2021

Investigation of 20 August 2019 Catastrophic Debris Flows Triggered by Extreme Rainstorms Near Epicentre of Wenchuan Earthquake

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Recommended Citation

Peng, D.,Zhang, L.,Wong, H.,Fan, F.,& Zhang, S. (2021). Investigation of 20 August 2019 Catastrophic Debris Flows Triggered by Extreme Rainstorms Near Epicentre of Wenchuan Earthquake. *5th World Landslide Forum*. http://dx.doi.org/https://doi.org/10.1007/978-3-030-60319-9_8

5th World Landslide Forum
Nov 2021Tokyo
https://wlf5.iplhq.org/

Investigation of 20 August 2019 Catastrophic Debris Flows Triggered by Extreme Rainstorms Near Epicentre of Wenchuan Earthquake

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Abstract

A strong earthquake could trigger a large number of co-seismic landslides and induce large amount of loose materials on steep slopes and in the gullies. Under strong rainfall conditions, these loose materials could induce devastating debris flows, which will endanger the resettled population and destroy the re-built infrastructures. From 19 to 20 August 2019, fourteen debris flows were triggered by extreme rainstorms near the epicentre of the Wenchuan Earthquake. Among the fourteen incidents, three of them produced debris flow dams, which changed the course of the Minjiang River and resulted in flooding at different parts of the reconstructed Miansi town. In addition, sixteen casualties, twenty two missing persons, and destruction of four main roads were reported. In this paper, one typical catchment, named as "Dengxi gully", near the epicentre of the Wenchuan earthquake (Sichuan Province, China) was chosen as a case study for remote sensing analysis, field investigation of landslide evolution and debris flow development before and after the catastrophic events. The debris flow in the study area was initiated in four stages: (a) generation of a large amount of loose materials from the Wenchuan Earthquake; (b) run-off erosion from co-seismic landslide material on hilly slopes and repeated mobilizations in steep channels over the years; (c) development of high intensity localised rainfall events; (d) wash out of accumulated materials in gully by the flood. The study of "8.20 debris flows" can provide a benchmark for analysis of long-term evolution of debris flows in order to identify potential continuing hazards in the earthquake-affected areas and make proper engineering decisions.

Keywords

Debris flows • Extreme rainstorms • Epicentre of earthquake • Wenchuan

Introduction

Debris flow is considered to be a type of movement within the landslide classification which commonly induce serious disaster in mountain areas. Due to its great velocity with long run-out distance and high capacity, large and heavy objects such as tree and rock (Wasowski et al. 2011; Hungr et al. 2014; Zhang et al. 2014; Fan et al. 2018b) are transported. Debris flows can have very to extremely rapid flows of saturated debris in deep channels such as a gully or a ravine and they are major hazards worldwide causing considerable damages to structures and infrastructures (Fan et al. 2018a). Debris flow is usually initiated by the erosion and entrainment of hill slopes and channel materials by overland flow (Domènech et al. 2019; Bezak et al. 2020), or sometimes, triggered by the outbursts of reservoirs built in the channels (Coe et al. 1997). Many geomorphological papers view the role of debris flows like a very active agent of landscape evolution and sediment transfer in mountain areas (Fan et al. 2019a; Yunus et al. 2020).

In the evening of August 19 to the morning of August 20, heavy rainfall occurred in the Wenchuan County and

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V. Vilímek et al. (eds.), *Understanding and Reducing Landslide Disaster Risk*,
ICL Contribution to Landslide Disaster Risk Reduction,
https://doi.org/10.1007/978-3-030-60319-9_8

Wolong Special Administrative Region of Aba Prefecture in China. This rainstorm resulted in mountain torrents and debris flow disasters affecting eleven towns in the Wenchuan County at different levels. Among the eleven towns, those located at Shuimo, Sanjiang, Yingxiu, Mianfan and Gengda in the Wenchuan County have suffered from disastrous damages. For the Wenchuan County, the main disasters induced by the heavy rainfall were mainly mountain torrents and debris flows. There were fewer landslide disasters (Fig. 1). According to field investigations and news reports, fourteen debris flows were induced on 20 August 2019, in the Coutou gully, Banzi gully, Dengxigou, Chediguan gully, Xiazhuang gully, Qipan Gully, Xingfu gully, Longtan gully, Mushan gully, Shuimo town (Fig. 1). During this period of time, tens of thousands of tourists were stranded by the debris flows. It also caused sixteen casualties, twenty two missing persons and destruction of four main roads. The direct economic losses was estimated to be 3.6 billion yuan. Under the influence of debris flow deposits, the whole riverbed had been uplifted, which directly caused river water blocking and diversion, and brought many adverse effects to post-disaster reconstruction, road restoration, industrial and agricultural recovery of the study area. According to previous literatures (Fan et al. 2019b), the Dengxi gully did not occur large-scale debris flow with more material sources and strong activity areas after Wenchuan earthquake.

The aims of this paper are to: (1) investigate the typical debris flow near the epicentre of the Wenchuan earthquake on 20 August 2019, and (2) analyse the formation condition and disaster characteristics of the rainfall-induced debris flows.

Regional Setting

The study area is the Dengxi ravine, with an area of 44 km^2, located in the town of Miansi. It is on the right bank of the Mingjiang River and 20 km away from the capital of Wenchuan County, Sichuan Province, China (Fig. 1a). It is 40 km away from the north of the Wenchuan earthquake epicentre (Fig. 1b). The relative elevation of the river valley is greater than 1100–1200 m, and the area in the vicinity of the river has typical alpine and canyon landscapes formed by strong erosion and down cutting (Fan et al. 2018a). The upslope elevation of the Dengxi gully is more than 4500 m asl, and the outlet of the valley is 1300 m asl.

The bedrock of the study area is primarily highly weathered Quaternary Jingningian Period intrusive granite, with intensely developed joints. The cover soil is thin and mainly composed of Quaternary glacial deposits, diluvium, colluvium and alluvium. Consequently, extensive collapses occurred during the Wenchuan earthquake and a tremendous amount of loose materials was retained on the steep hillslope and in the gullies, which developed massive co-seismic landslides (Shen et al. 2017).

The ravine is located within the Mianchi-Wenchuan zone of rainfall with an average annual rainfall of 719.7 mm between 1960 and 2015. The rainfall variability is large in different years. Most of the yearly rainfall occurs during the wet season from May to September. The groundwater is mainly magmatic rock fissure water with shallowly restored, where the supply is almost equal to the discharge (Zhang et al. 2012).

Methods

A GIS analysis platform is adopted to interpret satellite images over the study area. Three sets of Satellite images with a resolution of 1 m taken on 27 December 2014, 10 m taken on 25 April 2019, and 1 m taken on 29 October 2019 were collected to map the locations of rainfall-induced landslides. These were also used to analyse the features of the debris flow source areas, the flow paths and flow deposits in the study region to provide data about the amount of loose material available for the initiation of debris flows. A digital elevation model (DEM) with a spatial resolution of 10 m was used to generate slope angles and elevations.

Field investigations were undertaken to confirm visual interpretation based on the remote sensing data. The average deposit thickness, erosion and entrainment depth of the ravine was measured using a laser range finder. Material sources of debris flows are investigated. A large number of high-resolution pictures of coarse deposition materials were taken for grid-by-number analysis and runout characteristics analysis.

The distribution of 24-h rainfall in the Wenchuan County is collected from Aba Prefecture Meteorological Bureau. Hourly rainfall records from the meteorological station near the town of Mozi and the Wenchuan County were used to determine the rainfall intensity/duration for each debris flow-producing rainstorm.

Disaster Characteristics and Formation Condition

Disaster Characteristics

Material sources findings and landslide inventory mapping are an essential first step in the analysis of debris flows and characteristics development in the study area. The evolution of loose materials in the present study can be quantified using satellite images (Fig. 2a–c) (Fan et al. 2019a). In the rainy season, hillslope deposits reactivate, where a considerable portion of these hillslope deposits either slid downhill

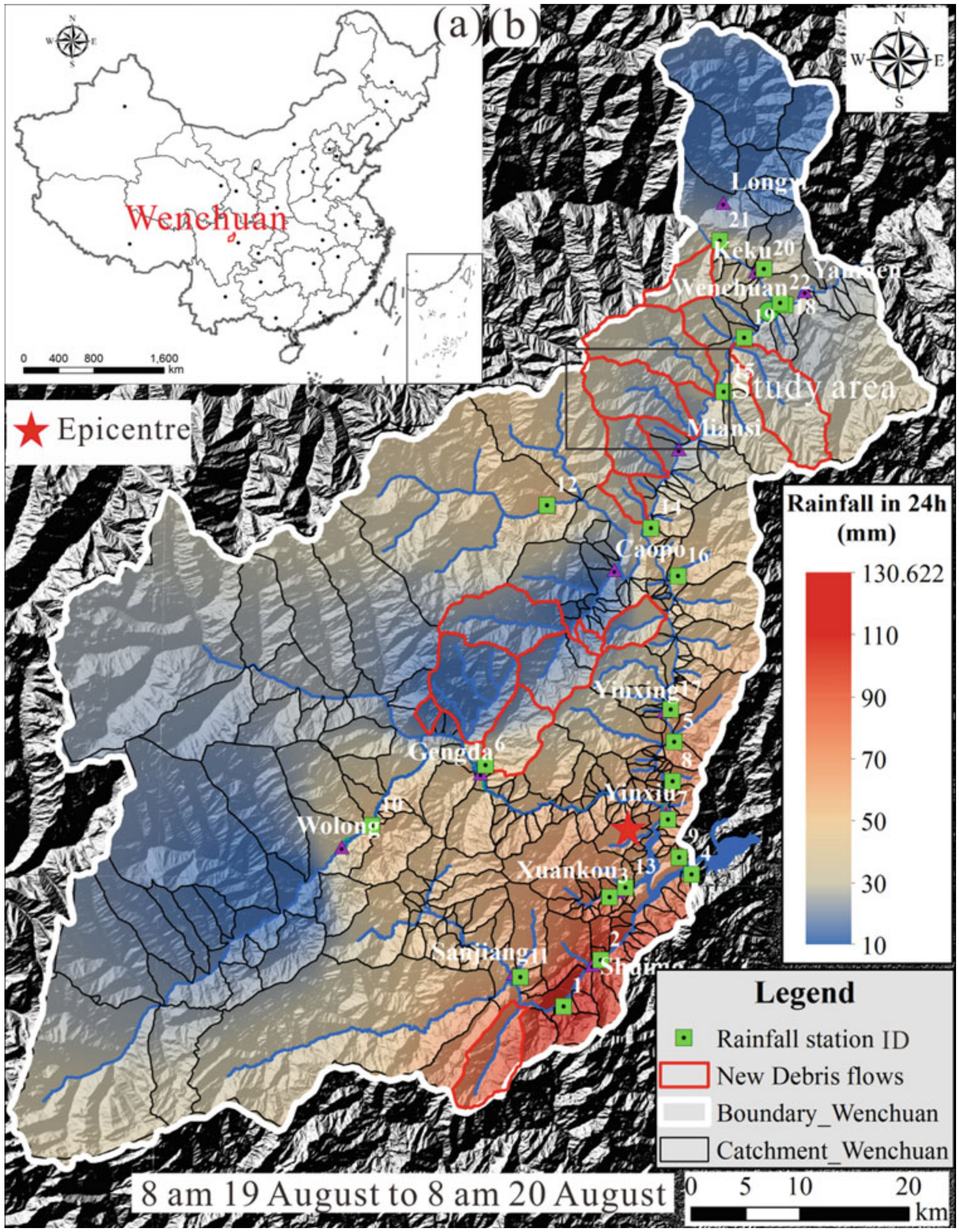

Fig. 1 Location of study area. **a** Location of Wenchuan in China; **b** Distribution of debris flows and rainfall at 24 h from 8 am 19 August to 8 am 20 August occurred on 20 August 2019 in Wenchuan County and location of earthquake epicentre and rainfall stations

or washed into existing channels by surface runoff, and turn into channel deposits (Zhang and Zhang 2017). According to the material source, the area of the Dengxi gully is divided into the source area and flow-deposits area (Fig. 2d).

Interpretation of the remote sensing images and field observations in the Dengxi catchments of Miansi town showed: (1) according to remote sensing imaging taken on 27 December 2014, six years after the Wenchuan earthquake, the total volume of the 125 hillslope deposits shortly after the Wenchuan earthquake was 18.08×10^6 m^3 and the total volume of the channel deposits was 9.04×10^6 m^3 (Table 1); (2) according to field investigations and remote sensing imaging taken on 25 April 2019, before the “8.20” debris flows (Figs. 3 and 4), the number of fresh landslides was 24. The volume of fresh landslides and original landslides were 2.02×10^6 and 11.75×10^6 m^3, respectively. The total volume of the channel deposits was 12.76×10^6 m^3 (Table 2); (3) widespread shallow slope sliding were present on high elevation and steep slopes in areas with granitic bedrock. A total of 22 fresh landslides of various sizes were mapped with a total landslide area of 1.163 km^2 and a total volume of 2.59×10^6 m^3, which were much smaller than those occurred between 2008 and 2014 (Table 3). Moreover, an abundance of loose material accumulated in the channel after 20 August 2019 rainstorms (Fig. 2c).

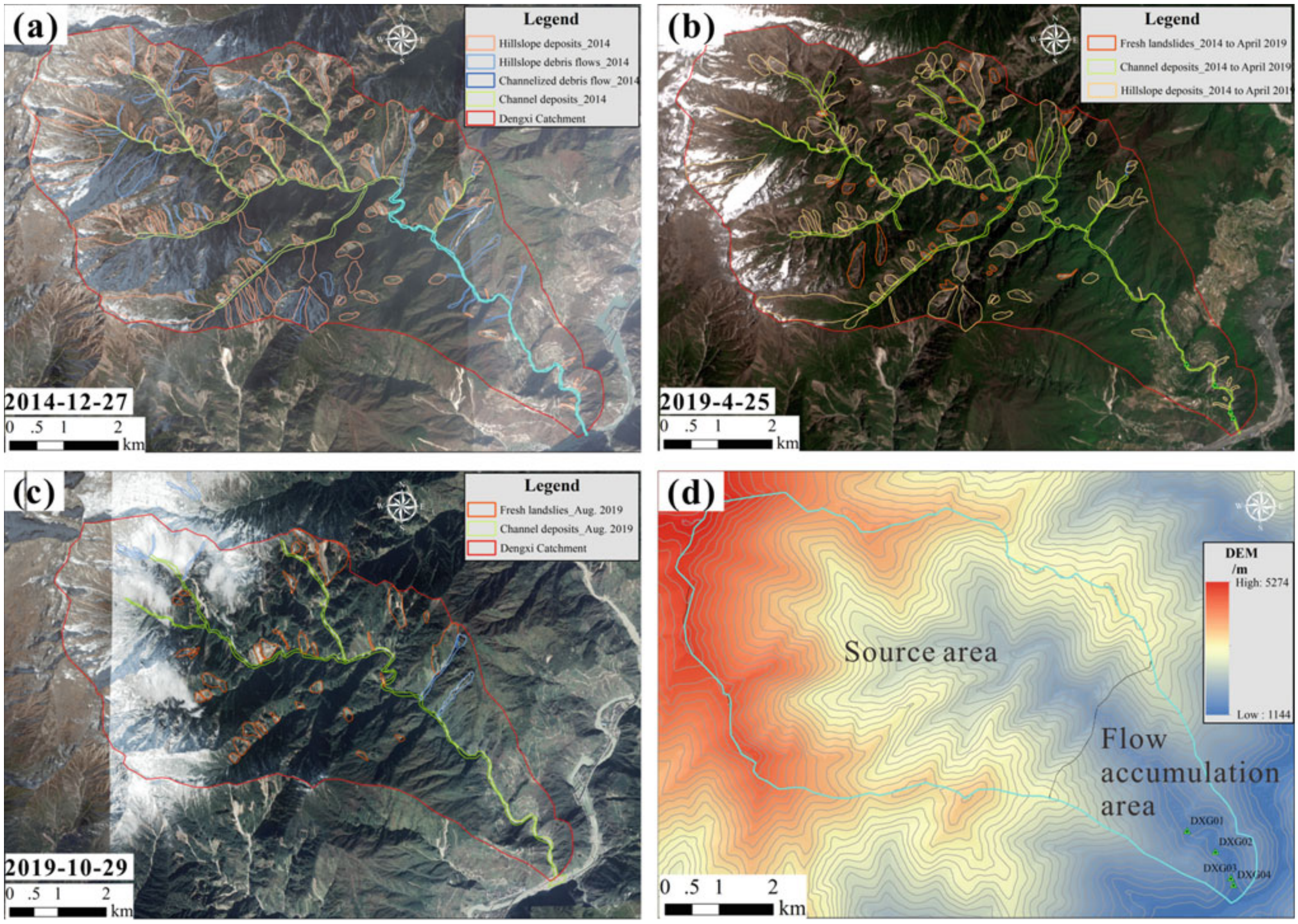

Fig. 2 Remote sensing imaging from three different data shows the landslide and debris flow development in the Dengxi gully catchment. **a** Source materials after the Wenchuan Earthquake (taken on 12 December 2014); **b** Aerial photograph before the event (taken on 25 April 2019); **c** Aerial photograph after the event (taken on 27 September 2019); **d** The topographic map of the Dengxi debris flow and location of field test

Table 1 Landslide materials identified through remote sensing imaging taken on 27 December 2014, six years after the Wenchuan earthquake

Type	Number	Total area (km^2)	Volume (10^6 m^3)
Hillslope deposits	125	8.610	18.08
Channel deposits A	8	0.862	8.61
Channel deposits B	1	0.216	0.43
Total	–	9.688	27.12

The co-seismic landslide materials were from run-off erosion from hillslopes and repeated mobilisations in steep channels between 2008 and 2019. The accumulated material in the gully was washed out by the flood. In rainfall conditions, the co-seismic landslide collapsed and deposits were washed away. From the initiation form, the debris flow is channel-activated. Through post-earthquake field experiment on sites, the mechanism of turning accumulations from floods to debris flows in channels at regions with strong earthquake occurrence are illustrated (see Fig. 3).

Formation Conditions

At 8:30 a.m. on 20 August 2019, Wenchuan meteorological station issued the rainfall report for the past 24 h from 8:00 a.m. on August 19 to 8:00 a.m. on August 20, one station had heavy rainfall, 130.7 mm in Baishi Village, Shuimo town; 16 stations had heavy rainfall. From 0:00 a.m. to 7:00 a.m. on 20 August 2019, the maximum accumulated rainfall in Wenchuan county was 65 mm (Fig. 1). At 0:00 a.m. to 3:00 a.m. on 20 August 2019, the precipitation in Baishi

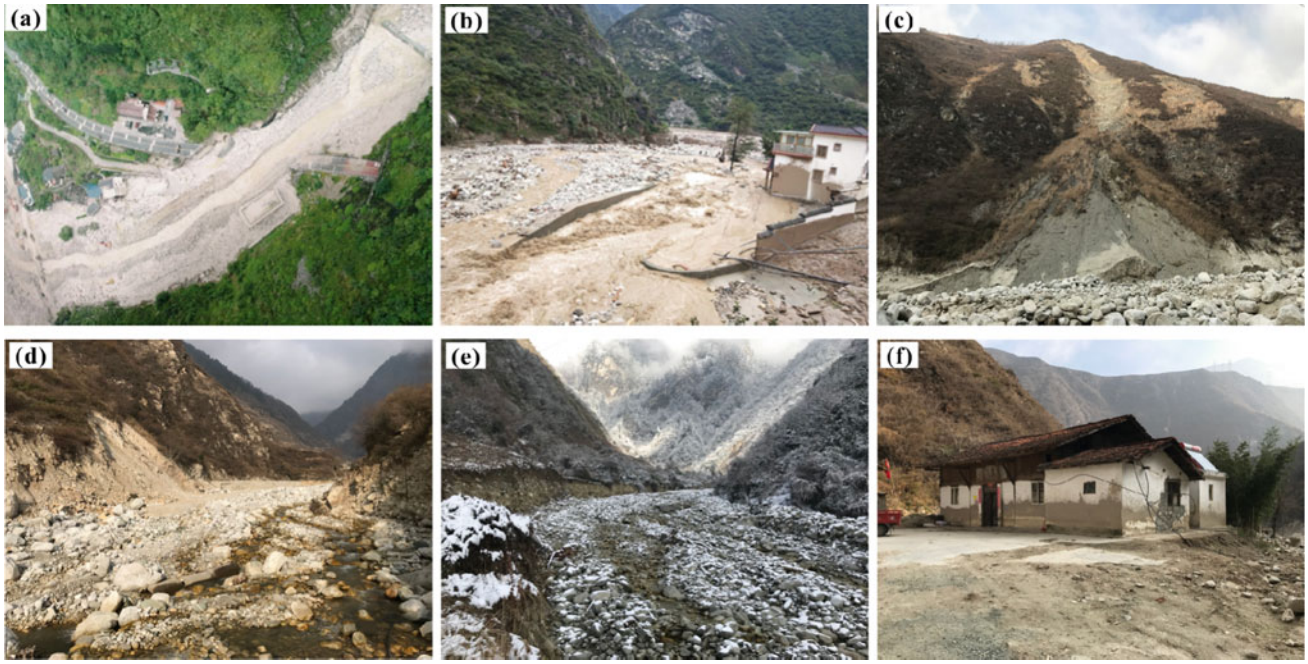

Fig. 3 Field investigation photos. **a** The Dengxi gully debris flow (taken on 20 August 2019) (credit: Sichuan Highway Planning, Survey, Design and Research Institute Ltd); **b** Outlet of the Dengxi gully and the blocked Mingjiang River induced by debris flows (taken on 20 August 2019); **c** Fresh landslide (taken on 24 December 2019); **d** River bank erosion the downstream of a gully (taken on 24 December 2019); **e** Channel erosion in the upstream of a gully (taken on 22 December 2019); **f** Broken house 20 m above river course (taken on 24 December 2019)

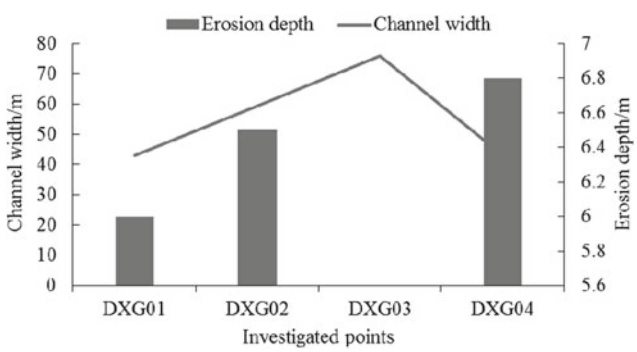

Fig. 4 Erosion depth at different investigated sites (for location of points see Fig. 2d)

Village, Shuimo Town, Wenchuan County had reached 76.8 mm (Fig. 5). The nearest distance between the rainfall station and debris flow is 5 km, named Banzigou rainfall station and ID 15 with a rainfall value of 55.2 in 24 h.

According to the previous research reports (Zhou and Tang 2014; Fan et al. 2018a, 2019b), the ID threshold graph is associated with 85 debris flows events in the Wenchuan earthquake-stricken area (Fig. 6). It can be seen from Fig. 6 that the rainfall intensity inducing this event is far higher than the debris flow threshold ($I = 18.6D^{-0.87}$), which is located in the debris flow occurrence area of the model), nevertheless, the rainfall intensity is slightly smaller than the ID threshold

Table 2 Landslide materials identified through field investigations and remote sensing imaging taken on 25 April 2019, before the "8.20" debris flows

Type	Number	Total area (km^2)	Volume (10^6 m^3)
Fresh landslides	24	0.869	2.02
Original landslides	98	5.043	11.75
Channel deposits A	19	1.198	8.39
Channel deposits B	1	0.324	4.37
Debris flow runout material	*	*	*
Total	–	7.434	26.53

Table 3 Landslide materials identified through field investigations and remote sensing imaging taken on 29 October 2019, after the "8.20" debris flows

Type	Number	Total area (km^2)	Volume (10^6 m^3)
Fresh landslides	22	1.163	2.59
Original landslides	83	4.264	9.51
Channel deposits A	17	1.663	11.64
Channel deposits B	1	0.279	2.79
Debris flow runout material	1	0.058	0.87
Total	–	7.427	27.40

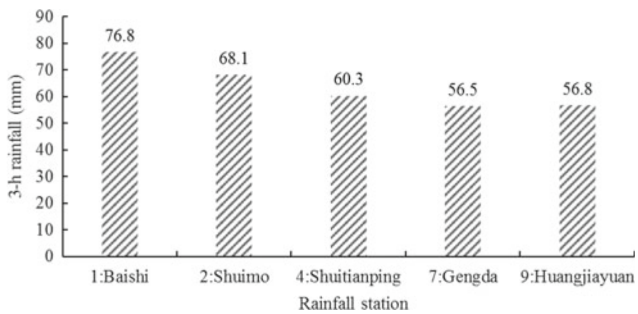

Fig. 5 3-hr rainfall before debris flow occurred in Wenchuan County meausured by five rain gauges

($I = 66.36D^{-0.79}$) proposed by Zhou and Tang (2014). In 2010, the cumulative rainfall of the "8.13" mass debris flow was 62.9 mm. The critical hourly rainfall intensity is 32.2 mm. The average hourly rainfall is 6.99 mm. The accumulated rainfall of this debris flow is 87.5 mm. The critical hourly rainfall intensity is 24.2 mm (SKLGP 2019).

According to local residents, there were many heavy rainfalls in the early stages of this event during the period from June to August. The early rainfalls raised the moisture content of the loose materials in the relevant areas and made it close to the saturated state. On this basis, heavy early rainfalls directly caused the occurrence of debris flow.

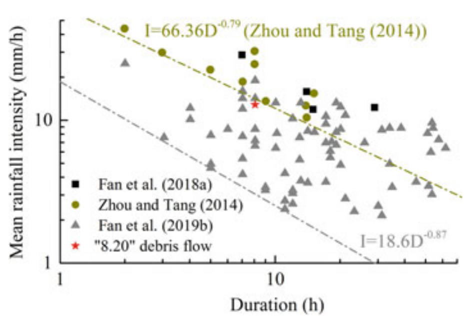

Fig. 6 Compasion in rainfall intensities between the 8.20 debris flow and other debris flow events in the Wenchuan earthquake area

Conclusion and Suggestion

The 8.20 debris flows showed the following main features:

(1) A total of fourteen catastrophic debris flows occurred in the same period from 19 to 20 August 2019 in the earthquake zone and destroyed local urban housing and infrastructure. According to typical Dengxi debris flow, a total of twenty two fresh landslides of various sizes were mapped with a total landslide area of 1.163 km^2 and a total volume of 2.59×10^6 m^3, which were much smaller than those occurred between 2008 and 2014.

(2) Co-seismic landslide materials were run-off erosion from hillslopes and repeated mobilisations in steep channels during 2008–2019. From the initiation, most of the debris flows are channel-activated. Moreover, an abundance of loose material accumulated in the channel after 20 August 2019 rainstorms.

(3) The critical hourly rainfall intensity of "8.20" debris flows is 24.2 mm, which is much smaller than "8.13" mass debris in 2010 with a value of 32.2 mm. the rainfall intensity inducing this event is far higher than the debris flow threshold ($I = 18.6D^{-0.87}$).

(4) At present, rainfall stations are mostly located in urban areas or gullies, meaning it is impossible to truly reflect the rainfall in mountainous areas. In order to achieve timely and accurate meteorological warnings, it is necessary to increase the arrangement of rainfall stations in mountain areas. At the same time, it is necessary to carry out real-time meteorological early-warning of geological disasters.

Acknowledgements The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administration Region, China (No. UGC/FDS25/E11/17).

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