8	104.2	33	5.1
1976	9	1	104.1	32.5	5.1
2008	5	12	103.5	31	5.1
2008	5	17	103.5	31.2	5.1
2008	5	13	103.5	31.3	5.1
2008	5	14	104	31.4	5.1
2008	11	16	104.7	32.2	5.1
1900	8	0	103.5	30.5	5
1913	8	18	104.5	31.8	5
1932	0	0	102.2	31.8	5
1933	8	25	103.4	31.7	5
1948	10	10	103.7	32	5
1952	8	31	103	31.2	5
1960	3	24	103.7	32.3	5
1976	8	16	104.6	32.5	5
1989	3	1	102.49	31.5	5
1999	11	30	104.4	31.4	5
1999	9	14	104.1	31.6	5
2006	6	21	105	33.1	5
2008	6	11	103.4	30.9	5
2008	5	12	103.3	31	5
2008	5	12	103.5	31	5
2008	5	12	103.5	31	5
2008	5	12	103.8	31	5
2008	5	13	103.4	31.3	5
2008	5	17	103.5	31.3	5
2008	5	12	103.8	31.3	5
2008	6	9	103.8	31.4	5

2008	7	15	104	31.6	5
2008	5	15	104.2	31.6	5
2008	8	7	104.7	32.1	5
2008	5	20	104.9	32.3	5
2008	6	5	105	32.3	5
2009	11	28	103.8	31.23	5
2009	6	30	103.98	31.46	5
2010	5	25	103.49	31.17	5

Part 2. Earthquakes larger than M=7 since 1713 A. D.

Year	Month	Day	Long	Lat	Mag
1879	7	1	104.7	33.2	8
2008	5	12	103.4	30.95	8
1933	8	25	103.4	31.9	7.5
1976	8	16	104.1	32.6	7.2
1976	8	23	104.3	32.5	7.2
1713	9	4	103.7	32	7

Appendix C

Volume of Historic Landslides that Caused Damming

Source: Chai et al. (1995)

Name	Year	Volume (Mm3)
Quanlu	1965	309
Chana	1943	160
Tanggudong	1969	110
Luchedu	1935	100
Bitanggou	1963	100
Haikou-Majingzi	1974	100
Diexi-Xiao Lake	1933	75
Ganhaizi	1920	50.98
Taoling	1941	48
Diexi-Xiaoqiao	1933	46.5
Niugundang	1968	40
Saleshan	1983	31
Diexi-Gongpeng	1933	30
Xintan	1985	30
Zhebozu	1965	29
Majiaba	1986	28.8
Zhouqu	1981	25
Bagacun	1959	24
Shankou	1980	18
Touzhaigou	1991	18
Guxiang	1953	17
Jipazi	1982	15
Shaling	1982	15
Diexi-Downer Bailazhai	1933	13.2
Diexi-Da Lake	1933	12.76
Sijigou	1989	12
Jinchuan	1981	10
Zhouchangping	1982	10
Huangguancao	1986	10
Liujiaping	1989	10
Laozuochang	1989	10
Heishe	1983	8.1
Jiaxi	1952	8

Zhongyangcun	1988	7.65
Diexi-Upper Shuimogou	1933	7.5
Menshishan	1971	7
Baimeiya	1974	7
Tianbao	1982	7
Diexi-Yuerzhai	1933	6.75
Yanzigou	1989	6.27
Niujiaodong	1982	6
Changtian	1985	6
Xiguokou	1950	5.62
Jiguanling	1994	5.3
Hongshancun	1990	5.09
Tangbulanggou	1964	5
Guanjiayuanzi	1981	5
Hongtupo	1990	4.33
Liangjiazhang	1983	4.12
Liziyidagou	1981	3
Dawanzi	1991	2.7
Gaosongshu	1981	2.1
Zhaojiatang	1973	2
Yankuang	1978	2
Tangyanguang	1961	1.65
Zhongtingxiang	1983	1.65
Tubagou	1984	1.2
Maidi	1971	1
Yamchihe	1980	1
Denglongshan	1991	1

Appendix D
Volume of Historic Dammed Lakes

Name	Year	Volume (Mm3)
Yigong	2000	2259
Tanggudong	1967	680
Bagacun	2959	480
Diexi	1933	400
Tangjiashan	2008	302
Tsao Ling	1941	157
Jiayi	1941	120
Yijiang	1996	60
Tiantai	2004	60
Nantou	1999	35
Huanglianxia	1982	20
Hongshiyan	2014	50

Appendix E

Volume of Dammed Lakes formed by the 2008 Wenchuan Earthquake

Source: Xu et al. (2009)

Name	Volume (Mm3)
Tangjiashan	300
Xiaojia bridge	22.3
Tangjia-wan	15.2
Upstream Xiaogang-jian	11
Shibangou	11
Laoying-yan	10.1
Guantan	10
Donhekou	10
Downstream Xiaogang-jian	7
Nanba	6.86
Guanzipu	5.85
Sunjia-yuanzi	5.6
Zhugen bridge	4.5
Yanyang-tan	4
Liuxianggou	3
Haiziping	3
Kuzhuba	2
Iinjie village	2
Heidong-ya	1.8
Fengmingqiao	1.8
Hongcun	1.5
Huoshigou	1.5
Hongshihe	1.2
Xiejiadianzi	1