

Post-earthquake changes and prediction of debris flow scales in Subao River Valley, Beichuan County, Sichuan Province, China

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Abstract Subao River lies along the Beichuan–Yingxiu fault in Beichuan County, which has been heavily impacted by the Wenchuan earthquake on 12 May 2008 and has become sources of many geo-hazards. On 24 September 2008, a rainstorm triggered a large debris flow in the catchment, causing several deaths and significant damages. A case study on changes of the debris flow was conducted in the river. The peak discharges were calculated in the Guanmenzi, Huangnidi, and Daanshan gullies. Results indicated that the peak discharges corresponded to various return periods in different gullies: 200 years in Daanshan, 100 years in Huangnidi, and 50 years in Guanmenzi. However, the triggering precipitation in these three gullies was only of a 20-year return period. The debris flows had undergone significant changes. Analysis indicated that the changes should be ascribed to the flow characteristics, initiation conditions, and the channel blockage impacted by the rapid accumulation of loose material. Channel blockage was the principal factor increasing the scale of the debris flow. The values on the blocking coefficient were presented based on density, height, and other characteristics of dams. Finally, all of the peak debris flow discharges of the Subao River Valley for a 20-year return period were calculated using the recommended blocking coefficient values.

Keywords Wenchuan earthquake · Debris flow · Peak discharge · Blocking coefficient · Subao River

Introduction

The area most seriously affected by the Wenchuan earthquake is in the transition zone between the Tibetan Plateau and the Sichuan Basin. The area is characterized by high mountains, deep valleys, and crossing faults. The rocks are sharply deformed due to frequent, strong tectonic movements (Jin et al. 2008; Lin 2008; Luo et al. 2008). Given these conditions, the earthquake has caused more than 15,000 geo-hazards and over 10,000 sites of potential geo-hazards (Yin 2008; Huang and Li 2008; Wang et al. 2008). Rock avalanches and landslides were in domination, which have induced many dammed lakes (Cui et al. 2008; Chen et al. 2008).

These landslides and avalanches provided considerable loose materials for debris flows, which are expected to be more frequent and an active period of about 20–30 years (Cui et al. 2008, 2009; Xie et al. 2009).

On 24 September 2008, 72 debris flows occurred in Beichuan County during a rainstorm, which killed 42 people and destroyed roads, seriously threatening the temporary resettlement sites (Tang and Liang 2008). The Subao River gully, to the west of Leigu township of Beichuan County, is one of the 72 debris flow gullies. In the gully, 10 tributaries and the main channel formed debris flows and 11 deaths resulted from this event (You et al. 2010). This catchment has become one of the areas with the highest potential for serious debris flow hazards.

This is a critical time for post-disaster restoration and reconstruction, and debris flows have been one of the limiting factors. To study the changes of the debris flow

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sizes and provide a reference for debris flow prevention and control in areas affected by earthquakes, the research on scale changes of debris flow in Subao River Valley were conducted.

Study area

The study area is on the west of Leigu township, about 8 km south of Beichuan County, 60 km north of Mianyang City, and 180 km north of Chengdu, the capital of Sichuan Province (Fig. 1).

Catchment overview

The Subao River, flowing from west to east, is the second order branch of Anchang River. It has a drainage area of 72.21 km² and its mainstream length is 16.5 km, in the middle of catchment. The relative relief is 1,597 m, with a mean relief ratio of 92.8%. Annual average runoff is 0.86×10^8 m³ and annual average discharge is 35 m³/s, with the maximum of 120 m³/s and minimum of 0.4 m³/s.

Geomorphologic setting

The Subao River Valley is in the Longmenshan Mountain. The highest and lowest elevations in the catchment are 2,318 and 721 m, respectively. The channel is mainly U-shaped with width varying from a few meters to tens of meters. Slope gradients are generally greater than 25°, with some up to 40°–50° or more. The total areas of steep farmlands ($\geq 25^\circ$) are 46.76 km², occupied 64.76% of the total area of the catchment. Data summarizing the slope gradient is shown in Table 1.

Table 1 Subao River Valley slope classification data

	<15°	15°–25°	25°–35°	≥35°	Total
Area/km ²	7.64	17.81	22.76	24.00	72.21
Ratio/%	10.58	24.66	31.52	33.24	100

Geological setting

The Subao River lies on the eastern edge of the Tibetan Plateau, a region of high relief and complex geology (Densmore et al. 2007). The area is controlled by the Beichuan reverse fault, Leigu flat strike–slip fault, and Qinglinkou overturned anticlinorium (Fig. 2). The main geological structures are trending southwest–northeast; thus, the rock strikes are also northeast-trending. The Beichuan reverse fault, the main central fault of the fold belt, is northern extension of the Yingxiu–Beichuan thrust fault. It passes through Leigu–Qushan–Chenjiaba in a northeasterly direction and is vertical or steeply dips to the northwest. The fault thrust the Mesoproterozoic basement and metamorphosed Paleozoic rocks towards the southeast over the generally unmetamorphosed rocks of the Longmenshan Mountains (Chen and Wilson 1996). It is this fault that caused the “5.12” Wenchuan earthquake. The Leigu flat strike–slip fault, a branch of the Yingxiu–Beichuan thrust fault, goes through the upper reach of Subao River and connects with the main fault at Renjiaping. The Qinglinkou overturned anticlinorium axis strike is northeast 45° and the axial plane dip is northwest with a dip angle of roughly 70°.

In the study area, Paleozoic rocks and loose Quaternary deposits can be found. Some Paleozoic rocks show mildly dynamic metamorphism, likely due to the intense dynamic regional metamorphism associated with the activities of the Beichuan fault. Its main lithological types are phyllite,

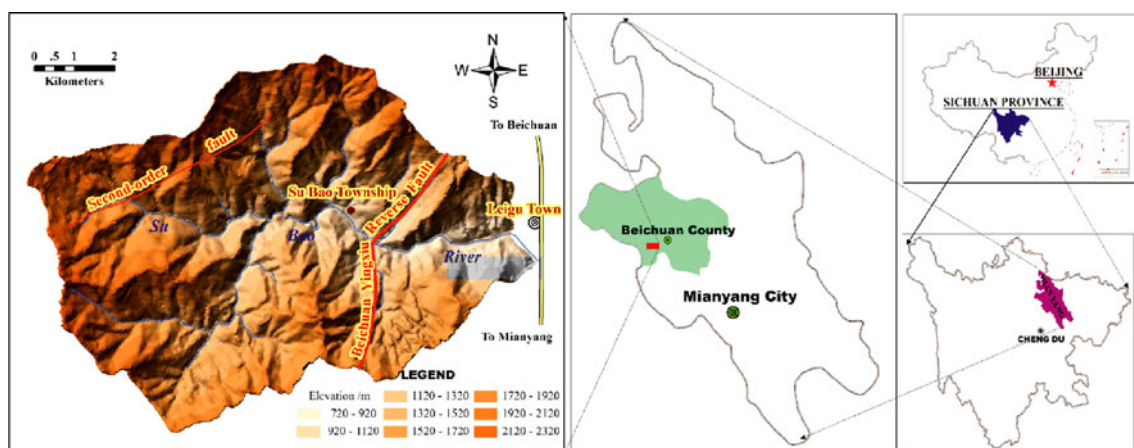
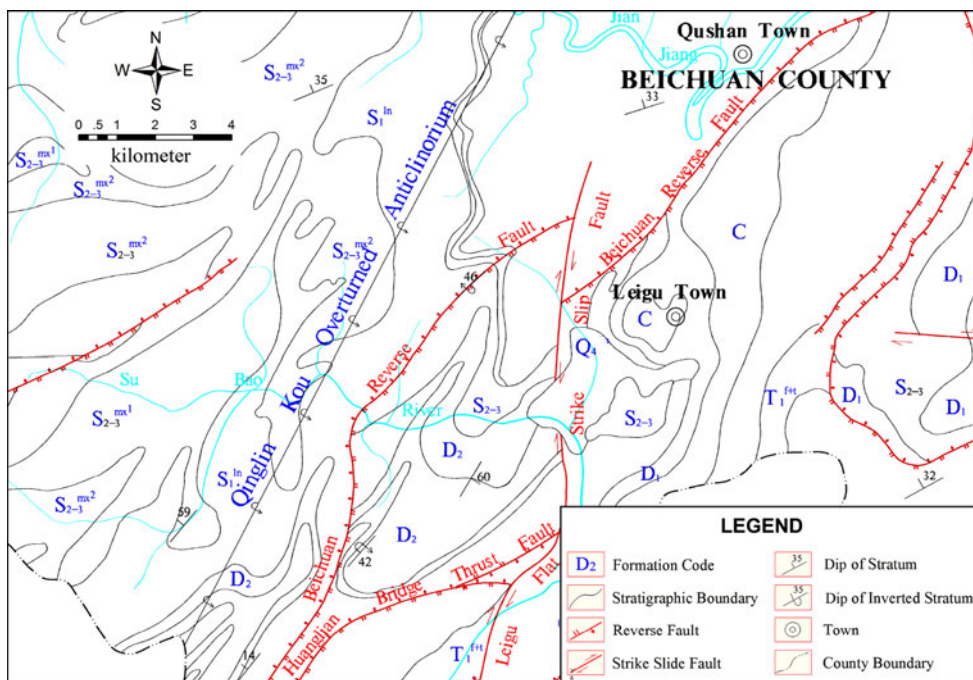


Fig. 1 Location and relief map of the Subao River Valley. The Beichuan–Yingxiu Reverse Fault, a northeastern-striking thrust fault, runs through the low river valley. The “5.12” Wenchuan earthquake originated on this fault

Fig. 2 Simplified geological map of the Subao River Valley. Q_4 Quaternary, T_1^{+1} Lower Triassic Feixianguan and Tianjingshan formation, C Carboniferous strata, D_2 Middle Devonian strata, D_1 Lower Devonian strata, S_{2-3} Middle to Upper Silurian strata, S_{2-3}^{mx} Middle to Upper Silurian Maoxian Group (this group is divided into three members), S_1^n Lower Silurian Longmaxi Group



slate, limestone, sandstone, and shale. Other Paleozoic rocks are shallow and marine in character. Their main lithological types are limestone, sandy lime, bioclastic limestone, and sand-shale. The Quaternary loose deposits are primarily characterized by alluvial soil, residual deposits, and debris flow deposits. Some pebbles and boulders, which are terrace deposits, can be found at the mouth of the debris flow gullies.

The study area lies in the transition zone from the Sichuan basin to the northwest and the Sichuan plateau to the west. In this area, new tectonic movements are manifested mainly as intermittent uplifts characterized by apparent differences between vertical and horizontal displacements. The Beichuan fault runs through Beichuan County, which was destroyed by the earthquake. The fault has caused frequent earthquakes in the past. According to the “seismic ground motion parameter zonation map of China” (GB18306-2001), revised after the earthquake, the seismic peak ground acceleration was 0.20g and the seismic intensity was VIII for Beichuan County.

Meteorological and hydrological setting

The study area has a subtropical monsoon climate with four normal seasons, a mild climate, and an average temperature of 15.6°C. The annual average precipitation is 1,399.1 mm, with an annual maximum of 2,340 mm, a daily maximum of 101 mm, and an hourly maximum of 32 mm. Most rainfall occurs between June and September, accounting for 71–76% of the annual rainfall and in some cases up to 90% (1981) (Fig. 3).

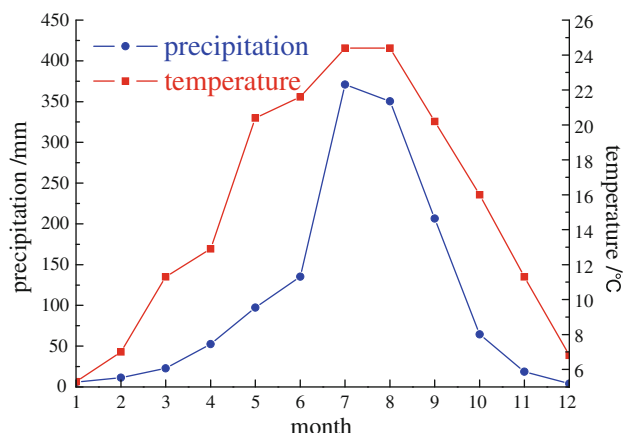


Fig. 3 Monthly average temperature and rainfall from 1971 to 2000 in Beichuan County

The average annual rainfall decreases from the southeast to the northwest in Beichuan County. Leigu township is located in the heavy rainfall zone, with an average annual rainfall of 1,400–1,460 mm.

From 1–22 September 2008, it was exceptionally dry in Beichuan County. Only 57 mm of rain was recorded at the Beichuan rainfall station, and just 41 mm were recorded at the Leigu station. However, on 23 September, heavy rainfall occurred all through Beichuan County. According to Tangjiashan rainfall station records, 57.99 mm of rain fell between 0:00 and 5:00 on 24 September. The group of debris flows started at about 6:00 am on 24 September and the 1-h (5:00–6:00 am) rainfall intensity reached 41 mm in the Subao River Valley, an intensity with a recurrence

interval of 20 years (Tang and Liang 2008; You et al. 2010).

Hazards induced by the earthquake

Landslides and rock avalanches

The combination of intense tectonics, fractured bedrock, and quickly changing weather in the Subao River Valley formed plenty of residual deposits on the slope, most of which on slope $>25^\circ$. Such deposits are prone to landslides or rock avalanches. Along the main Subao River, the earthquake caused a group of rock avalanches and five large-scale landslides (Fig. 4; Table 2). Other hazards occurred along the branches of the river. These landslides and rock avalanches supplied the debris flows with a considerable amount of loose deposits.

Debris flows

The heavy rainfall triggered a group of debris flow in 10 gullies of the catchment (Table 3), which killed 11 people and caused severe damage to properties and infrastructures, including temporary accommodations, residential houses, transportation routes, emergency power facilities, and communication systems. Many farms were washed away or buried. The environment has been seriously damaged. The losses were greater than those directly caused by the earthquake.

Changes in debris flow magnitude after the earthquake

No debris flows have been recorded in Subao River Valley before the earthquake. According to field survey, the size

of the debris flows exceeded by far the size of pre-earthquake debris flows in neighboring areas. The deposits exceeded $2.7 \times 10^6 \text{ m}^3$, raising the channel bed by up to 10 m. In order to study the scale changes of debris flows, the peak discharges were calculated in the Daanshan, Huangnidi and Guanmenzi gullies.

Cross-section method

The maximum cross section was determined using debris flow traces from both sides of the channel. Then the peak discharge is given by the product of the cross-section area and average velocity. And the velocity is calculated by (Fei and Shu 2004):

$$V_c = \left(R_c^{2/3} \times I_c^{1/2} \right) / n_c \quad (1)$$

where V_c is the average debris flow velocity through the cross section, R_c is the hydraulic radius, I_c is the hydraulic gradient, and n_c is the bed roughness.

$$Q_c = W_c \times V_c \quad (2)$$

where Q_c is the peak debris flow discharge and W_c is the cross-section area.

Figure 5 shows cross-section profiles of the gullies and Table 4 lists the calculated discharges.

Rain-flood method

The rain-flood method is useful for calculating peak discharge. It assumes that debris flow concurs with flood flows with a certain recurrence interval that can be calculated using hydrological method. Then, according to the characteristics of the debris flow and gully, the peak discharge

Fig. 4 Orthophoto map and diagram of the distribution of disasters in the Subao River Valley. *D1* the number of the debris flow gully, which has 15 debris flow gullies, *B1* the number of the rock avalanche, *H1* the number of the landslide

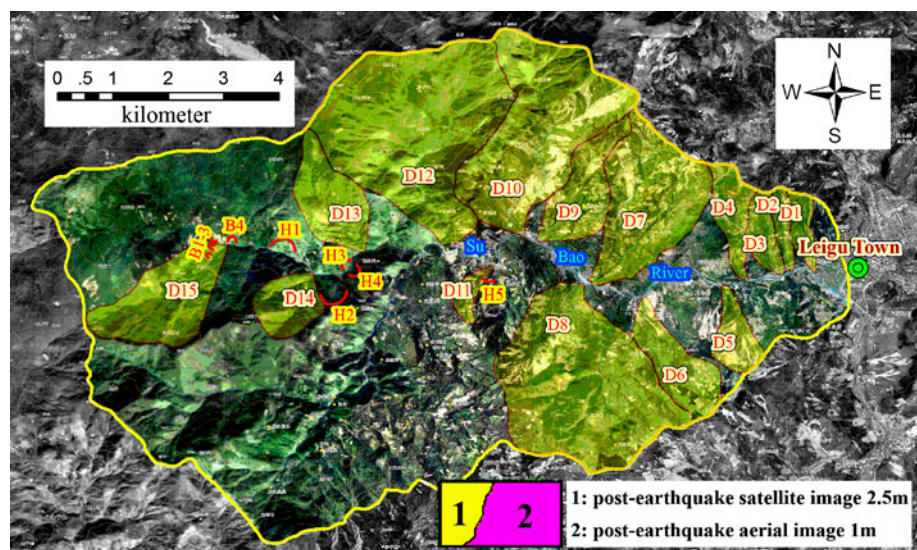


Table 2 Landslides and rock avalanches characteristics of Subao River Valley

No.	Top elevation (m)	Height (m)	Width (m)	Mean depth (m)	Volume (m ³)	Category
B1	1,500	60	1.5	1.0	90	Rock fall
B2	1,500	70	1	1.0	70	Rock fall
B3	1,460	50	2	1.5	150	Rock fall
B4	1,460	40	1.5	2.0	120	Rock fall
H1	1,420	40	55	4.0	8,800	Landslide
H2	1,440	200	85	9.0	153,000	Landslide
H3	1,180	200	75	1.5	22,500	Landslide
H4	1,200	140	90	7.0	88,200	Landslide
H5	1,040	150	140	6.5	136,500	Landslide

Table 3 Topographic features of the debris flow gullies in the Subao River Valley

No.	Gully name	Area (km ²)	Length (km)	Highest (m)	Lowest (m)	High difference (m)	Relief ratio (‰)
D1	Jiangjiagou	0.41	1.59	1,323	734	589	352
D2	Gangou	0.37	1.63	1,323	737	586	342
D3	Huijiaping	0.57	1.70	1,410	739	671	390
D4	Shaojiagou	1.05	2.39	1,549	750	799	317
D5	Xiaojiaping	0.78	1.57	1,640	755	885	557
D6	Xiaopingshan	1.33	2.52	1,674	790	884	333
D7	Daanshan	3.57	3.51	2,110	810	1,300	333
D8	Huangnidi	6.35	3.91	1,760	813	947	206
D9	Guanyintang	1.52	2.90	2,110	845	1,265	415
D10	Guanmenzi	5.50	4.44	2,359	850	1,509	306
D11	Jinzhuoyuan	1.20	1.66	1,765	872	893	512
D12	Chayuantou	7.39	4.53	2,282	930	1,352	254
D13	Leijiaping	1.62	2.61	2,245	1,030	1,215	443
D14	Zhongliangzi	1.00	1.33	2,026	1,160	866	617
D15	Banongshan	2.63	2.77	2,318	1,380	938	322

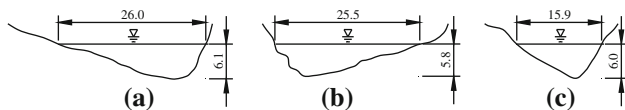


Fig. 5 Typical measured cross-section profiles of debris flows in the three gullies of the Subao River Valley (unit, meters) **a** Daanshan gully, **b** Huangnidi gully, **c** Guanmenzi gully

of debris flow can be estimated using (Zhou et al. 1991; Wu et al. 1993):

$$Q_C = (1 + \Phi)Q_P \cdot D_C \tag{3}$$

where Q_P is the peak rain flow with a recurrence interval of p , D_C is the blocking coefficient, and Φ is the correction coefficient for the debris flow discharge defined as:

$$\Phi = (\gamma_C - \gamma_W) / (\gamma_H - \gamma_C) \tag{4}$$

where γ_C is the debris flow density, γ_W is the density of water (1.0 t/m³), and γ_H is the density of solid matter in the debris flow (2.7 t/m³).

Using formulae 3 and 4, the peak debris flow discharges for the three gullies at different recurrence intervals were calculated. The results are shown in Table 5.

Comparison of the results

Tables 4 and 5 indicate that the debris flow discharge calculated by the cross-section method was equivalent to that of a 200-year return period in the Daanshan gully, a 100-year return period level in the Huangnidi gully, and a 50-year return period level in the Guanmenzi gully as calculated using the rain-flood method. However, the precipitation that actually triggered the debris flows in the three gullies was only equivalent to that of a 20-year return period. The results show that debris flow discharge calculated using the cross-section method is significantly greater than that calculated using the rain-flood method. Thus, the calculations generated by the rain-flood method were smaller than the actual discharge in the area affected by the earthquake.

Table 4 Typical cross-section characteristics and cross-section method results for velocities and peak discharge for the three gullies in the Subao River Valley

Gully name	Area (m ²)	Hydraulic radius (m)	Relief ratio (‰)	Velocity (m/s)	Peak discharge (m ³ /s)
Daanshan	78.2	2.0	145.0	10.26	802
Huangnidi	89.6	2.3	137.5	10.97	983
Guanmenzi	49.7	2.8	133.4	12.32	612

Table 5 Rain-flood method results for the three gullies at different recurrence intervals

Gully name	Frequency [<i>P</i> (%)]	Peak flow [<i>Q_P</i> (m ³ /s)]	Correction coefficient (Φ)	Block coefficient (<i>D_C</i>)	Peak discharge [<i>Q_C</i> (m ³ /s)]
Daanshan	0.5	118	2.18	2.20	827
	1	108	1.69	2.00	579
	2	96	1.33	1.80	405
	5	82	1.06	1.60	269
	10	70	0.84	1.40	180
Huangnidi	0.5	202	2.18	2.20	1,412
	1	183	1.69	2.00	986
	2	164	1.33	1.80	687
	5	138	1.06	1.60	454
	10	117	0.84	1.40	302
Guanmenzi	0.5	172	2.18	2.20	1,207
	1	156	1.69	2.00	842
	2	140	1.33	1.80	586
	5	117	1.06	1.60	387
	10	100	0.84	1.40	257

Causal analysis of debris flow scale change

Precipitation

Following the earthquake, there were no significant changes in climate and rainfall did not increase significantly in the Beichuan region. The decrease in the rainfall triggering thresholds, rather than the increase in rainfall intensity caused the debris flow group. The precipitation pattern meant that such a large-scale debris flow group could not have been triggered in this area prior to the earthquake. Tang and Liang (2008) studied the triggering precipitation and found that the antecedent cumulative rainfall and the thresholds of 1-h rainfall were 272.7 and 41 mm, respectively. Compared with the pre-earthquake data, the former decreased by approximately 14.8–22.1% and the latter decreased by approximately 25.4–31.6%. A similar situation also appeared in Taiwan after the Chi-Chi earthquake. In the area affected by the Chi-Chi earthquake, the rainfall threshold for debris flow was rapidly lowered after the earthquake (Lin et al. 2003; Shieh et al. 2009). Therefore, the debris flow scale change was only related to the decrease in the triggering rainfall.

Topography

The earthquake has generated a 240-km-long surface rupture, particularly along the Beichuan–Yingxiu fault, along which vertical and horizontal displacements up to 6.2 and 4.9 m were resulted (Xu et al. 2008). Although the seismic wave caused surface ruptures and hazards, it hardly changed the overall landform. The most obvious and common topographical changes were the micro-relief changes induced by landslides and rock avalanches. With respect to debris flow gullies, neither the channel relief ratio nor the length or area of the drainage area displayed substantial changes. Therefore, from the point of view of topographical change, the changes of debris flow sizes were related to the increase in loose materials due to the micro-relief changes rather than the topographical changes in the area affected by the earthquake.

Loose materials

No debris flows have ever been recorded before the earthquake in the study area, probably because of the lack of loose materials. The earthquake severely damaged the surface and induced a large number of rock avalanches and

landslides that supplied sufficient loose materials. Based on field surveys, several gullies were transformed into debris flow gullies. Debris flow characteristics also changed after earthquakes. You et al. (2010) argued that the densities will increase by 10–30% due to the presence of loose deposit. Xie et al. (2009) noted that the debris flows occurring after the earthquake were viscous in character and their densities were mostly between 2.0 and 2.3 t/m³.

The loose materials have abundant pore density and low shear strength. Thus, they are prone to initiating and forming a debris flow. This explains why the rainfall triggering threshold was so small. The rapid and sharp increase in loose materials caused the change of characteristics and the conditions necessary for initiating the debris flow group.

Valley conditions

According to field observations and remote sensing interpretation, loose materials commonly blocked channels in the study area. The hazards had a dominant zonal distribution that exceeded 60 × 10⁴ m²/km² within 10 km of the seismogenic fault. Quite a few materials have accumulated in gullies and even blocked channels other than those on the slope. The loose materials significantly changed the flow capacity of the channels. In this instance, large-scale debris flows were prone to occurring with heavy rain. Therefore, channel blocking increased the size of the debris flows in the area affected by the earthquake.

According to above analysis, it can be concluded that the rapid and sharp increase in loose materials led to the change of characteristics and the conditions necessary for initiating the debris flow. The loose materials also significantly changed the flow capacity of the channels. If these materials, still hanging on the slopes, slide into the channels they will further increase the possibility of channel blocking. The channel process, coupled with the slope process, eventually evolves into a large-scale debris flow. Consequently, when predicting or evaluating the scale of post-earthquake debris flows, the characteristics of debris flows and channel blocking must be considered.

Amended blocking coefficient values

The blocking coefficient is an important element in calculating the peak debris flow discharge using the rain-flood method. It is determined either by checking published tables or through calculation. The former is based on field survey and the latter is based on measured precipitation and peak debris flow discharge. The coefficient is usually between 1.0 and 3.0.

Amendment of the blocking coefficient should involve consideration of dam density, type, and height. Dam density is the number of dams per unit length. If the channel has more than one dam, the dams may break one by one after the upstream dam breaks. The type of dam affects dam stability. An earth dam is less stable and is more prone to breaking than a stone dam. The latter is particularly stable if composed of large blocks. In addition, dam height has a significant impact on peak debris flow discharge once the dam breaks. Based on the density, type, and height, the recommended blocking coefficient values were presented based on field survey and interpretation of remote sensing data from the study area (Table 6).

Prediction for debris flow scales in Subao River Valley

In addition to being related to the solid materials in flows, the debris flow density is related to rainfall intensity. Greater rainfall intensity tends to initiate bigger stones and more debris. As a result, the debris flow has higher density. The debris flows densities were largely between 2.0 and 2.3 t/m³ in the areas. According to field investigation and testing, the debris flow density was 2.0 t/m³ for a 20-year precipitation return period.

Dams formed by landslides are common in the study area, about 3 per km and with height of less 3 m. Based on the data in Table 6, the blocking coefficient should be 2.0–3.0 for precipitation of 20-year return period. It is important to note that the coefficient may vary for each gully based on their circumstances.

According to the above conditions, the peak debris flow discharges of Subao River Valley for a 20-year

Table 6 Recommended blocking coefficient values for the Beichuan region

Blocking coefficient		Classification index		
Level	Value	Dam density	Dam height	Type of dam
Extremely serious blocking	>5.0	>5	>10	Composed of soil, without stones
Very serious blocking	4.0–5.0	3–5	5–10	Mainly composed of soil, with a few stones
Serious blocking	3.0–4.0	1–3	3–5	Mainly composed of stones, with some residual slope sediments
Slightly blocking	2.0–3.0	<1	<3	Mainly composed of stone blocks, with some soil

Table 7 Rain-flood method results for debris flows in the Subao River Valley for a 20-year precipitation return period

No.	Gully name	Concentration time (h)	Storm intensity (mm/h)	Peak flow (m ³ /s)	Blocking coefficient	Peak discharge (m ³ /s)
D1	Jiangjiagou	0.90	91.84	9.92	2.10	50.63
D2	Gangou	0.95	91.84	8.81	2.10	44.94
D3	Huijiaping	0.86	91.84	14.15	2.10	72.23
D4	Shaojiagou	1.07	91.84	24.31	2.10	124.04
D5	Xiaojiaping	0.67	91.84	21.21	3.00	154.62
D6	Xiaopingshan	1.05	91.85	30.88	3.00	225.15
D7	Daanshan	1.13	91.85	80.72	4.10	804.21
D8	Huangnidi	1.27	91.85	136.48	3.00	994.93
D9	Guanyintang	1.07	91.84	36.39	3.00	265.25
D10	Guanmenzi	1.30	91.85	116.27	2.20	621.59
D11	Jinzhuyuan	0.66	91.84	33.07	2.20	176.78
D12	Chayuantou	1.31	91.85	156.22	2.10	797.19
D13	Leijiaping	0.95	91.84	39.32	2.00	191.11
D14	Zhongliangzi	0.53	91.84	29.57	2.00	143.73
D15	Banongshan	0.99	91.84	63.39	2.20	338.86

precipitation return period were calculated using Eq. 3. The results are shown in Table 7.

Discussion

Subao River Valley, which lies on the Beichuan–Yingxiu thrust fault, was heavily impacted by the Wenchuan earthquake. A large number of geo-hazards caused which provided plenty of loose material for debris flow. Since the debris flows group on 24 September 2008, this catchment has been the most seriously affected by debris flow and debris flow activities will continue for some time.

The debris flows are much greater than those in the neighboring areas. This was mainly due to the rapid and sharp addition of loose materials. On the one hand, loose materials supplied sufficient materials for the debris flow. On the other hand, they blocked the debris flow channels and significantly changed their flow capacity. Once the dam broke, peak discharge increased and the erosion capacity was greatly enhanced, resulting in a larger-scale debris flow.

All of the debris flows traveled out of valley mouths because of the short channels. After 2–3 debris flows like the “9.24 debris flows group”, the trend of debris flow activities will likely decline in the catchment. The fine-grained surface materials prone to being taken away by debris flows and the loose materials will gradually consolidate over time and their shear strength will increase. Thus, it was predicted that the debris flow activities in this catchment will cease after 3–5 years. However, in the short term, the debris flows of this catchment will be frequent and large-scale. Therefore, debris flow control projects should not be carried out during the active debris flow phase.

Conclusions

In this paper, the amended blocking coefficient values were presented based on dam density, type, and height. The recommended values were based on field survey and the interpretation of remote sensing data following the “9.24 debris flow group”. They can be used to predict or evaluate the debris flow scale in the Beichuan region. However, these values may be unfit for other areas affected by the Wenchuan earthquake. In future, in addition to conducting researches on debris flows in the Wenchuan area, blocking experiments should be conducted in other areas to further optimize the blocking coefficient values.

In the Beichuan region, precipitation of a 20-year return period is likely. Therefore, in this paper the peak debris flow discharges of Subao River Valley under this situation were calculated, which has significance for post-disaster restoration and reconstruction in the catchment.

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