

Chapter 2

A Panoramic View of the Landslides Triggered by the May 12th, 2008 M_w 7.9 Earthquake in Wenchuan, China



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Abstract This paper reviews studies of the landslides triggered by the 2008 M_w 7.9 Wenchuan earthquake as a panoramic view of a vast number of slope failures. It examines (1) descriptions of the disastrous coseismic bedrock landslides, (2) the coseismic landslide database, (3) landslide influence factors and the spatial distribution pattern, (4) spatial landslide susceptibility mapping, and (5) effects of earthquake-triggered landslides on landscape evolution. The Wenchuan earthquake triggered massive large-scale bedrock landslides, which resulted in serious casualties and property damage. At least 197 481 landslides were identified, being distributed within an elliptic area of approximately 110 000 km². Their total area and volume were approximately 1160 km² and 6–10 km³. They constitute the largest landslide database related to an individual earthquake ever recorded worldwide. Many factors might have affected these slope failures, such as topography, geology, strong ground motion, and surface deformation related to earthquake magnitude and the properties of the seismogenic faults. Associated with this, areas with the following features are more susceptible to landslides: high slope angles; close proximity to the Yingxiu–Beichuan surface fault rupture; hanging wall of the reverse fault; east-, southeast-, and southward slope aspects; peak ground accelerations larger than 0.2 g; sandstone, siltstone, or granitic underlying rocks; and IX–XI intensity levels. A significant number of methods for earthquake-triggered landslide assessments have been used, including the Newmark method, statistical methods, and combinations of both. The resultant assessment maps provide useful information for the rehabilitation and reconstruction of the affected area. In addition, some researchers have studied the relationships between coseismic landslides and crustal uplift, landscape evolution in the affected area, and the long-term effect of earthquake-triggered landslides on the environment, which will be helpful for promoting the advancement of research on this subject.

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2.1 Introduction

It has been more than ten years since the M_w 7.9 earthquake that occurred on May 12th, 2008 in Wenchuan. This event has received much attention from geoscience communities around the world [12, 19, 21, 25, 32, 40, 42]. This huge shock took place in a mountainous area with steep terrain, and the strong ground shaking it caused triggered massive coseismic landslides of an unprecedented number, giving rise to a number of studies [2, 6, 8, 18, 40]. Such large-scale downslope movement of soil and rock involves complex mechanisms and a variety of natural conditions, necessitating further research.

This paper reviews these studies and is broken down into the following sections: various extremely large and disastrous coseismic landslides, the coseismic landslide database, landslide influence factors and the spatial distribution pattern, landslide susceptibility mapping, and the effect of earthquake-triggered landslides on landscape evolution. These contents permit us to create a panoramic view of the landslides triggered by the 2008 Wenchuan earthquake.

2.2 Extremely Large and Disastrous Coseismic Bedrock Landslides

The Wenchuan earthquake-triggered landslides directly caused approximately 20 000 deaths, which account for approximately 25% of the total death toll from the event [43, 45]. A portion of these was caused by the huge and disastrous bedrock landslides that took place during the shock. Table 2.1 lists eleven typical examples of extremely large landslides. For instance, the Wangjiayan landslide that occurred at Beichuan buried approximately half of the old Beichuan County and resulted in the deaths of more than 1600 residents (Fig. 2.1). The elevations of the back edge and front edge of this landslide are approximately 940 m and 650 m, respectively. Its runout distance is approximately 550 m with a sliding direction roughly N80° E. It is located at the hanging wall of the seismogenic fault with a source area at approximately 400 m from the fault. During the earthquake, the area where this slope failure occurred suffered shaking of XI intensity [28]. It was reported that this large landslide has been progressively active since 1985 due to rainfall and human activity. There were many ground fissures on the slope before the earthquake, and the quake finally triggered this large-scale landslide [44].

The largest landslide triggered by the Wenchuan earthquake occurred at Daguangbao, located in Gaochuan, Anxian County (Fig. 2.2). It resulted in the collapse of a 3040 m high mountain and the accumulation of material in a valley at a 1380 m elevation. The total length of the landslide was approximately 4650 m.

Table 2.1 Eleven extremely large landslides triggered by the 2008 Wenchuan quake

Name	Location	Area (10^4 m ²)	Volume (10^6 m ³)	Lithology
Wangjiayan	31° 49' 34" N, 104° 26' 53" E	12.5	4	Siltstone, sandstone, and siliceous rock
Daguangbao	31° 38' 28" N, 104° 06' 41" E	720	1000	Limestone, dolomite
Tangjiashan	31° 50' 22" N, 104° 25' 58" E	72	20	Siltstone, sandstone, and siliceous rock
Niujuangou	31° 02' 43" N, 103° 26' 58" E	49	4	Fine-grained diiorite
Wenjiagou	31° 33' 11" N, 104° 09' 05" E	300	100	Limestone, fine sandstone, mudstone
Yuejiashan	31° 26' 52" N, 103° 58' 45" E	90	20	Granodiorite
Donghekou	32° 24' 30" N, 105° 24' 30" E	104	12	Carbonaceous and siliceous slate, phyllite, and dolomitic limestone
Woqian	32° 18' 23" N, 104° 57' 48" E	67	15	Limestone, dolomite, marble, phyllite
Xiejadianzi	31° 18' 03" N, 103° 50' 19" E	29	0.45	Plagioclase and amphibole schist
Taihongcun	31° 58' 30" N, 104° 35' 49" E	60	4.8	Shale, siliceous rock, dolomite, and limestone
Beichuanxinzhong	31° 49' 45" N, 104° 27' 34" E	12	2.5	Thick layer limestone

The landslide covered approximately 7.20×10^6 m² with a volume of approximately 1×10^9 m³. It occurred in an X intensity area on the hanging wall of the seismogenic fault approximately 4.5 km away. As a typical landslide, it was composed of a giant potentially unstable block caused by the intersection of a rock layer and two groups of structural planes, sliding in the N80° E direction in the downslope motion. Several studies [1, 11, 28, 46] have shown that the accumulated material of this landslide largely maintained the original structure of the bedrocks with a moderate disintegration of its body, forming a deposit with a length of 4.2 km and a width of 2.2 km. Several other large-scale slope failures occurred downstream of the Daguangbao landslide, e.g., the Laoyingyan landslide (Fig. 2.2) with a volume of approximately 15×10^6 m³, approximately 1 km from Daguangbao.



Fig. 2.1 The Wangjiayan landslide triggered by the 2008 Wenchuan earthquake



Fig. 2.2 The Daguangbao and Laoyingyan landslides. Photo taken by Huang and Fan [10]

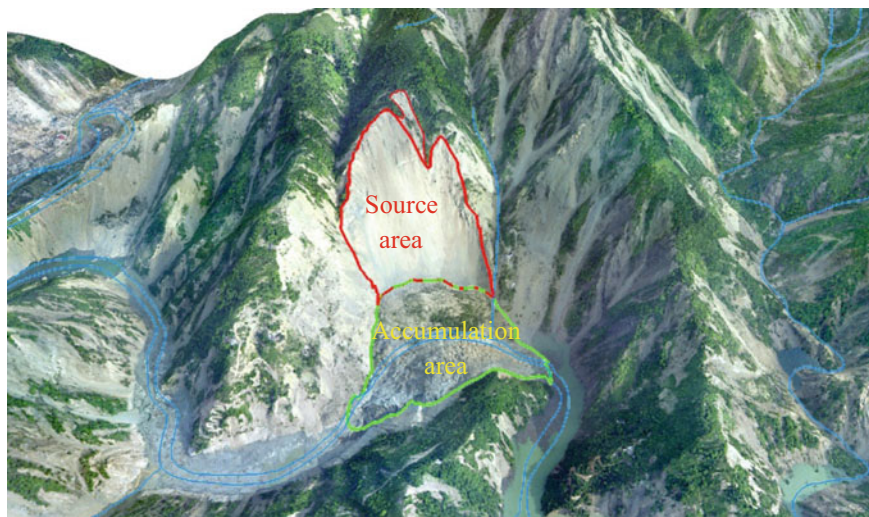


Fig. 2.3 The Tangjiashan landslide

Another large landslide, Tangjiashan, occurred on the right bank of the Jianjiang River. It completely blocked this river, resulting in the largest and most dangerous dammed lake formed by the earthquake (Fig. 2.3). The back and front edges of this landslide are approximately 1260 m and 640 m high, respectively. Its sliding distance was approximately 1150 m in a north-northwest direction. The landslide dam along the river is approximately 800 m long with a maximum width of 610 m and a maximum height of 120 m. This landslide is also located at the hanging wall of the seismogenic fault, approximately 2 km from the fault itself, within an area that experienced XI degree intensity damage. Numerical simulations have shown that the maximum speed the landslide reached was 22 m/s and that there were approximately four stages during the failure: (1) the earthquake force caused progressive destruction of the slope body, (2) the slide body moved downslope at a high speed, (3) this impacted on the slope of the opposite bank causing disintegration, and (4) this blocked the Jianjiang River thereby damming the lake [39].

2.3 Database of Landslides Triggered by the Wenchuan Earthquake

2.3.1 Landslide Inventory

Immediately after the 2008 Wenchuan earthquake, many satellite companies and Chinese government departments quickly organized image shooting of the affected

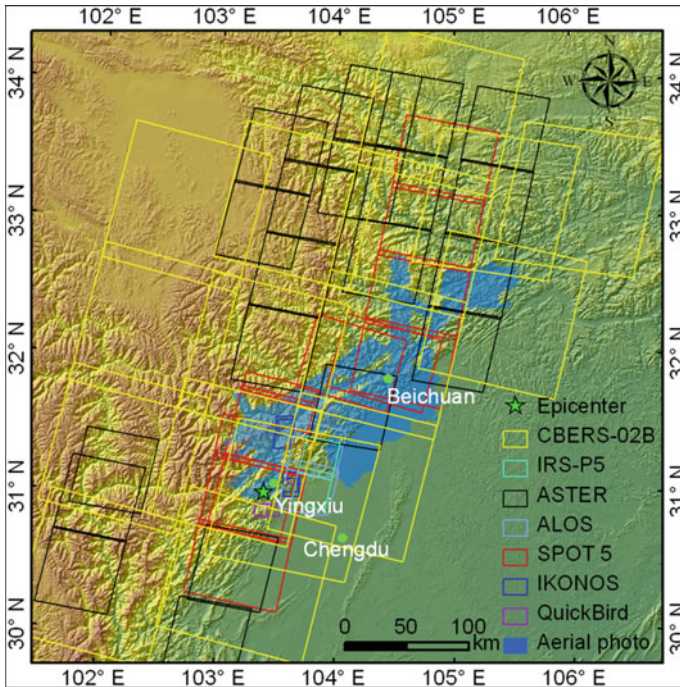


Fig. 2.4 Coverage of post-earthquake images related to the Wenchuan quake

area, and many available satellite images and aerial photographs were released. Based on the visual interpretation of these pictures, Xu et al. [40] constructed a detailed database of the landslides triggered by the earthquake and verified part of it by field investigations. Figure 2.4 shows the coverage of the satellite images and aerial photographs used in their work. Post-earthquake satellite images were from SPOT 5, CBERS02B, IKONOS, ASTER, IRS-P5, QuickBird, and ALOS with 1, 2, 2.4, and 5 m resolutions. In addition, in the remote areas from the epicenter where high-resolution images were not available, satellite images from Google Earth were used to delineate hundreds of landslides (Fig. 2.4). Pre-earthquake images were obtained from SPOT 5, Landsat ETM+, and Google Earth [40]. Figure 2.5 shows pre- and post-earthquake QuickBird images along the Minjiang River in the affected area. A comparison of the images shows that the Wenchuan earthquake triggered massive landslides that destroyed significant amounts of forest and vegetation.

The inventory mapping shows the Wenchuan earthquake triggered at least 197,481 landslides, distributed in an area of approximately 100 000 km² and with a total occupation area of approximately 1 160 km² (Fig. 2.6). Most of the landslides (196 007 landslides, with a total area of 1 150.622 km² and accounting for 99.25% and 99.19% of the respective totals) occurred in a smaller area of approximately 44 031 km². The number of landslides triggered by the Wenchuan event is the largest amount triggered by an individual earthquake or an earthquake sequence ever reported. Based

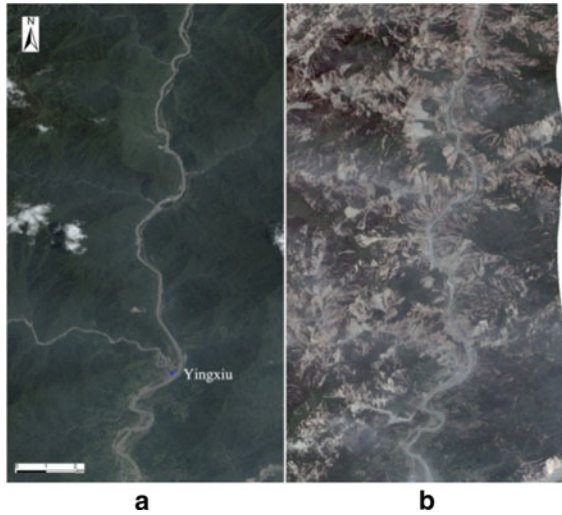


Fig. 2.5 QuickBird images along the Minjiang River, which was struck by the Wenchuan earthquake. **a** Pre-earthquake image mainly composed of forests in green. **b** Post-earthquake image mainly composed of coseismic landslides in light gray

on the “landslide volume–area” power law relationship fitted from the volume of each deposit of the 1415 landslides triggered by the earthquake based on pre- and post-quake DEMs, the total volume was calculated to be approximately 10 km^3 in the source areas [38].

After the Wenchuan earthquake, many research teams released inventories of landslides triggered by this event. Table 2.2 lists twelve typical inventories from the literature. These inventories provide important knowledge for understanding the spatial patterns, hazard analysis, and mechanisms of the earthquake-triggered landslides; however, most of them have some shortcomings, such as incompleteness, positive and negative errors from automatic extraction, only using points to locate landslides rather than polygons to delineate landslide boundaries, and delineating many individual landslides into one landslide. These shortcomings have resulted in significant differences between them, which are likely related to the research aims and characteristics of the researchers. This section presents the inventory of the Wenchuan earthquake-triggered landslides prepared by Xu et al. [40], since it strictly follows the criteria for landslide inventories [30] and is the most detailed and complete of the inventories, even including those of small-scale and those that occurred in areas that are distant from areas of human activity.

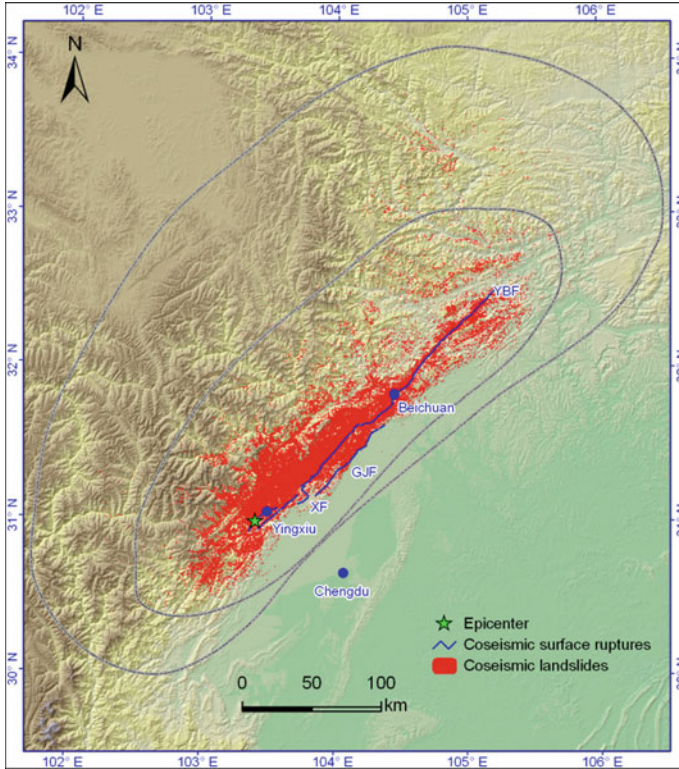


Fig. 2.6 Distribution of landslides triggered by the 208 Wenchuan earthquake. The larger ellipse is the approximate limited area and the smaller one represents the primary distribution area. YBF: Yingxiu–Beichuan fault; GJF: Guanxian–Jiangyou fault; XF: Xiaoyudong fault

2.3.2 *Landslide Characteristics and Spatial Distribution*

The Wenchuan earthquake-triggered landslides are characterized by their extremely high number, high-density distribution, large-scale individual slope failure, and broad distribution and clustering. Large-scale bedrock landslides tend to have long runout distances, high speeds, short duration times, large energy, rock fragmentation, complex mechanisms, and the presence of a “throwing effect”, and thus often cause serious disasters. The spatial distribution of these landslides exhibits a nearly elliptical shape, with a long axis roughly the same as the strike of the seismogenic fault.

The majority of the landslides triggered by the Wenchuan earthquake were mostly concentrated around the surface rupture zones, implying a strong control by the causative structure [34]. Most of the landslides occurred to the northeast of the epicenter, extending some distance in that direction, consistent with the unidirectional rupturing mechanism of the seismogenic fault. Alternatively, they are mainly

Table 2.2 Database of landslides triggered by the Wenchuan earthquake

No.	Method	Type	Number	Landslide area (km ²)	Source
1	VI	Plg	197481	1160	[40]
2	VI	Pt	11308		[8]
3	VI	Pt	16704		[9]
4	VI	Plg	43842	632	[14]
5	VI	Pt, Plg	13085	418.85	[20]
6	VI	Pt	60104		[6]
7	AE	Plg	73367	565.8	[18]
8	VI	Plg	48007	712	[31]
9	VI	Plg	56000	811	[2]
10	VI	Plg	5154	1139	[7]
11	AE	Plg	57150	396	[16]
12	VI	Plg	6727	54.6	[23]

Note *pt* point; *plg* polygon; *VI* visual interpretation; *AE* automatic extraction

distributed on the hanging wall of the seismogenic fault, especially in the section between the town of Yingxiu and Beichuan County.

The density of the landslides shows obvious differences along the fault. The landslides along the section from Yingxiu to Beichuan County, which is dominated by thrust, are much more numerous than those along the section north of Beichuan dominated by strike-slip. There are several high-density landslide areas, such as the hanging wall area of the Yingxiu–Beichuan fault between Yingxiu and Beichuan County, the area between the Yingxiu–Beichuan surface rupture and the Guanxian–Jiangyou surface rupture, and the area northeast of Beichuan crossed by the surface rupture. Furthermore, in the hanging wall area far from the seismogenic fault, there are also dense coseismic landslides, mainly along the rivers. The long strip-like area between the Yingxiu–Beichuan surface rupture and the Guanxian–Jiangyou surface rupture also has an area of high landslide density, though it is less dense than that on the hanging wall of the Yingxiu–Beichuan fault [6, 8, 40].

2.4 Landslide Susceptibility Mapping and Hazard Assessment

Earthquake-triggered landslide assessments can provide information about which locations are more susceptible to landslides and which are more stable, which is helpful for the reconstruction and mitigation of subsequent hazards in the affected area. Several important factors play a role in this, such as sample selection, models, and the distribution of the landslides. After the Wenchuan earthquake, quite a few methods were used, primarily the Newmark method and appropriate statistical

methods. The Newmark method has two advantages: it does not need real landslide distribution data, nor does it need to consider the physical mechanism. For example, Wang et al. [26] proposed a simplified Newmark method for an emergency hazard assessment of landslides triggered by the Wenchuan earthquake in the eleven counties most severely struck by the quake. They used the instantaneous peak ground acceleration, engineering geological lithology grouping, and topographic data to develop a model for landslide hazard assessment based on the ArcGIS software. Godt et al. [5] employed topographic and geologic data and strong ground shaking to prepare a map of the landslide susceptibility of the area struck by the Wenchuan earthquake when no landslide inventory was available at that time. The resulting accuracy of the Newmark method, however, is often unsatisfactory because a significant number of the regional parameters it needs are difficult to obtain, and thus, the method often relies on generalized values [29].

Statistical methods are more suitable than the Newmark method for researching random processes in nature, including landslides, and have thus been widely used in the susceptibility mapping and hazard assessment of the Wenchuan seismic region. These methods need landslide inventories, which are difficult to obtain directly after earthquakes, and thus the completion of the mapping by this approach may take additional time. Nevertheless, the resultant map can be quite consistent with the distribution of real landslides. For example, Xu et al. [33] used a weight of evidence model and a simple binary statistical method to map the earthquake-triggered landslide hazard in the Qingshui river area struck by the Wenchuan quake, where at least 2,321 landslides have been identified. A comparison shows that the success rate of the mapping is 71.8%, which is a moderate degree of accuracy. Song et al. [22] proposed a hybrid method based on the Bayesian network and obtained an accuracy of approximately 93% in the assessment of a small study area of Beichuan County.

Selecting training samples from a landslide inventory is important for the quality of landslide susceptibility mapping. To address this issue, Xu et al. [35] designed three strategies for landslide sampling including centroids of large landslides, centroids of all landslides, and randomly selected points from all landslide polygons. In addition, support vector machine (SVM) models that consider four kernel functions were used to check the importance of kernel functions in SVM modeling. The results showed that radial basis function based SVM modeling with randomly selected samples from a landslide polygon inventory is most successful. In another study by Xu et al. [36], four landslide susceptibility models (bivariate statistics, logistic regression, artificial neural networks, and SVM) were used to study a small watershed strongly struck by the Wenchuan earthquake. The results showed that the logistic regression generates the highest success rate (80.34%), which is a counterexample to the contention that computing technique-based models usually have better performance than traditional models. Based on the back-propagation artificial neural network model, Li et al. [13] carried out landslide susceptibility assessments for earthquake- and rainfall-triggered landslides in an area of Qingchuan County struck by the Wenchuan earthquake. Their results showed that the mapping of rainfall-triggered landslide susceptibility by considering slope angle, elevation, slope height, and distance to rivers has the best success rate, and the assessment of earthquake-triggered landslide susceptibility by

considering slope angle, elevation, slope height, distance to the rivers, and distance to faults has the best performance. Their study provides a reference for selecting influence factors in the assessment of rainfall- and earthquake-triggered landslide susceptibility. Wang et al. [27] combined the Newmark displacement model and logistic regression to develop a mechanism-based landslide occurrence probability model and adopted it for the use in the Wenchuan and Beichuan Counties. The success rates of the model in these two areas were 79.7% and 75.3%, respectively, which are acceptable.

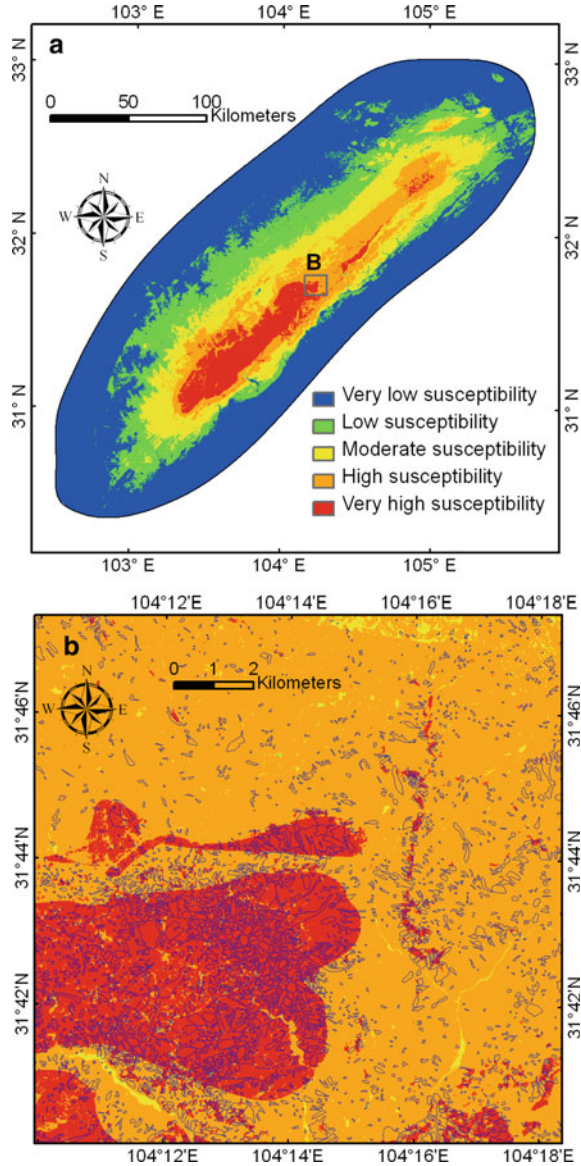
As the Wenchuan earthquake affected a significant area where numerous landslides were triggered, the landslide susceptibility and hazard assessment of the entire affected area based on complex statistical methods is very time-consuming and difficult to implement. Only a few studies of this subject based on simple statistical methods have been carried out. For example, Xu et al. [41] used the weight index model, which is a bivariate statistical approach, to perform a landslide susceptibility assessment with a large inventory of landslides triggered by the earthquake. In addition, eight cases of different combinations of landslide impact factors were considered in their work to reveal the probable effect of impact factors on the landslide susceptibility assessment and the most suitable combinations of influence factors for landslide susceptibility mapping. It was found that the combination of fault rupture, topographical, and geological factors was the best, which yielded a considerably high success rate of up to 90% (Fig. 2.7).

2.5 Geomorphologic Evolution of the Affected Area

Earthquake-related crustal uplift and broad coseismic landslides play a couple of contradictory roles in landscapes. Crustal uplift builds topography, whereas coseismic landslides destroy it. The confrontation between these two factors has received much attention in recent years. The Wenchuan earthquake caused significant crustal uplift and thus promoted the orogenic effect in the area [42]. The wide-distribution, high-density, and large-scale coseismic landslides triggered by the earthquake reduced the influence of crustal uplift on the regional topography. Therefore, this earthquake provides an unprecedented chance to examine this subject.

Based on the information obtained from the automatic extraction of post-earthquake satellite images and subsequent manual checking, Parker et al. [18] established a landslide inventory that contains 73,367 landslides with a total area of 565.8 km². A landslide “area–volume” power law relationship was used to calculate the total volume of the landslides as 5–15 km³. The crustal uplift caused by the earthquake was derived from the coseismic deformation based on a combination of C- and L-band Synthetic Aperture Radar offset data inverted from ascending and descending tracks [3] which is only 2.6 ± 1.2 km³. This unexpected result, i.e., the volume of coseismic landslides being larger than the crustal uplift, shows that the Wenchuan earthquake did not play an orogenic role, but may have led to a reduction in the topography [18]. This is interpreted as the crustal uplifts having been caused

Fig. 2.7 a Mapping of Wenchuan earthquake-triggered landslide susceptibility. **b** Enlargement of (a)



by more frequent small earthquakes that triggered only a small number of landslides, thus playing a positive role in orogeny. Another possibility is that the relationship between crustal uplift and coseismic landslides caused by earthquakes of similar magnitudes is irregular and cannot be calculated using multiple earthquake cycles. In addition, the seismogenic fault of the Wenchuan earthquake is highly partitioned, and the relationship between its crustal uplift and landslide erosion is different in the

thrust fault and strike-slip fault segments. The Parker et al. [18] study has received extensive attention and discussion. For example, based on a visual interpretation of the high-resolution remote sensing images, Xu et al. [37] prepared a more objective and complete landslide inventory for the Wenchuan earthquake and asserted that Parker et al. [18] delineated multiple small landslides as one large landslide in many cases, which undoubtedly would have greatly increased the total volumetric results of the coseismic landslides. Thus, the total volume of the coseismic landslides may have been overestimated.

Using a method similar to Parker et al. [18], Li et al. [16] updated the findings on the coseismic landslide erosion caused by the Wenchuan earthquake. Their results showed that the total volume of landslides triggered by the Wenchuan earthquake was approximately 2.8 km^3 , which is much smaller than that found by Parker et al. [18]. This new result is roughly equivalent to the crustal uplift ($2.6 \pm 1.2 \text{ km}^3$). Assuming the landslide materials can be moved out of the area by rivers during earthquakes, the crustal uplift caused by the quake could be substantially offset by the coseismic landslides.

Li et al. [16] also predicted the crustal uplift of a reverse fault earthquake by considering the earthquake magnitude and the parameters of the rupture surface. Combined with the power law relationship between the total volume of coseismic landslides and earthquake magnitude, the equilibrium relationship between the crustal uplift and the coseismic landslides was obtained [16]. The results are in good agreement with the 1999 Chi-Chi earthquake of Taiwan, China. They also suggested that moderate earthquakes (M_w 6–7) might play a more important role in orogenesis than larger earthquakes because the decrease in coseismic landslides is more significant than the decrease in the amount of crustal uplift for earthquakes of smaller magnitudes [16]. This result is essentially consistent with the analysis and inference of Parker et al. [18]. Nevertheless, many other factors, such as lithology, climatic conditions, focal depth, and tectonic settings, have not been taken into account. Therefore, there is considerable uncertainty and further worthwhile research on this subject.

In the study of landscape changes caused by the Wenchuan earthquake, the time required for landslide deposits to be moved out of the area is an important factor that needs to be considered. Wang et al. [24] assessed the time taken for fine particles (size $<0.25 \text{ mm}$) from coseismic landslides to be moved out of the earthquake-affected area based on the daily suspended sediment discharge from 16 major rivers between 2006 and 2012. The results showed that the amount of suspended sediment discharged after the earthquake is approximately 3–7 times that of before the earthquake. Nevertheless, the output of the rivers in the $68,719 \text{ km}^2$ area from 2008–2012 was only approximately 92.5 million tons, which is much less than the estimated amount of fine-grained materials (about 480 million tons) from the Wenchuan earthquake-triggered landslide as determined by deposit grain-size distributions. Their study also used post-earthquake sediment export rates to estimate the maximum time for fine particles to be moved out over 100 years. The study demonstrates that the density of landslides and runoff intensity have an important influence on the length of time the river systems are affected by coseismic landslides.

Li et al. [15] evaluated the relationship between the locations of the coseismic landslides and rivers in the Wenchuan quake area. Based on the landslide number, area, and volume, the connectivity between the coseismic landslides and rivers was quantified. The results showed that approximately 43% of the total landslide volume was connected with the river system in the affected area. The output of fine particles (size <0.25 mm) from the Wenchuan earthquake landslides was positively correlated with the landslide density on a basin scale; however, whether connectivity is considered or not, the statistical correlation is indistinguishable. The weaker than expected connectivity may have an effect on suspended sediment production due to the high mobility of fine particles on slopes, even though they may have had no connection with the river system. The transport of large particles, which accounts for more than 90% of the total landslide volume, may be strongly affected by the location of landslides. This study is helpful in understanding the mechanism of landslide material migration in the affected area.

Earthquake-triggered landslides will undoubtedly increase the regional topography erosion rate in the short term (one year to several decades) [4]. To evaluate whether earthquake-triggered landslides can contribute significantly to landscape erosion over a longer period of time (over thousands to millions of years), Li et al. [17] simulated the volumes of landslides triggered by earthquakes with different magnitudes and calibrated the results using the coseismic landslide data from the Wenchuan and Lushan earthquakes. The results showed that the long-term coseismic landslide erosion rate has an equivalent magnitude to the long-term regional erosion rate, which is 0.5–1 mm/year. This indicates that the earthquake-triggered landslides in the frontal Longmenshan Mountains are a primary mechanism of long-term erosion.

2.6 Conclusion

There are far more scientific papers and reports about the Wenchuan-triggered landslides than are introduced in this paper; however, we have summarized the most relevant, important, and innovative aspects of the research. The 2008 Wenchuan earthquake triggered approximately 200 000 landslides, representing the largest number of landslides related to an individual earthquake ever recorded. It may be the result of a variety of factors, such as the ground-reaching source rupture, thrust faulting, strong ground shaking, steep terrain, low strength of slope materials, or other special geologic conditions. This event has also generated a very meaningful discussion on the relationship between seismic crust uplift and coseismic landslide denudation. Studies on the Wenchuan earthquake-triggered landslides will further our understanding of the occurrence and complex mechanisms of coseismic landslides, help in formulating landslide disaster prevention and mitigation strategies, and reveal their long-term impact on the landscape evolution of the affected area. In addition, they also provide important scientific reference for the research of other earthquakes. In brief,

the Wenchuan earthquake event is a benchmark for the study of earthquake-triggered landslides.

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