Characteristics of debris flows recorded in the Shenmu area of central Taiwan between 2004 and 2021

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Abstract. The data of debris-flow events between 2004 and 2021 in the Shenmu area Taiwan were presented and discussed in this paper. Total of 20 times of debris-flow events were observed in 18 years. Debris flows in the Shenmu area usually occurred in the Aiyuzi Stream during the rainy season, May to September, and about once per year between 2009 and 2017.

10 The rainfall thresholds from the observed data were proposed as I_{max}, R_{24}, and R_t of 9, 23, and 67.8 mm, respectively. The rainfall data also implied that the trend curves of intensity-duration (I-D) were different before and after 2009, which due to the extreme rainfall event, Typhoon Morakot in 2009. The I-D curve obtained from the post-2009 data was proposed as the baseline of debris-flow I-D relationship in the study area. The extreme rainfall event also influenced the flow speed (average 14.3 m/sec before 2010 and 4.46 m/sec after 2010) and the occurrence frequency of debris flow (1.83 times per year before

15 2009 and 0.75 times after 2009). Recent findings indicated that the ground surface vibrational signals of debris flows were potentially useful for debris-flow early warning in terms of accumulated energy, and the characteristic frequency of debris flow in the study area was below 40 Hz. The dataset and the rainfall thresholds in this study permits the comparison with other monitored catchments and is advantageous to the global debris-flow dataset.

1 Introduction

20 The debris flows have become a common disaster in Taiwan in the past two decades (Huang et al., 2013; Huang et al., 2016; Huang et al., 2017). To understand the characteristics, especially the triggering factors, of debris flows, devices and monitoring stations had been installed and established at the areas prone to the debris flows. Given the environmental conditions at the mountain areas in Taiwan, it is more desired to deploy the monitoring instrumentation at the potentially streams, especially at the upper sections of them. But it usually encounters problems, like the power supply and

25 communication interruption, when trying to install sensors at distant mountain areas. It is difficult for debris-flow research to obtain the full-scale experimental data that can represent the in-situ conditions. Instead, the observation data from these monitoring stations in Taiwan provides valuable information for debris-flow characteristic studies (Huang et al., 2013; Hürlimann et al, 2019).

30 In Taiwan, the debris flow monitoring system had been built by Taiwan government, the Soil and Water Conservation Bureau (SWCB), by designing and applying different types of monitoring stations (Wang et al., 2011; Huang et al., 2013). Permanent and automatic monitoring devices were installed on sites to collect data about debris flows. In a potential area, the debris flows usually occur in a low frequency and are considered as uncommon events when comparing to other natural hazards, e.g., the heavy rainfalls. But at some locations, the occurrence frequency of debris flow is higher than other

35 locations (Marchi et al, 2021). The Shenmu area in Taiwan is the one where debris flows had occurred more often than other locations, and almost once every year in the past 18 years (2004 to 2021).

The studies about debris-flow characteristics started from Japan and China (Marchi et al., 2021). A review by Hürlimann et al. (2019) has addressed the collected information from nine monitoring sties and discussed the achievements and the types

40 of monitoring systems. The monitoring site conditions, local features of Shenmu area, and debris flow events were used as an important monitoring case in many studies (Huang et al, 2013; Huang et al., 2016; Lee at al, 2017; Wei et al, 2018; Hürlimann et al., 2019). Therefore, the available data collected from the Shenmu Debris Flow Monitoring Station during the period of 2004 to 2021 were used for this work. It should be noted that there were no debris flows occurred after 2017, and the tables and figures in this study present the results of recorded debris-flow events.

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This study focuses on the rainfall data obtained from recorded debris-flow events in the Shenmu area, and the potential indicators or factors that could be used for debris-flow early warning. The purpose of this research includes the discussion of rainfall characteristics, in terms of rainfall intensity (I), duration (D), and accumulated rainfall (R), and the recent findings about the impacts of extreme weathers, variation of soil moisture, and ground surface vibrational signals of debris flows. A

50 dataset of debris flows recorded in the Shenmu area between 2004 to 2021 is presented in this study. The event data were collected from various available sources. The data prepared in this study include dates of debris flow events, time of debris flow occurrence (whenever available), the triggering rainfalls (rainfall intensity, accumulated rainfall, and duration), and a brief review of soil moisture and vibrational signal graphs (for some events).

55 Early research reveals the potential I-D curves from the global event data (Caine, 1980; Guzzetti et al., 2008). These curves can be used as a baseline, the minimum rainfall thresholds, for debris flows by considering the rainfall intensity and duration of a given area. The dataset prepared for this study was compared with the global I-D curves. The rainfall data obtained and used in this study are from the Shenmu Village rainfall station (23°31.9645'N, 120°50.62'E) maintained by the Central Weather Bureau (CWB) and from the Shenmu debris flow monitoring station (23°31.6938'N, 120°51.3927'E) maintained by

60 the Soil and Water Conservation Bureau (SWCB). These data were collected from the instrumentation installed in the study area and were used to describe the important characteristics of debris-flow *I-D* curves in the Shenmu area and compare them with the global debris-flow database. Analysis of debris-flow rainfall thresholds is also discussed from different approaches. The change of rainfall thresholds used for debris flow early warnings by the local government, and the characteristics of

maximum hourly rainfall, effective accumulated rainfall, and rainfall intensity-duration (I-D) of debris flow events in Shenmu are described and compared here.

Other monitoring data that could be potentially useful for the debris-flow early warning are also discussed in this study, including the soil moisture and ground surface vibrational signals. The impacts of extreme weathers, the Typhoon Morakot in 2009 in this study, are also analysed and compared using the flow speeds, estimated from the video cameras available online for several events, and the occurrence frequency of debris flow. Conclusions are made to highlight the contributions of this work at the end.

2 Study area and monitoring system

The study area is at the Shenmu Village, the location of three highly potential debris-flow torrents. The three debris-flow torrents, Aiyuzi Stream (DF226), Huosa Stream (DF227), and Chusuei Stream (DF199), join into Heshe Stream around the entrance of the village and the entire basic area is about 72.2 km^2 (Huang et al., 2013; Hürlimann et al., 2019). These streams belong to the watershed of Chen-Yu-Lan River in the central part of Taiwan. The terrain and landslide areas of streams and the basic info are shown in Fig. 1 and Table 1, respectively. In the study area, the debris flows commonly occurs at the Aiyuzi Stream due to its shorter length and larger landslide areas located in its upstream since Typhoon Morakot in 2009 (Huang et al., 2013). The slope angles in the upper stream areas of the debris flows are between 30° and 50° and especially the average slope in the Aiyuzi Stream watershed is about 39.3° (Wei et al., 2018), based on the fact that over 75% of the Aiyuzi Stream watershed area has slopes greater than 32 ° (Huang et al, 2007). A great percentage of the watershed was affected by significant landslides (Fig. 1). With the observation from the sites and from the videos of debris flows in Aiyuzi Stream, the debris flows in the Shenmu area are classified as granular flows. In many field investigations, boulders are often 1-2 m in diameter, and boulders with a diameter of more than 4-5 m can be seen in the accumulation of debris along streams.

Among the three debris-flow torrents in the study area, the Aiyuzi Stream is the focus of this study. Aiyuzi Stream is the stream in the upper stream of the Chen-Yu-Lan River catchment area. The total length of this stream is about 3.731 km, the watershed area is 405.02 hectares, and the topographical elevation is between 1,200 to 2,500 m. According to Chen et al. (2012), the landslide ratio (landslide projected area/total catchment area) of this catchment area is about 12% ~ 34.2% (during 1996 to 2009), and there is a trend of increasing year by year.

Based on the rainfall data (from June 1987 to February 2017) from the Shenmu Village Station of the Taiwan's Central Weather Bureau (CWB), the average annual rainfall in the Aiyuzi Stream watershed area is about 3,054.7 mm, of which the average total accumulated rainfall in the rainy season (from April to October each year) is 2,644.5 mm (Wei et al., 2018).

Because of the abundant rains and landslide-induced debris at the upstream, with steep slopes (about 39.3º in average) at the region, debris flows often occurred in the Aiyuzi Stream during heavy rains and typhoons.

Since the ChiChi Earthquake in 1999, the environmental conditions in the mountain areas at the central Taiwan had become vulnerable to heavy rainfalls and typhoons. Rainfall-induced shallow landslides occurred more often than ever, resulting in abundant soil, rocks, and debris accumulated in the streams. Debris flow disasters in 2000 had caused general public's attention since then. To protect the people living at the debris-flow prone areas, the Taiwan government started to establish the debris flow monitoring stations in 2002 and later had developed mobile monitoring stations and portable units to meet different needs. More and more observation data were obtained as the debris flow almost occurred annually from 2004 to 2009. In the study area, the debris flow occurred in 2004 was the first officially observed event with available monitoring data.

The Shenmu debris flow monitoring station was established in 2002 and is installed at 1,187 m asl at the confluence of three potential debris flow torrents (Fig. 2). Different sensors are installed on the site of the monitoring station, to observe and collect data for debris-flow warning and disaster repsonses. The monitoring options installed in the Shenmu aera includes direct and indirect measures for debris flows. The direct option refers to the devices that can capture, issuing warnings, and measure the status of debris flow when occurred. These devices used in Shenmu are wire sensors and geophones. The wire sensor simply issues a signal "broken" when a debris flow passing through and breaking the wire over the channel. The geophone detects the ground surface vibration, and the debris flow is recognized when a peak from the vibration records is evident (Huang et al, 2016; Huang et al, 2007; Huang and Chen, 2022). The signals from the wire sensors and geophones indicate the occurrence of debris flow and the timing when a debris flow is running through the locations of these instruments. Other monitoring options, including rain gauges, soil moisture sensors, CCD camera, and flow speed meter are used as supporting devices to help confirm the occurrence of debris flows. False alarms are inevitable during the debris flow monitoring and cross-check is necessary and important.

Among the monitoring data, rainfall is the most used and important information for debris flow warning and analysis. The signal of ground surface vibration is another considerably useful factor for indicating the occurrence of debris flow (Huang et al., 2017; Wei et al, 2018). The change of water content at the underground soil is detected by the soil moisture sensors, and the data are useful for potential estimation of shallow landslides. Figure 2 shows the detailed layout of the Shenmu monitoring station, including rain gauges (TK-1, Takeda Keiki Co.), geophones (GS-20 DX, Geospace), wire sensors, soil moisture sensors, and video cameras (PTZ camera). Similar to the geophones, two broadband seismic sensors (Yardbird DF-2, Academia Sinica Taiwan) are also installed along the Aiyuzi Stream (Huang et al., 2017).

The Typhoon Herb in 1996 had caused debris flows in the channel of Chusuei Stream. Frequent debris flows occurred in the Shenmu area after 1996. In July 2001, with the heavy rainfalls, Typhoon Toraji had caused sever casualties and property loss to the people in the Shenmu area. Therefore, SWCB started to build the debris flow monitoring station in Shenmu since 2002. From that time, the local monitoring system has operated to continuously collect the observation data of debris flows in the study area. Table 2 shows the observed event list of Shenmu area.

The events in Table 2 implies that the debris flows occurred almost every year during 2009 to 2014, total of 9 debris-flow events in 6 years. Compared to the period between 2004 and 2008, the debris flow occurred 10 times in 5 years. It is noted that, after the extreme rainfall event of Typhoon Morakot in 2009 (from Aug. 7 to Aug. 9, the accumulated rainfall of 1,872 mm in the Shenmu area), all the observed debris flows occurred at the Aiyuzi Stream. The possible explanation to this condition is the shorter length and relatively more landslides at the upper-stream areas of Aiyuzi Stream after 2009, when compared with the other two streams (Table 1). With abundant debris source at the upstream sections and heavy rainfalls, these factors contribute to the frequent occurrence of debris flow in the Aiyuzi Stream. After 2014 until 2021, there is only one record of debris flow in Shenmu (Table 2). It seems that the occurrence frequency has reduced from once per year during 2009 to 2014, to very few in the past 7 years (from 2015 to 2021). From Table 2, the average frequency of occurrence is about 1.11 times per year during the period from 2004 to 2021 (20 debris-flow events in 18 years). Comparatively, the average frequency of debris flow occurrence is 1.83 times per year from 2004 to 2009 (11 debris-flow events in 6 years) and is 0.75 times per year after 2009 (9 debris-flow events in 12 years).

The main cause of the frequent debris flow in Shenmu was partially from the abundant debris source because of the landslides. The landslide increments in Table 3 were estimated based on the satellite image processing. When considering the landslide areas at the mid-to-upper stream sections, it has been noticed that the variation of landslide increments was quite different before and after 2009. In August 2009, Typhoon Morakot had caused severe landslides at the study areas and Fig. 3 shows the abrupt jump of landslide increments in 2010. The increment ratio of landslide at Aiyuzi Stream was higher than that at the other two streams. Given the conditions of smaller catchment area and higher landslide increment ratio, debris flows were expected to be easier to occur at the Aiyuzi Stream because of its abundant debris source at the upstream sections. The number of post-2009 debris flow events confirmed the inference about the frequent debris flows at the Aiyuzi Stream.

As stated above, from 1999 to 2009, the environment of the study area had tended to reach a balance after the ChiChi Earthquake at central Taiwan. The landslide increment had eased during this period. After 2009, the environmental conditions had significantly changed due to the Typhoon Morakot in 2009. More landslide areas had resulted in debris flows every year during 2009 to 2014. Until now, the Shenmu is still under the threat of debris flow during typhoons and heavy rainfalls.

According to the available satellite images from 2009 and 2014 to 2017, the mid- and downstream section widths of the three streams had changed marginally (Table 4). The widest downstream channel is at the Huosa Stream, about 121 m, and the width of Heshe Stream, the stream of confluence, is about 132 m since 2009. It is noted that the debris flows didn't change the stream channel width too much but had accumulated abundant sediment and debris during and after the debris flows (Fig. 5).

3 Characteristics of debris flow at the study area

3.1 Rainfall Thresholds- RTI

The current rainfall warning threshold of Shenmu area was developed by Jan and Lee (2004) and an index, Rainfall Triggering Index (RTI), which is the product of hourly rainfall (I) and effective accumulated rainfall (R_t) was used to determine the rainfall level of debris flow warning. For a given rainfall event, the value R_t reflects the influence of antecedent rains of a 7-day period and is calculated following Eq. (1). Fig. 6 illustrates the definitions of a rainfall event. The Eq. (1) shows the expression of R_t, where R_o is the current daily rainfall of an event, R_i is the daily rainfall of previous i-th day before current event and α is the weighting factor applied to antecedent daily rainfall. The weighting factor changed normally between 0.5 to 0.8 based on the rainfall patterns and α of 0.7 is applied to the current debris flow early warning in Taiwan.

$$R_t = R_0 + \sum_{i=1}^{7} \alpha^i \times R_i \tag{1}$$

The value of R_t is divided into nine levels, from 200 mm to 600 mm with intervals of 50 mm, to represent the rainfall thresholds at different locations. Based on the debris-flow case history, the rainfall threshold of the study area was 250 mm during 2000 to 2020 and is 300 mm since 2021, due to the decreasing occurrence frequency of debris flows in the area.

3.2 Rainfall Thresholds- I_{max}, R_{24}, R_t

According to Huang et al. (2013), the case history of debris flows and heavy rainfalls in the Shenmu area implies rainfall thresholds of the maximum hourly rainfall (I_{max}) of 8 mm, and the effective accumulated rainfall (R_t) of 67 mm, before 2012. By adding additional and available rainfall data, Table 5 shows the events during 2014 to 2017. In addition to the effective accumulated rainfall, the accumulated rainfall of 24 hour (R_{24}) before the occurrence of a debris flow was considered in this study. For those events that no debris flow occurred, the R_{24} was estimated by assuming the debris flow would occur at the time of I_{max} during an event. Fig. 7 and Fig. 8 show that plots of I_{max}-R_{24} and I_{max}-R_t based on the data of Huang et al. (2013)

and this study. The plots show a slightly different rainfall thresholds of I_{max} of 9 mm and R_t of 67.8 mm, and R_{24} of 23 mm as another rainfall threshold. The cases of $I_{max} \geq 9$ mm and $R_{24} \geq 23$ mm, and $I_{max} \geq 9$ mm and $R_t \geq 67.8$ mm are 33 and 32 cases, respectively, from the collected data. Among them, there are 10 debris flows, implying that the case percentage of debris flow is 30.3% and 31.3%, respectively. Another sets of rainfall thresholds are proposed as $I_{max} \geq 16.5$ mm and $R_{24} \geq 51.5$ mm, and $I_{max} \geq 16.5$ mm and $R_t \geq 75.2$ mm, which results in the debris-flow case percentages of 40.0% and 38.1%, respectively. The abovementioned approach represents the debris-flow warning margins of rainfall in terms of I_{max}, R_{24}, and R_t, as shown in the plots (the orange and red dash-lines). These numbers may be not high enough to be used for practical prediction of debris-flow occurrence. However, based on the case history, these rainfall thresholds (I_{max} and R_t), as well as the RTI threshold of 300 mm, are considered reasonable as check points for debris flow disaster monitoring in the Shenmu area.

3.3 Rainfall thresholds- I-D curve

In addition to the rainfall thresholds of RTI factor, the statistics of rainfall data obtained about the occurrence of debris flows shows additional characteristic relation of rainfall intensity (I) and duration (D). The records of rainfall data were collected from the rain gauges installed near and at the site of debris flow monitoring. The I-D relation has been studied and considered as the basis of defining rainfall thresholds for debris flows. Early research reveals the potential I-D curves from the global event data (Caine, 1980; Guzzetti et al., 2008). The I-D data of debris-flow events in Shenmu area is listed in Table 2 and the I-D curves are illustrated in the following Fig. 9 to Fig. 11.

Fig. 9 shows the intensity-duration plots of debris flows in Shenmu. The I-D data in this figure was estimated using the whole duration of each event and were obtained from the Shenmu Village Rainfall Station of Central Weather Bureau (CWB) and Shenmu Debris Flow Monitoring Station of Soil and Water Conservation Bureau (SWCB), respectively. The regression trends of data from both stations are similar with slight difference (dash-line of CWB and dash-dot line of SWCB, in Fig. 9), due to the locations where rainfall was measured. It was also noted that the trends (the slopes of regression curve) in Fig. 9 were not in consistent with those from previous research (Caine, 1980; Guzzetti et al., 2008). All the I-D data of Shemu fall above the global minimum rainfall I-D threshold (the blue line in the figure).

Fig. 10 shows the I-D plots estimated during the period from the event start to one hour before the occurrence of debris flows. It was noted that the trends of Fig. 10 were quite different to those in Fig. 9 and were considerably in consistent with those from previous research. Most of the data in Fig. 10 are within 48-hr duration. The trend line of SWCB in Fig. 10 is highly consistent with the one (green line) of 48-hr duration from the literature (Guzzetti et al., 2008), with similar slopes. The results from Fig. 10 implies that the duration hours used for estimating the rainfall I-D of each event should be counted based on the period from the event start to one hour before the occurrence of debris flow, rather than counting on the whole

225   event durations. In addition, the rainfall data from SWCB are more reasonable in analysis since the rainfall station of SWCB is closer to the locations of debris flow occurrence than that of CWB.

Among the debris flow events in Shenmu, a catastrophic event of Typhoon Morakot in 2009 had caused extremely heavy rainfalls in the mountain areas, resulting in severe landslides, floods, and debris flows. Because of the significant impact of
230   Typhoon Morakot in 2009, the geological conditions and local environment of Shenmu had greatly changed. Different trends in the plots of rainfall data obtained before and after 2009 revealed the influence of severe weathers, as shown in Fig. 11. Both trends of post-2009 rainfall data show similar sloping as those from the literatures. Among these curves, the trend obtained from the rainfall data of SWCB station is highly in consistent with the curve of 48-hr duration from the literature. The post-2009 data regression curve of SWCB (i.e., $I = 16.01 \times D^{-0.238}$) reasonably represents the rainfall I-D of debris flows,
235   with the minimum boundary of 48-hr duration line ($I = 7.01 \times D^{-0.238}$) as reference. The hourly rainfall of 7 mm from the Fig. 11 is comparable with the proposed debris-flow rainfall threshold 9 mm of I_{max} in this study. Both values can be considered as the warning triggers and used to define the response procedures for debris flow disaster management in the Shenmu area.

3.4 Debris-flow flow velocity

The flow velocity was estimated by geophone data and CCD video clips in several events at the Aiyuzi Stream. Table 6
240   summarizes the flow velocity estimation, as well as the rainfall information before the occurrence of debris flows. It had been noted that the flow velocity of debris flow was quite higher before 2010, with the average velocity about 14.4 m/sec. After 2010, the average flow velocity of debris flow was much lower, about 4.5 m/sec, except the one obtained in the 1110 Heavy Rainfall in 2011, which was only about 1.8 m/sec. The possible explanation of the lower flow speed of debris flow at the Aiyuzi Stream after 2009 is the reduced slope at the mid- to downstream sections, due to the accumulation of debris from
245   events.

3.5 Soil moisture and vibrational signals

Regarding the debris-flow warning, the soil moisture obtained from the site provides another aspect of evaluation. The variation of soil moisture with time had been analysed with the rainfall records and the occurrence of debris flows (Tsai et al., 2014). However, the continuous measurement of soil moisture was not well carried out within the whole monitoring
250   period. The lack of this information had made the regression analysis of debris-flow occurrence and soil moisture not available. Another factor used for determination of debris-flow occurrence are the ground vibrational signals. These data are mainly used for research purpose and considered as additional information for debris-flow disaster response. (Huang et al., 2016; Huang et al., 2017). Previous study has shown that the characteristic frequency of the ground vibration signals generated byt the debris flows was between 10 and 40 Hz (Huang et al., 2016; Huang et al., 2017). The processed broadband
255   signals revealed the lower frequency of debris-flow fronts between 0 and 10 Hz and were captured earlier than those from

the geophones (Huang et al., 2016). Figure 12 shows that the processed signal data (in terms of cumulative energy in the figure) had peaks when debris flows approached the monitoring station.

From the recent research (Wei et al, 2018), it was found that the cumulative energy and the slope of cumulative energy in the 10-second interval (overlapping 50%) and in the 5-40 Hz frequency can be used as the interpretive indicators of the debris flow. However, the short time window between the time detected by sensors and the arrival of debris flows at the residential areas limits the capability of ground surface vibration signals in debris-flow early warning. Another recent study about the debris-flow vibrational signals was analysed using the machine learning methods (Huang and Chen, 2022), revealing the characteristic patterns of signals of debris flows in terms of averaged accumulated energy (6-seccond average) and the time interval of peaks (10 seconds before and after the peaks). The analysis results from studies indicate that the ground surface vibrational signals can be treated as a reference factor and are potentially useful for debris-flow early earning. Current research gives a promising indicator but is not applicable for disaster response.

Conclusions

With examination of several aspects of the debris flow events in Shenmu area, the analysis led to the following conclusions.

The rainfall characteristics of debris flow in Shenmu mainly focus on the rainfall thresholds, in terms of maximum hourly rainfall (I_{max}), 24-hour accumulated rainfall (R_{24}), and effective accumulated rainfall (R_t). The value of RTI-based effective accumulated rainfall has changed from 250 mm (during 2000 to 2020) to 300 mm (since 2021), due to the declining occurrence of debris flows in the area. Based on the case history in the Shenmu area, other proposed sets of rainfall thresholds are I_{max}, R_{24}, and R_t are (9, 23, 67.8) and (16.5, 51.5, 75.2), all in mm. These values are considerably useful for debris flow disaster monitoring.

Another perspective of rainfall characteristics in Shenmu is the rainfall intensity and duration when debris flow occurred. Debris flows usually occur during the rainy season, especially during May to August of the year in this area. They are more likely to occur during heavy rainfalls or intense typhoons. Precipitation thresholds of the initiation of debris flows are comparable to a global dataset. Compared to the global threshold of rainfall duration less than 48 hours (D<48), the regression curve of rainfall I-D in the study area has similar slope, indicating that shorter heavy rainfalls with average $I \geq 7.0$ mm h^{-1} could trigger debris flows after 2009.

Based on the observed debris flow events, the average frequency of occurrence is about 1.11 times per year during the period from 2004 to 2021. Comparatively, the average frequency of debris flow occurrence is 1.83 times per year from 2004 to

2009 and is 0.75 times per year after 2009. The average frequencies of debris flow occurrence in Shenmu area implies that there was at least one debris flow occurred every year in the past 18 years. Also, it is noted that the occurrence frequency before 2009 is about twice the value after 2009, indicating that the impacts of extremely heavy rainfalls, the Typhoon Morakot in 2009, had significantly changed the local environment and the basin conditions at the upper stream sections. A lot of debris had been transported from the upper streams in 2009. Therefore, the debris source coming from the unstable shallow slopes along the upper stream sides may have reduced in a large amount after 2009. In fact, there is no debris flow observed in the study area since 2018. We expect that the amount of debris source is getting to a balance level in this area.

The reducing trend of debris flow occurrence after 2009 is reasonably due to the less landslides at the upper stream areas and fewer events of heavy rainfalls. The debris source has reached to a balance after 10 years since the Typhoon Morakot in 2009. Another possible evidence of fewer occurrence of debris flow is the flow speed of debris flows. The observed flow speed of debris flow from available data was abut 14.3 m/sec before 2009 and had become to a much lower value of 4.46 m/sec after 2009. The reasonable explanation of the slower flow speed after 2009 is due to the gentler slopes at the mid-to-downstream sections after years of debris settlement and less intensity of rainfall events in the past decade.

The monitoring results of past events shows that the peak values and rising energy from the ground surface vibrational signals were detected a few minutes earlier before the debris-flow's arrival at the monitoring devices. The characteristic frequency of signals was between 0 and 40 Hz and the cumulative energy and the slope of cumulative energy in the 10-second interval (overlapping 50%) can be used as the interpretive indicators of the debris flow. However, the limitation of short evacuation time window needs to be improved, either by more data analysis or different monitoring layout on the site, before being used as the indicator of debris-flow occurrence in the future disaster response.

The dataset prepared in this study is useful for further analysis regarding the mechanism and characteristics of debris flows in Taiwan, as well as advantageous to the global debris-flow dataset. It should be mentioned that the time series of rainfalls recorded by the rain gauges in the Shenmu area for the whole monitoring period is not completely available. Another problem is that the lack of systematic topographic surveys had restricted the estimation of sediment deposited along the stream channels in the Shenmu area, resulting in the difficulty of evaluating the magnitude of debris flows. The previous issues could be resolved by conducting regular on-site surveys and with the help of advanced monitoring technology in the future.

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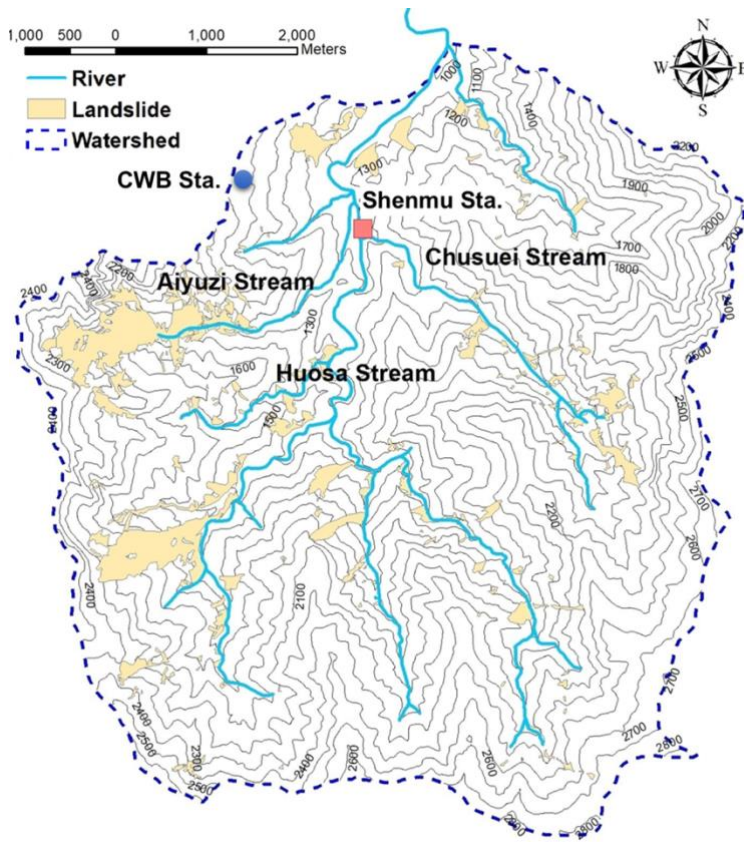
Figure 1: The maps of terrain and the landslide areas (after 2009) of Shenmu area. (adapted from Huang et al., 2019)

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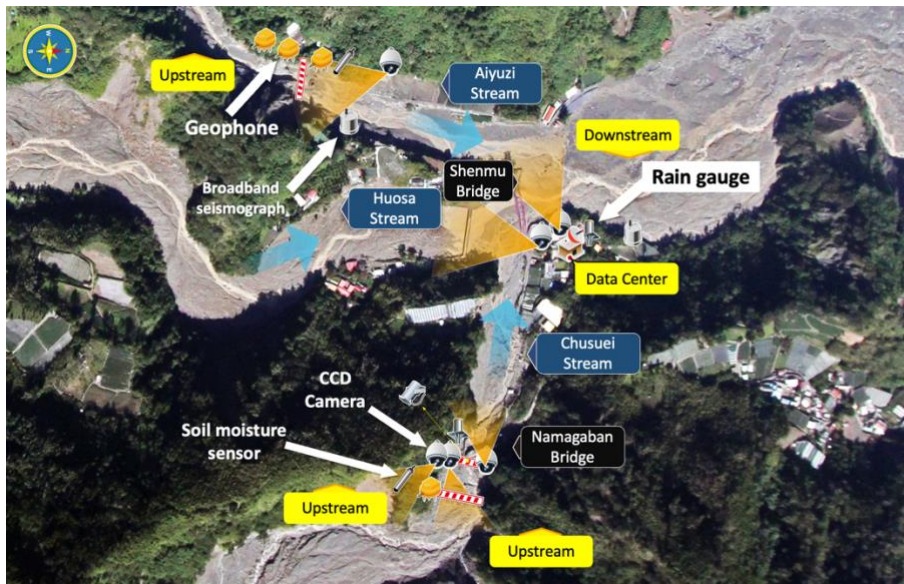
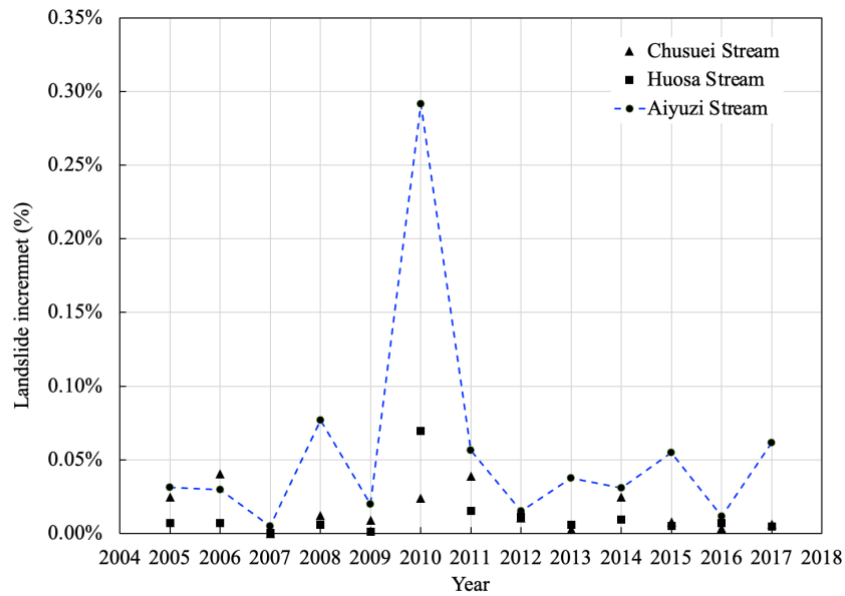


Figure 2: The layout of sensors installed at the Shenmu monitoring station. (base map credit: GIS Research Center, Feng Chia University, Taiwan).

390   **Figure 3: Landslides increment ratio of the study area.**

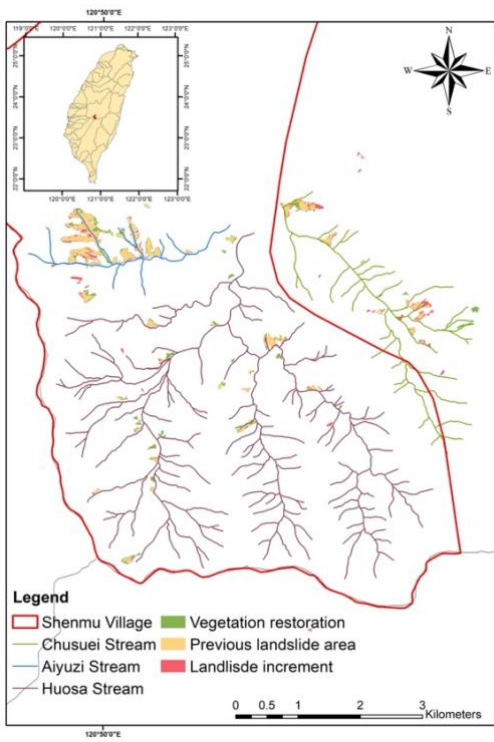
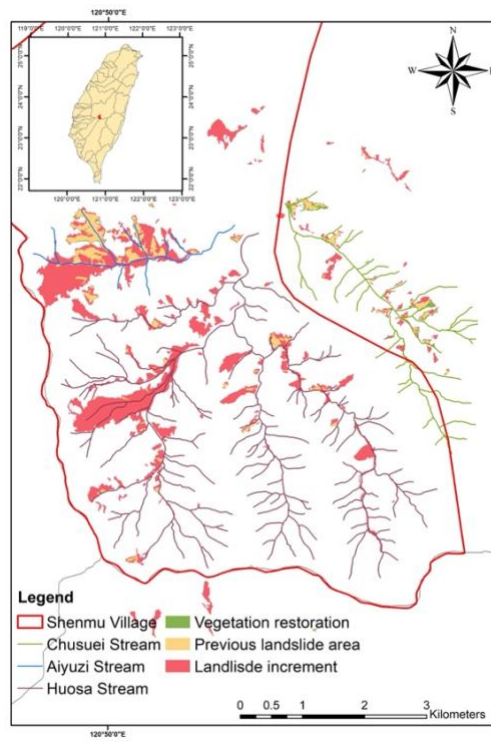
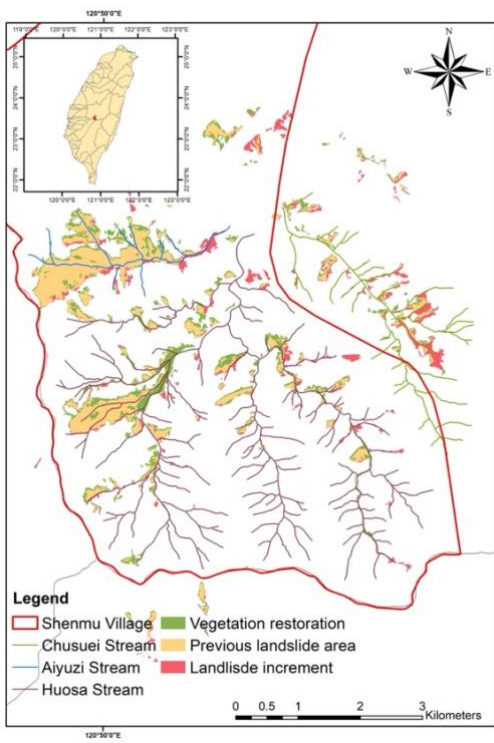
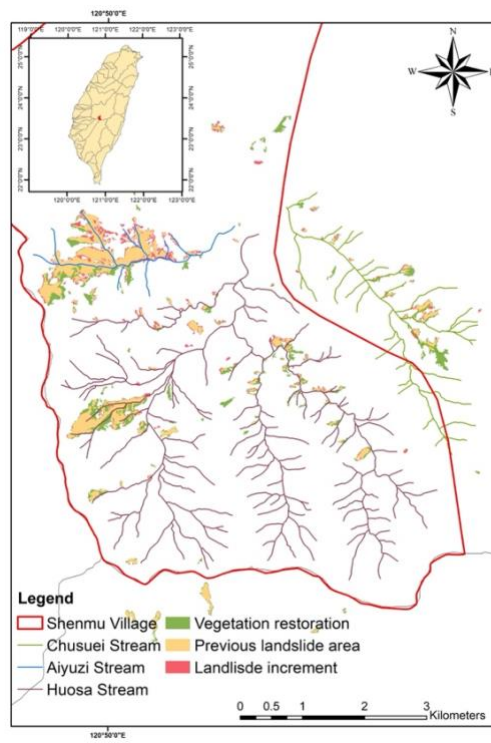



Figure 4: The landslide increments of (a) 2009 (b) 2010 (c) 2011 (d) 2017.

(a)

(b)

(c)

(d)

Figure 5. The photos of the site near the mouth of Aiyuzi Stream (a) Aug. 12, 2009 (b) July 19, 2011 (c) Sep. 26, 2015 (d) June 9, 2017. (Photo credits: GIS Research Center, Feng Chia University, Taiwan).

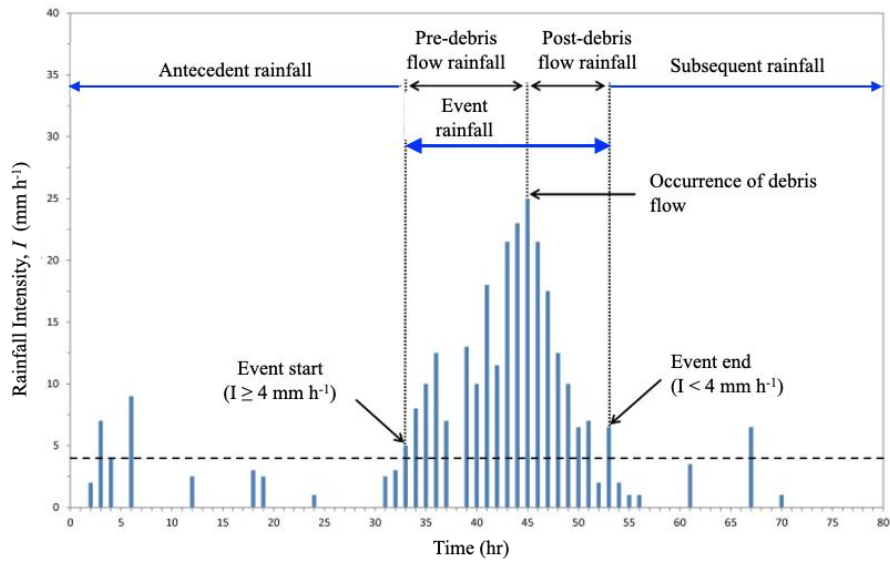



Figure 6: Schematic diagram of the definition of a rainfall event.

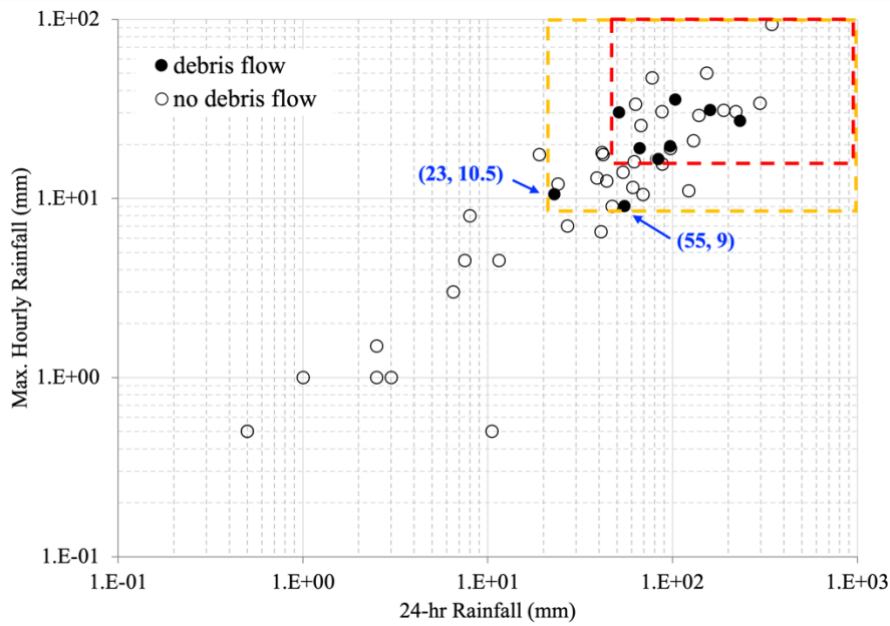



Figure 7: The max. hourly rainfall and 24-hr rainfall of events in the Shenmu area.

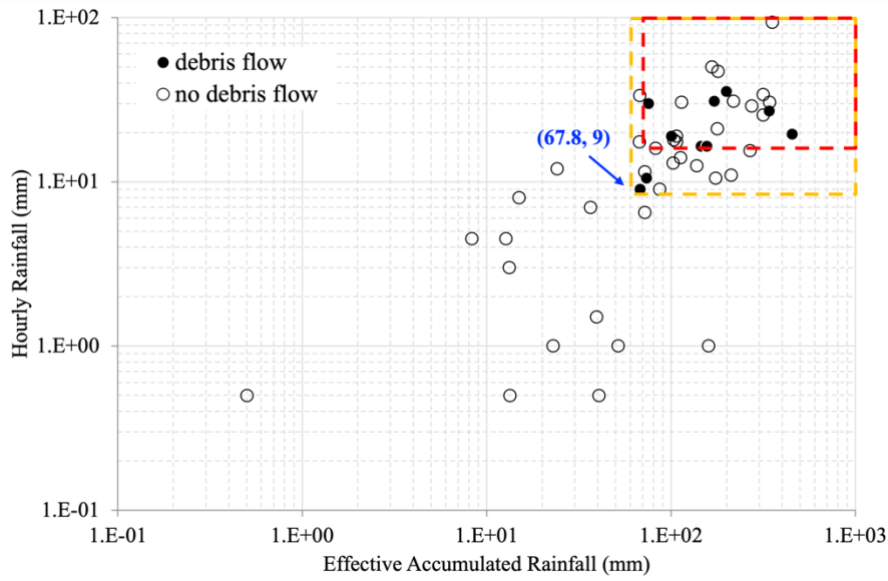



Figure 8: The max. hourly rainfall and effective accumulated rainfall of events in the Shenmu area.

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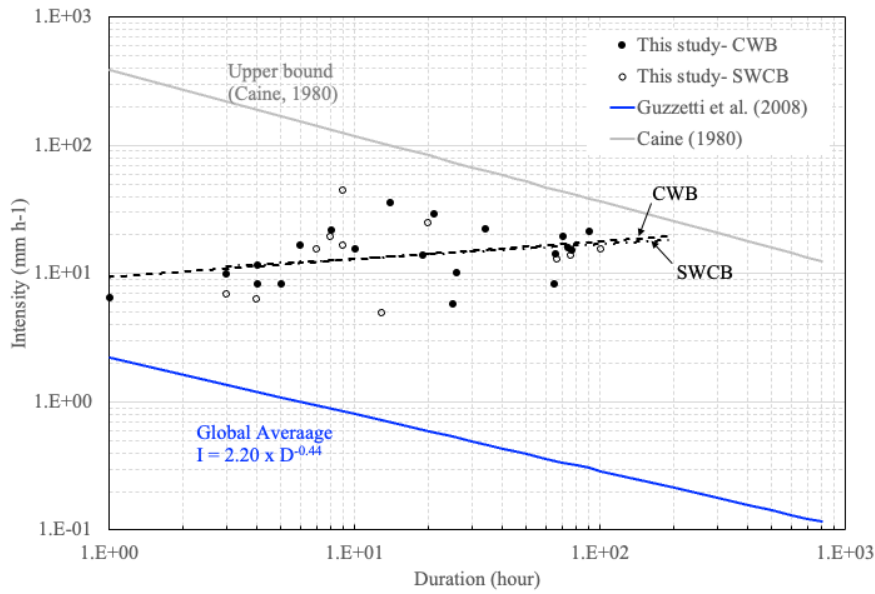


Figure 9: The rainfall intensity-duration conditions of debris flow in Shenmu.

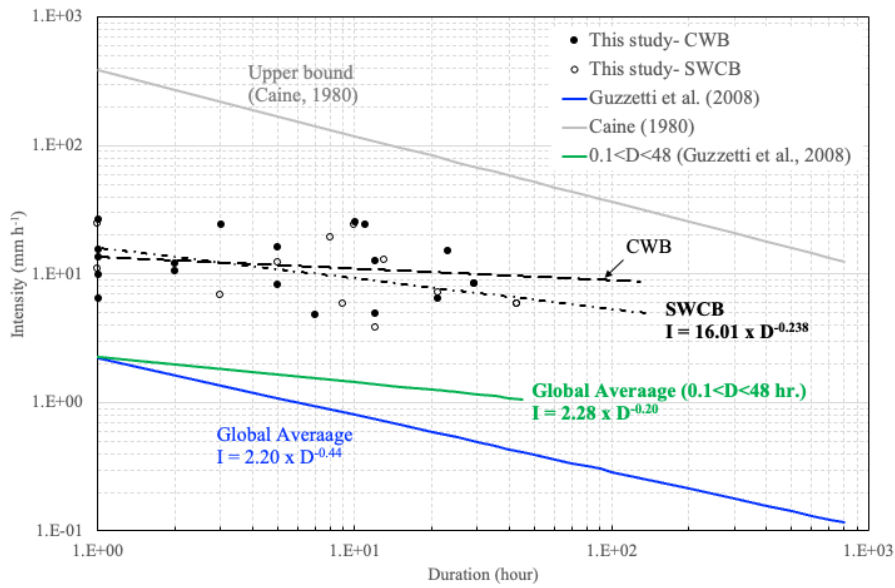



Figure 10: The I-D conditions 1 hour before the occurrence of debris flows in Shenmu.

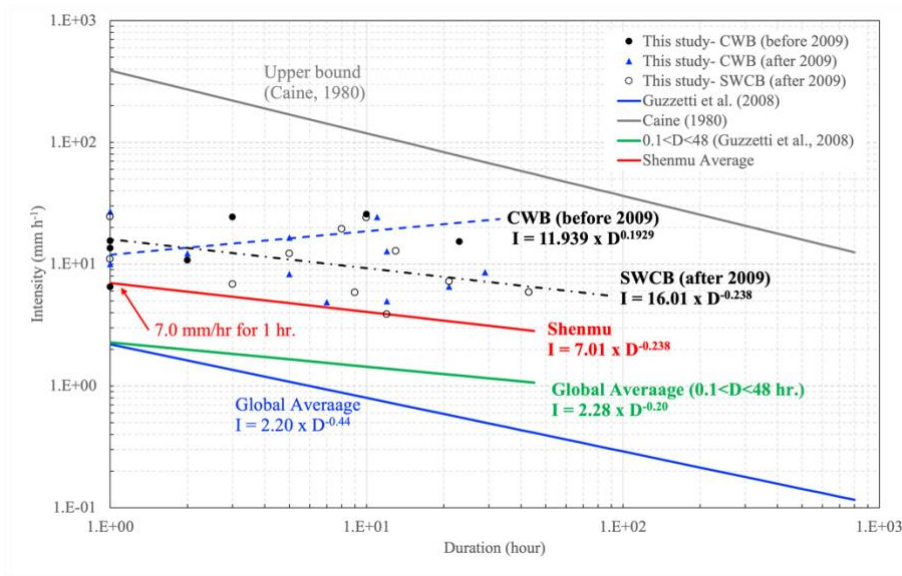



Figure 11: The I-D conditions of debris flows in Shenmu before and after 2009.

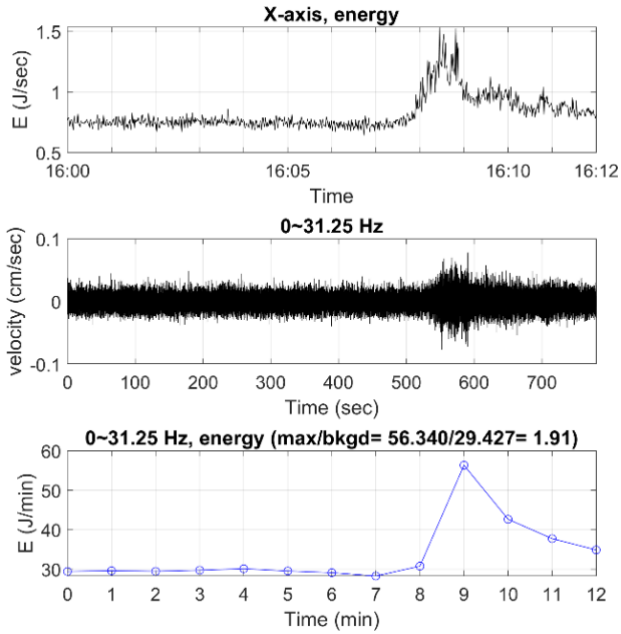
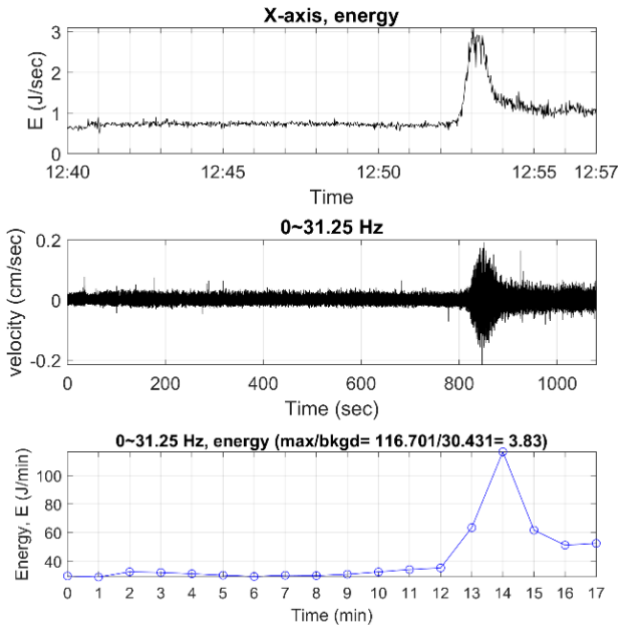
(a)

(b)

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Figure 12: Energy of vibrational signals (a) 0504 Rainfall in 2012 (b) 0520 Rainfall in 2014 (Huang et al., 2019).

Table 1: The total landslide area in Shenmu after 2009 (Huang, et al., 2013)

Debris Flow No.	Stream	Length (km)	Catchment Area (m^2)	Total Landslide Area (m^2)
DF199	Chusuei Stream	7.16	8,615,600	332,900
DF227	Huosa Stream	17.66	26,200,000	1,493,200
DF226	Aiyuzi Stream	3.30	4,006,400	998,500

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Table 2: Debris flow events in the Shenmu area.

No	Date (Y/M/D)	Event	Location (stream)	Time of occur.	Warning (Y/N)	Hazard Type	Shenmu Rainfall Sta. (CWB)					Shenmu Monitoring Sta. (SWCB)				
							Date/Time	I_1	D_1	I_2	D_2	Date/Time	I_1	D_1	I_2	D_2
1	2004/5/20	0520 Heavy Rainfall	Aiyuzi	14:53	-	DF	5/20 13:00~16:00	11.67	4	10.8	2.0	5/20/13:00~16:00	-	-	-	-
2	2004/5/21	0521 Heavy Rainfall	Aiyuzi	16:08	-	DF	5/21 16:00~21:00	16.75	6	13.5	1	5/21/16:00~21:00	-	-	-	-
3	2004/5/29	0529 Heavy Rainfall	Aiyuzi	16:19	-	DF	5/29 16:00~17:00	6.50	1	6.5	1	5/29/16:00~17:00	-	-	-	-
4	2004/6/11	-	Aiyuzi	16:42	-	DF	6/11 16:00~19:00	8.38	4	15.5	1	6/11/16:00~19:00	-	-	-	-
5	2004/7/02	Typhoon Mindulle	Aiyuzi	09:16 16:41	-	DF	7/2 08:00~7/5/6:00	19.73	71	24.3 25.7	3 10	7/2/08:00~7/5/6:00	-	-	-	-
6	2006/6/09	0609 Rainfall	Chusuei Aiyuzi	08:32 (at Aiyuzi)	Y	DF	6/8 11:00~ 6/11/12:00	15.85	74	15.3	23	6/8/11:00~ 6/11/12:00	-	-	-	-
7	2007/8/13	0809 Rainfall	Chusuei	-	-	DF, FLD	8/12 12:00~ 8/13/13:00	10.15	26	-	-	8/12 12:00~ 8/13 13:00	-	-	-	-
8	2007/8/18	Typhoon Sepat	Chusuei	-	-	DF, FLD	8/18 00:00~ 8/20/17:00	8.38	65	-	-	8/18/00:00~ 8/20/17:00	-	-	-	-
9	2007/10/06	Typhoon Krosa	Aiyuzi	-	-	DF	10/6 09:00~ 10/7/19:00	22.53	34			10/6/09:00~ 10/7/19:00	-	-	-	-
10	2008/7/17	Typhoon Kalmaegi	Chusuei, Aiyuzi	-	-	DF, FLD	7/17 21:00~ 7/18/10:00	36.07	14			7/17/20:00~ 7/18/04:00	44.06	9	-	-
11	2009/8/08	Typhoon Morakot	Chusuei Huosa Aiyuzi	at Aiyuzi: 04:39	Y (04:41, 8/8)	DF, LS	8/7/1:00~ 8/10/18:00	21.37	90	8.55	29	8/6/11:00~ 8/10/15:00	15.58	101	5.88	43
12	2011/7/13	0713 Heavy Rainfall	Aiyuzi	14:33	N	DF	7/13/15:00~17:00	10.00	3	10.00	1	7/13/15:00~18:00	6.25	4	11.00	1
13	2011/7/19	0719 Heavy Rainfall	Aiyuzi	03:19	N	DF	7/18/23:00~ 7/19/17:00	13.87	19	16.50	5	7/18/23:00~ 7/19/05:00	15.43	7	12.20	5
14	2011/11/10	1110 Heavy Rainfall	Aiyuzi	13:29	N	DF	11/10/2:00~ 11/11/2:00	5.76	25	4.96	12	11/10/2:00~ 11/10/14:00	4.92	13	3.88	12
15	2012/5/04	0504 Heavy Rainfall	Aiyuzi	15:56	N	DF	5/4 12:00~ 16:00	8.30	5	8.30	5	5/4/14:00~ 16:00	6.83	3	6.83	3
16	2012/6/10	0610 Rainfall	Aiyuzi	10:34 15:14	Y (20:33, 6/10)	DF	6/10 4:00~ 6/12 21:00	14.38	66	4.86 12.75	7 12	6/10/3:00~ 6/12/21:00	12.88	67	5.83 12.81	9 13
17	2013/5/17	0517 Heavy Rainfall	Aiyuzi	07:02, 5/19	Y (07:02, 5/19)	DF	5/19 6:00~ 13:00	21.75	8	12.25	2	5/19/6:00~ 13:00	19.44	8	19.44	8
18	2013/7/11	Typhoon Soulik	Aiyuzi	06:54, 7/13	Y (06:44, 7/13)	DF	7/12 20:00~7/13 16:00	29.40	21	24.36	11	7/12/22:00~ 7/13/17:00	24.55	20	24.10	10
19	2014/5/20	0520 Heavy Rainfall	Aiyuzi	12:53	N	DF	5/20 13:00~ 22:00	15.75	10	27	1	5/20/13:00~ 21:00	16.39	9	24.5	1
20	2017/6/01	0601 Heavy Rainfall	Aiyuzi	11:40, 6/02	Y (13:44, 6/02)	DF	6/1 15:00~ 6/4 19:00	15.40	77	6.52	21	6/1/16:00~ 6/4 19:00	13.86	76	7.21	21

I_1, I_2 : the rainfall intensity (mm hr^{-1}) of the whole event and of the duration between the event start to one hour before the occurrence of debris flow, respectively; D_1, D_2 : the rainfall duration (hour) of the whole event duration and of the duration between event start to one hour before the occurrence of debris flow, respectively; DF: debris flow; FLD: flood; LS: landslide. -: not available.

Table 3. Annual landslide increments (m^2) from 2005 to 2017 in Shenmu area.

Year	Chusuei Stream	Huosa Stream	Aiyuzi Stream	Year	Chusuei Stream	Huosa Stream	Aiyuzi Stream
2005	210,196	186,560	117,238	2012	91,007	293,469	56,752
2006	342,699	179,173	111,793	2013	22,853	154,012	141,260
2007	1,043	14,552	17,634	2014	210,291	245,631	115,568
2008	101,531	153,507	288,463	2015	65,171	127,627	205,958
2009	76,642	27,396	74,971	2016	31,272	188,270	43,086
2010	201,523	1,807,496	**1,093,685**	2017	51,913	120,809	230,972
2011	329,184	398,638	212,154				

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Table 4. The channel width (m) of mid- to downstream.

Stream Year	Chusuei	Huosa	Aiyuzi	Heshe* (the confluence)
2009	76.14	121.84	71.75	132.35
2014	74.88	121.64	71.48	132.81
2015	74.70	122.53	71.11	132.40
2016	75.56	121.83	71.42	132.89
2017	75.83	121.65	70.99	132.80

* The channel width (m) measured at about 200 meters downstream to the confluence of the three

potential debris flow torrents.

Table 5. Case history of rainfalls and typhoons in the Shenmu area from 2014 to 2017.

Event	Year	Mo	Day	DF^*	I_{max} (mm)	R_{24} (mm)	R_t (mm)
0520 Heavy Rainfall	2014	5	20	Y	35.5	103.5	199.15
0606 Heavy Rainfall	2014	6	6	N	14	54	112.09
Typhoon Hagibis	2014	6	13	N	13	39	102.44
Typhoon Matmo	2014	7	23	N	30.5	219.5	341.79
0520 Heavy Rainfall	2015	5	23	N	17.5	42	106.88
Typhoon Chan-Hom	2015	7	11	N	19	97.5	106.90
Typhonn Soudelor	2015	8	6	N	29	138.5	272.84
0611 Heavy Rainfall	2016	6	11	N	18	41.5	103.30
Typhoon Meranti	2016	9	14	N	9	47	86.51
Typhoon Malakas	2016	9	16	N	47	77.5	179.08
Typhoon Megi	2016	9	27	N	31	189	217.50
0601 Heavy Rainfall	2017	6	2	Y	19.5	97.5	451.78
0613 Heavy Rainfall	2017	6	14	N	21	129.5	177.60
0613 Heavy Rainfall	2017	6	15	N	11	122.5	211.32
0613 Heavy Rainfall	2017	6	17	N	25.5	67.5	315.63
Typhoon Nesat and Haitang	2017	7	29	N	50	153	166.44
Typhoon Nesat and Haitang	2017	7	30	N	15.5	88	266.75

$^*DF$: debris flow

Table 6: The flow speed of debris flow in Aiyuzi Stream.

Event	Date	Flow Speed (m s^{-1})
Typhoon Midule	July 2, 2005	13.3
Typhoon Morakot	4:36, Aug. 8, 2009 (first wave)	13.0
	16:57, Aug. 8, 2019 (second wave)	17.0
0713 Heavy Rainfall	July 13, 2011	4.26
1110 Heavy Rainfall	Nov. 10, 2011	1.77
0610 Heavy Rainfall	June 10, 2012	4.26
0520 Heavy Rainfall	May 20, 2014	4.87