Bull Eng Geol Environ (2009) 68:187–194
DOI 10.1007/s10064-009-0201-6

ORIGINAL PAPER

Rainfall-triggered debris flows following the Wenchuan earthquake

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Received: 20 October 2008 / Accepted: 12 February 2009 / Published online: 22 April 2009

Abstract On 24 September 2008, 72 debris flows were triggered by heavy rainfall in the central part of the area affected by the Wenchuan Earthquake. This paper describes the process of debris-flow initiation and transport in the study areas and presents field observations on the roles of rainfall, lithology and the presence of faults. It is likely that following the ground shaking, the critical amount of accumulated precipitation and the hourly rainfall intensity necessary to initiate debris flow was reduced compared with values before the earthquake. A case study in the Xishanpo gully is presented; the debris flow from which caused a thick accumulation in the already devastated city of Beichuan. It is concluded that the whole of the area shaken by the Wenchuan Earthquake is now more susceptible to debris flows, which may be initiated by localized heavy rainfall. Care must be taken to properly assess this new type of geo-hazard.

Keywords Debris flows · Intensive rainfall · Accumulated precipitation · Lithology · Wenchuan earthquake · Rainfall conditions · Seismic landslides

Introduction

A debris flow is defined as a poorly sorted mixture of soil, rock, vegetation and water that rapidly flows down a slope in response to gravity (Varnes 1978; Iverson 1997). Debris flows can pose significant geological hazards and are an important geomorphic process in high-relief landscapes (Costa and Wieczorek 1987). They form an important link between hillslopes and channel networks, because they transport large volumes of sediment from hillslopes to adjacent valleys (Webb et al. 1988; Benda 1990; Eaton et al. 2003). During the early morning of 24 September 2008, a heavy rainstorm in Beichuan County, Sichuan Province, triggered numerous debris flows in the central part of the area affected by the 12 May 2008 Wenchuan earthquake. Some 42 people were killed in Beichuan County and many roads in this mountainous area were damaged. A debris flow in the Xishanpo gully moved earth, debris and boulders down into the older part of Beichuan city and buried most of it. Fortunately, nobody died as all the residents had already been evacuated to other, more secure places after the Wenchuan Earthquake.

On 24 and 25 September 2008, geohazard scientists from the State Key Laboratory of Geohazard Prevention (SKLGP) visited the Beichuan area to define the aerial extent of the events and investigate the debris-flow source areas, the transport paths and the deposits. The primary focus of this study was to analyze the rainfall conditions that had triggered the debris flows and to study the processes which lead to the generation of earthquake-related debris flows in this setting. As the earthquake and debris flows occurred within four months, it provided an opportunity to assess the significance of the Wenchuan earthquake for the occurrence of subsequent debris flows, as well as to explain the initial conditions triggering these devastating hazards.

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The study area

The study area, situated in the central Wenchuan earthquake-affected area, belongs administratively to Beichuan

County of Sichuan Province. It is 160 km from the northern part of Chengdu, at longitude 103°44′ to 104°44, latitude 31°41′ to 32°14′. The study area is 92 km from east to west and 59 km from south to north, covering 2,865 km^2 and accommodating approximately 161,000 people.

The strata exposed are Lower Palaeozoic in age. They include Cambrian sandstones and argillaceous limestones, Silurian slates and phyllites and limestones of Devonian and Carboniferous age (Fig. 1). The Quaternary deposits are unconsolidated and widely distributed in terraces and alluvial fans.

The structural orientation of the study area is NE/SW. The Yinxiu-Beichuan Fault, which triggered the Wenchuan Earthquake, is immediately southeast of the study area, and is developed as a NW dipping thrust fault with an angle of 60–70°. The Cambrian sandstones form its hanging wall, while its footwall consists of Silurian and Devonian limestones.

Beichuan County is situated in the transitional belt between the Sichuan Basin and the Western Sichuan Plateau, and is mainly composed of mountainous areas. The northwestern part is characterized by high mountains (generally 1,200–3,100 m asl); the central part has medium elevations, with rugged mountains and deeply incised valleys while the southeastern part has a lower relief (700–1,400 m asl). The highest mountain in the study area is Mt Chaqi with an elevation of 4,769 m asl while in the south east the elevation is only 540 m asl in the valley of the Jian River. This 47.9 km long river originates in the northwestern mountains and flows through the southeastern corner of the study area and into the Pei River. The drainage area is some 455 km^2 from which there is an average annual discharge of 102 m^3/s and an annual sediment discharge of 4–5 million tons.

The study area has a sub-tropical humid monsoon climate with an annual average temperature of 15.6°C (range 5.3–24.4°C, Table 1). It includes the Lutou Mountain, which is famous for its abundant precipitation. The annual average precipitation is 1,400 mm; the highest annual precipitation of 2,340 mm was recorded in 1967. As seen in Table 1, the rainfall is mostly concentrated in the period June to September, when 83% of the annual precipitation falls; the highest (90%) being recorded in 1981. Figure 2 shows the distribution of the precipitation in Beichuan County between 1971 and 2000 and indicates its irregularity in the study area. From the spatial distribution perspective, the trend is of decreasing precipitation from the southeast to the northwest.

Methodology

To study the features of the debris flows triggered by the heavy rainfall on 24 September, 2008, field investigations were carried out to determine the distribution and number of debris flow gullies. A typical debris flow drainage basin was chosen for detailed ground survey and investigation in order to analyze the source conditions and the characteristics of the flow channel and the depositional fan. The discharge and run-out of the debris flow were calculated from the data obtained by surveying a typical transverse section through the flow channel, where the mud traces of the debris flow on the gully banks were still visible.

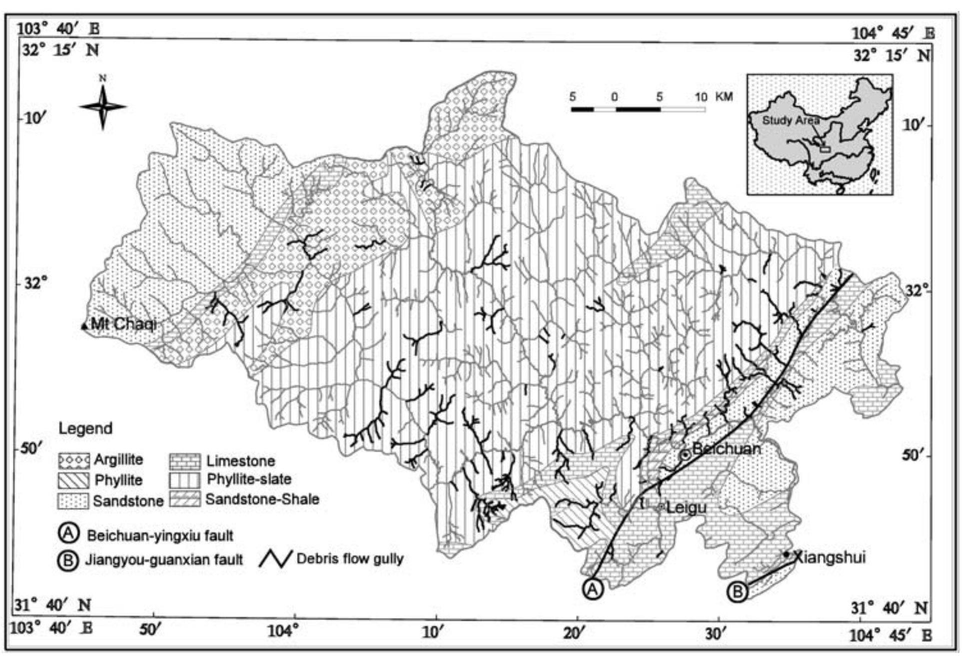

Fig. 1 Simplified geological map and debris flow inventory map of the study area, Beichuan County of Sichuan Province

Table 1 Average temperature and precipitation in the Beichuan County area from 1971 to 2000

Month	1	2	3	4	5	6	7	8	9	10	11	12	Year
Temperature (°C)	5.3	7.0	11.3	12.9	20.4	21.6	24.4	24.4	20.2	16.0	11.3	6.8	15.6
Precipitation (mm)	5.9	11.4	22.8	52.6	97.3	135.3	370.8	350.4	206.6	64.4	18.6	4.1	1399.1

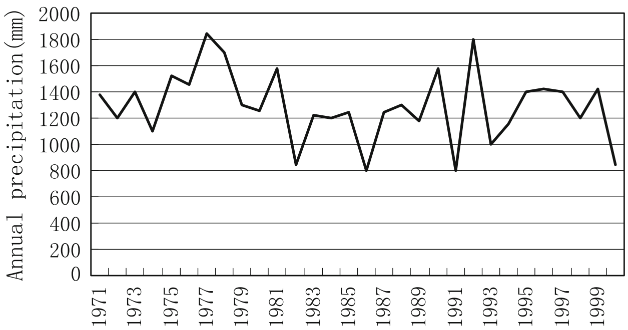

Fig. 2 Annual precipitation in Beichuan County from 1971 to 2000

The Ministry of Land and Resources of China had completed the aerial photography of the study area by 18 May, 2008. These photographs were used to determine the locations of landslides and landslide dams in the earthquake-stricken areas and to analyze the road damage due to landslides, so as to provide a basis for disaster rescue operations and emergency response. As the resolution of these aerial photographs is 0.5 m, they could be used to analyze the features of the debris flow source areas in the study region. More importantly, they could be used to determine the distribution and numbers of landslides triggered by the Wenchuan Earthquake in the debris flow source areas and thus provide data about the amount of loose material available for the initiation of debris flows. These aerial photographs were used to compile maps of debris flow source areas, flow paths and flow deposits. As there were no aerial photographs or other remote-sensing imagery taken after the 24 September debris flows available for interpretation, the distribution of the debris flows and the characteristics of the typical debris flow source areas were mapped by ground investigation in the debris flow gullies.

The 1:50,000 topographic map and a Digital Elevation Model (DEM) were used to analyze the topographic features of the debris flows, whereas the gradients of the debris flow source areas were analyzed by using the 30 m DEM compiled by the China Geology Survey Bureau. The 1:100,000-scale geological map of the study area was used to evaluate the lithology and effect of faults. Rainfall records from three meteorological stations in the study area were used to determine the daily rainfall totals during all the debris flow events. Hourly precipitation data collected at three automated weather stations were used to determine the rainfall intensity for each debris flow-producing storm.

Results and data analysis

Rainfall

Before the Wenchuan Earthquake, there were two meteorological stations in the study area: the Beichuan Station and the Leigu Station. However, the earthquake damaged meteorological observation instruments and caused the loss of observation data during a certain period. Therefore, an extra automatic station was set up on the Tangjiashan Landslide to monitor the hydrological modifications of the barrier lake and to analyze the possibilities of dam breaches leading to flooding. Rainfall data are recorded hourly at all three stations, which gives a very good ground-based record of the rainfall. Figure 5 indicates the location of the three meteorological stations.

Rainfall during the summer season, 2008

Prior to 24 September, the summer of 2008 was marked by a relatively low amount of rainfall in the study area. Precipitation totals for July and August were 125 and 234 mm respectively at the Beichuan station. Comparing this with the monthly average precipitation in Table 1, it can be seen that in 2008, the precipitation in July and August was 66 and 33% lower than the average respectively. The area was extremely dry from 1 to 22 September; the precipitation recorded at the Beichuan Observatory was only 57 mm, and at Leigu Observatory only 40 mm.

On 23 September, the day before the debris flows occurred, both the Beichuan and Leigu Stations failed to record the precipitation. However, residents living near the Beichuan city described the rain as "… so hard with thousands of frightening thunder-like sounds for almost the whole night." Figure 3 shows the precipitation recorded at the Tangjiashan Station; this occurred in the early hours of the morning and late at night and amounted to a total of 173 mm. It is likely this heavy rainfall, including the 60 mm between 2,330 and 2,400 h was significant for the regional debris flows on 24 September.

Rainfall on 24 September 2008

Rainfall data for 24 September 2008 show 57.9 mm of precipitation at the Tangjiashan Station between 0:00 and 5:00 (Fig. 4). Following this, it is likely that the heavy

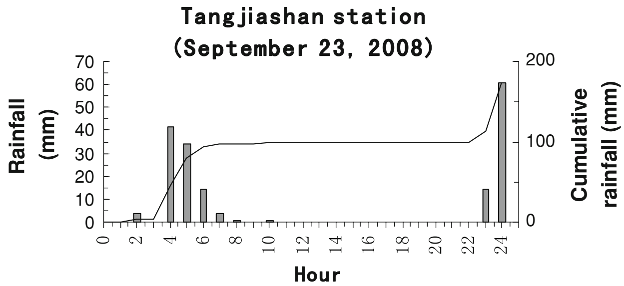

Fig. 3 Hourly and cumulative rainfall for the 23 September, 2008 at Tangjiashan station

rainfall recorded between 05:00 and 06:00 (41 mm per hour) triggered the ground instability. Eyewitness accounts provided data concerning the timing of most debris flow events. They said that the debris flows in the Xishanpo, Renjiaping and Zhaojia gullies, close to the Beichuan city area, and Zhaojiagou gully near Leigu town occurred at around 06:00. This observation indicates that the rainfall covered much of the study area, but of course total amounts varied spatially. The amount and the intensity/duration of the rainfall recorded in this area has a return period of about 20 years.

In order to assess the critical rainfall conditions causing debris flows before and after the earthquake, the Report on Investigation and Hazard Zonation of Geological Hazards in Beichuan County compiled by the Sichuan Department of Land and Resources in 2003 was consulted. Before the earthquake, the 3 day antecedent accumulated precipitation triggering debris flows in this area was concluded to be 350–380 mm. On 24 September, 2008, the antecedent accumulated precipitation triggering the debris flows was 272 mm, as recorded at Tangjiashan. Based on the data available in 2008, it would appear that following the earthquake a lower threshold was required to trigger the debris flows. After the earthquake, the triggering level for antecedent accumulated precipitation decreased by 15–22%, and the critical level for hourly rainfall intensity decreased by 25–31%. Such phenomena were also

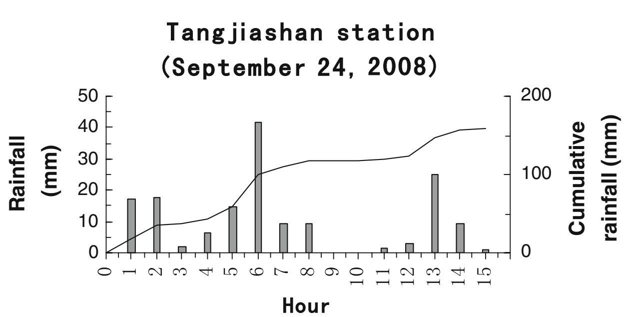

Fig. 4 Hourly and cumulative rainfall for the 24 September, 2008 at Tangjiashan station (Debris flows occurred at 5 am)

observed in the 1999 Taiwan Chi-Chi Earthquake area, where the hourly rainfall intensity and the critical accumulated precipitation triggering the debris flow decreased by 1/3 of the values used before the earthquake (Lin et al. 2003; Chen 2009; Chen and Hawkins 2009).

Effect of the lithology on debris flow generation

Lithology plays an important role in the occurrence of debris flows, as the rock type and its mechanical behavior directly determine the quality and the quantity of the loose material which is available for debris flow formation. The loose overburden material in the Wenchuan earthquake area mainly originated from the following sources:

(1) The landslides and rockfalls caused by the earthquake are the most important sources for debris flow material.
(2) The various Quaternary loose deposits on the slopes of the source areas. With the strong earthquake shaking, they were loosened and prone to develop into debris flows with high levels of surface runoff.
(3) Abundant loose deposits in the debris flow channel bottoms, mainly resulting from previous debris falls and debris slides along the gully sides. As a consequence of the earthquake, the volume of these loose deposits was greatly increased.

To illustrate the effect of lithology on debris flow occurrence, the locations of the source areas for the 24 September debris flows were overlain on the geological base map (Fig. 1). This indicates that 46 debris flow source areas (64% of the total) are located in the Silurian slates and phyllites, 11 (15%) in the Cambrian sandstones and sandy shales and only 8 (11%) in the Devonian and Carboniferous limestones. The remaining 7 debris flow sources (9%) are located in the carbonaceous sillcalite. To understand the susceptibility of particular lithologies to debris flows, the density of debris flow gullies in the different rock types was calculated per 100 km^2 surface area. It was found that phyllite and shale have a density index of 4.9; limestone 2.1 and sandstone 1.95.

The relatively smooth and flaky nature of the fragments of phyllite and slate probably account for part of sensitivity of these rocks to movement by debris flow. However, the tectonic history of this region (folding, interbed movement, faulting etc.) which caused the poor integrity and hence low resistance to weathering of these lithologies is also important. Commonly, these rock types have thick weathering layers enriched with clay minerals and due to their plasticity they provide abundant loose material for the formation of debris flows. Griffiths et al. (2004) studied the initiation and frequency of debris flows in the Grand Canyon, Arizona, and drew the conclusion that shales can

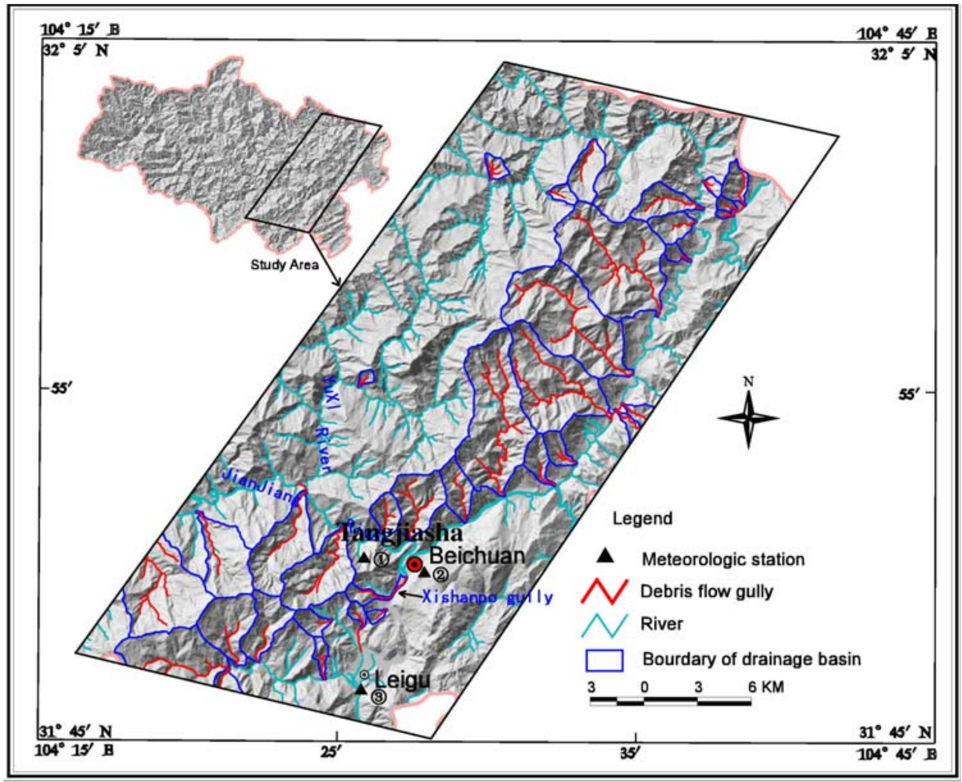

Fig. 5 Drainage system of debris flows in Beichuan area (*Solid triangle* with number represents the rainfall measurement station at ① Tangjiashan, ② Beichuan and ③ Leigu Station

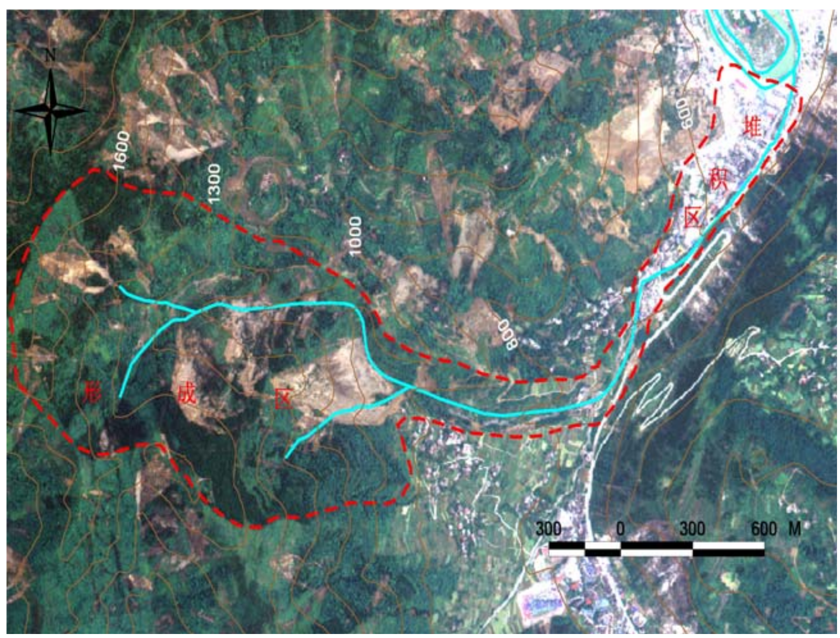

Fig. 6 Aerial photograph of the Xishanpo debris flow gully taken on 18 May, 2008 (prior to the heavy rainfall of 24 September)

provide the fine particles and clay minerals (for example, kaolinite and illite) that appear to be essential to long-distance debris flow transport. The weathered and fractured phyllite in the study areas also contain the fine particles and clay minerals that are essential for the viscosity and density required to transport large boulders over long distances.

The Cambrian sandstones and sandy shales in the hanging wall of the Beichuan-Yinxiu Fault were particularly severely affected by the ground shaking at the time of the earthquake, which caused intense fracturing of the strata. As a consequence, there were frequent landslides and rockfalls, as well as the accelerated accumulation of loose material in gullies which was easily disturbed by intensive rainfall.

Characteristics of debris flows

To explore the spatial distribution and the characteristic features of debris flows triggered by the heavy rainfall occurring on 24 September, 2008 in the Beichuan region, an emergency investigation was undertaken along the roads and rivers in the region, and found 72 gullies in which debris flows had occurred (Fig. 5). Due to their widespread distribution, their large numbers and the difficulty of their analysis, "rill" debris flows as described by Godt and Coe (2007) are not discussed here. From Fig. 5, it can be seen that the large majority of the debris flows were on the hanging wall side of the Beichuan-Yinxiu Fault, with only 7 gullies identified on the footwall side. There are 17 gullies in an elongate zone along the north-west trending Beichuan-Yinxiu Fault and a relatively high density of debris flow gullies along both banks of the Jian River, implying that, in addition to the topography, the fault and river system control the spatial distribution of the debris flows. The surface area of the individual catchments ranges from 0.3 to 26 km^2, with approximately 50% being <3 km^2; 12 gullies were in a drainage area of less than 1 km^2.

The Xishanpo gully (Fig. 5), some 450 m from Beichuan old city, was chosen as a case study to analyze the debris flow initiation and depositional processes resulting from the 24 September rainfall. The gully has a catchment area of only 1.54 km^2 and a channel length of 2.3 km. The upslope elevation is 1,040 m asl and the gully mouth is at 700 m asl. The highest part of the debris flow source area is at 1,740 m asl on the hanging wall side of the Beichuan-Yinxiu Fault and some 1.4 km from it. The lithology exposed in the source area is mainly Cambrian sandstone and sandy shale.

In the upper reaches of the Xishanpo gully, three landslides with surface areas of more than 10,000 m^2 were triggered by the Wenchuan Earthquake, as well as ten smaller landslides and rockfalls. The catchment area of the Xishanpo gully is delimited on the aerial photograph taken on 18 May 2008 in Fig. 6. It can be seen that the largest landslide is at 880 m to 1,200 m asl and has a length of 410 m and a width of 250 m. The average thickness is 10–15 m hence the volume of this landslide is estimated to be 1.1 million m^3. It blocked the drainage channel, forming a 120 m long deposit in the gully with a height of 5–10 m (Fig. 7).

Two other landslides can be identified in the upper reaches of the gully with an estimated total volume of 1.2 million m^3. In addition, the weathered near surface material and the Quaternary deposits would also have provided a large amount of loose material following the earthquake shaking. According to the interpretation of the aerial photographs and the preliminary survey of the site, the volume of these loose materials in the source area may reach more than 1.2 million m^3. Based on these data, the total calculated volume of loose material contributing to the formation of debris flows may reach 3.5 million m^3.

Witnesses living in Renjiaping village described the debris flow which started at around 6 am on 24 September, 2008. There was a thunderous noise and large amounts of water mixed with mud, debris and stones poured into the old city of Beichuan, already ruined by the effects of the earthquake. After 6 o'clock, the volume of the noise decreased and the debris flow gradually stopped, having lasted for about an hour, although large discharges still occurred until 10 o'clock.

The debris flow developed in two main stages:

1) the first stage is the mobilization of shallow landslides. The surface runoff causes the material precariously balanced on the sides of the slopes to move into the gully
2) in the second stage, the overland flow of water resulting from the intense rainfall was concentrated in the steep channels and scoured the debris from the gully in a debris flow; this phenomenon has been described as the "fire hose effect" (Coe et al. 1997; Griffiths et al. 2004). Figure 8 shows the channel character of the debris flow transport path, incised in old alluvial fans.

The debris flow initiation area was situated at an elevation between 1,150 m and 1,250 m asl. The fluid concentrated in the upper part of the channel flowed down to an elevation of 1,050 m and was blocked there by a barrier of loose landslide material that had been deposited in the gully bottom. The failure of this landslide dam produced a fast increase in the flow discharge. For the analysis of the debris flow discharge in this gully, two mud trace cross sections in the transport channel were surveyed: one in the upper part of the flow channel and the second in the lower part. The first cross-section at an elevation of 900 m asl is trapezoid in shape, 14 m wide and 5 m deep. The second one, at an elevation of 780 m asl, is rectangular, 32 m wide and 2.2 m deep. From these data it was calculated that the peak discharge of the debris flow reached 260 m^3/s, which appears to be a high value for a gully catchment area of 1.54 km^2. However, with the failure of the landslide dam in the gully, there would have been an instant dramatic increase in the flow discharge. Ground investigations of the deposition area indicate the run-out of the debris flow was some 340,000 m^3—a relatively high volume from such a small catchment.

Fig. 7 Photograph of debris flow that mobilized from a landslide on the south flank of Xishanpo gully. Relief from the landslide

Fig. 8 Photograph showing debris flow channel deeply incised in an old alluvial fan, debris flow tracks and source areas

After the debris flow moved out of the steep gully, it rushed into Beichuan old city (Fig. 9), forming an accumulation some 900 m long with a maximum width of 150–200 m. The surface area was 0.17 km^2 and the thickness of the deposits reached 9–12 m in the upper segments. Near the centre, the debris was 7–8 m thick, with clasts of 50–300 mm forming about 50% of the total deposit. Figure 10 shows the situation before and after the debris flow. Relatively large boulders and wood blocks are concentrated in the front part of the deposit. Comparing the property closest to the camera, it can be seen that six floors are visible on 12 June while following the debris flow deposits, only three storeys can be seen.

Fig. 9 Debris flows inundated old Beichuan city. Photograph taken September 24, 2008

Conclusions

From observations and the data collected following the debris flow events on 24 September, 2008, the following conclusions can be drawn:

(1) The heavy rainfall on 24 September 2008 triggered 72 debris flows in Beichuan County, resulting in 42 deaths and serious damage to roads as well as threatening the relocation areas allocated for the earthquake-stricken people.
(2) The Wenchuan Earthquake triggered abundant rock falls and landslides, which provided a large amount of loose material which could be moved in debris flows.
(3) High rainfall intensity in combination with an abundant antecedent accumulated precipitation contributed to the occurrence of the debris flows following the earthquake. The comparison between pre-earthquake and post-earthquake critical values for precipitation and rainfall intensity which would cause debris flows indicates that the strong earthquake has modified the conditions. After the Wenchuan Earthquake, the threshold value for accumulated rainfall was reduced by 15–22% while the critical value for the hourly rainfall intensity was reduced by 25–32% compared with the published 2003 values.
(4) Lithology is an important factor influencing the occurrence and distribution of debris flows, with the Silurian slates and phyllites being particularly prone to such movement. During tectonic folding and faulting, these rocks develop interbed shears and other fractures which tend to weather preferentially. The clay minerals released by this weathering facilitate the movement of the flow and the transportation of large rock blocks. The proximity of active faults

Fig. 10 Characteristics of the deposits due to the debris flow in Beichuan City (*the left photograph* was taken on 12 June, 2008; *the right photograph* was taken on 24 September, 2008)

and major rivers also has an influence on the spatial distribution of debris flows.

(5) Two stages are involved in the initiation of debris flows. The first stage is the shallow movement towards the drainage channels and the second stage is the flushing out of the loose debris (sometimes referred to as the "fire hose effect". Loose materials forming dams in the gully may temporarily block the mass movement; when these are breached there is an instant increase in the flow discharge. As loose material in the debris flow source areas is especially abundant after an earthquake, the speed, volume and distance may be much higher than would be expected from a relatively small drainage area. As a consequence, it is essential that particular attention is given to the added risk to the infrastructure, residential areas, roads, etc. after the occurrence of a strong earthquake.

(6) The occurrence of debris flows triggered by the heavy rainfall of 24 September indicates that the Wenchuan Earthquake areas are now particularly susceptible to debris flows which are likely to occur frequently within the next 5–10 years. As a consequence, it is necessary to reinforce the debris flow risk management of cities and towns in the elongate zone so heavily disturbed by the Wenchuan Earthquake. Monitoring and early warning systems should be installed in the potentially high risk areas and engineering measures should be taken to reduce the occurrence of and damage caused by debris flows.

Acknowledgments Funding was provided by 973 Program (2008CB425801) and the National Foundation for Natural Science of China (40772206). We thank Niek Rengers for his comments and suggestions on earlier versions of the manuscript.

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