DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

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泥石流：

灾害、风险、预测、防治

會議記錄

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Conference logo is based on a figure from S.M. Fleishman’s book on Debris Flows (Moscow: Geografgiz, 1951, p. 51).

Characteristics of the debris-flow-triggering rainfalls recorded in the Shenmu area of Central Taiwan: An update

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Abstract. The geological conditions are unstable in the mountain areas, so debris flows and landslides are common geohazards in Taiwan. To protect people from the threats of debris flows, the local government has set up monitoring stations at locations prone to debris flows and applied rainfall thresholds in response to debris-flow disasters. The Shenmu area is a famous location for debris flows in central Taiwan. Previous studies have shown that the debris flow occurred almost once per year between 2004 and 2021. The rainfall thresholds from the observed events are determined by the rainfall indices, the maximum hourly rainfall, Imax, and the 24-hour accumulated rainfall, R_{24}. Based on the data collected by the Shenmu Debris Flow Monitoring Station, the rainfall thresholds of 9 and 23 mm of I_{max} and R_{24} were proposed for the area. To better understand the rainfall thresholds in Shenmu, this study collected data from the nearby rainfall station operated by the Central Weather Bureau Taiwan and compared the rainfall characteristics with the previous study in the Shenmu area. The analysis implied that using $I_{max,24}$, the maximum hourly rainfall, and R_{24}, the accumulated rainfall, both calculated in the 24 h before the debris flow occurrence, are considerably better than other rainfall indices for debris-flow warning thresholds in the Shenmu area. The rainfall thresholds $I_{max,24}$, and R_{24} of 10 and 100 mm revealed a debris-flow capture percentage of 55.6%, and 4 and 10 mm revealed a 43.8% debris-flow capture percentage, based on the total of 52 recorded rainfall events.

Key words: *debris flow, rainfall thresholds, maximum hourly rainfall, accumulated rainfall*

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Характеристики дождей, вызвавших селевые потоки, зарегистрированные в районе Шэньму в Центральном Тайване: новые данные

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Аннотация. Геологические условия в горных районах нестабильны, поэтому селевые потоки и оползни являются распространенными геологическими опасностями на Тайване. Чтобы защитить людей от угроз селевых потоков, местные власти установили станции мониторинга в местах, подверженных сходу селей, и пороговые значения количества осадков, превышение которых свидетельствует об опасности. Район Шэньму – один из наиболее селеопасных в Центральном Тайване. Предыдущие исследования показали, что селевые потоки происходили почти один раз в год в период с 2004 по 2021 г.

Пороговые значения количества осадков в результате наблюдаемых событий определяются индексами осадков, максимальным количеством осадков за час I_{max} и накопленным за 24 ч R_{24}. На основании данных, собранных станцией мониторинга селевых потоков Шэньму, для этого района были предложены пороговые значения осадков $I_{max} = 9$ и $R_{24} = 23$ мм. Для этого в рамках исследования были собраны данные с близлежащей осадкомерной станции, управляемой Центральным метеорологическим бюро Тайваня, и полученные значения сравнены с величиной осадков, определенной в ходе предыдущих исследований в районе Шэньму. Анализ показал, что использование $I_{max,24}$ (максимального почасового количества осадков) и R_{24} (суммарного количества осадков, рассчитанных за 24 ч до возникновения селевого потока) дает более релевантные результаты, чем другие индексы осадков, для установления пороговых значений в целях предупреждения о селевых потоках в районе Шэньму. Использование пороговых значений количества осадков $I_{max,24}$ и R_{24}, равных 10 и 100 мм, дало положительный результат: удалось спрогнозировать 55,6% селевых потоков, а значения 4 и 10 мм – 43,8% из общего числа зарегистрированных случаев выпадения осадков, равного 52.

Ключевые слова: *селевые потоки, пороговые значения осадков, максимальные часовые осадки, накопленные осадки*

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Introduction

Taiwan is located in the path of monsoons and typhoons and is prone to earthquakes. The fragile geology conditions, due to the frequent heavy rainfalls and earthquakes, contribute to the various geo-hazards in the mountain areas. Therefore, the debris flow has become a common geo-hazard in Taiwan in the past two decades [*Huang et al., 2013; Huang et al., 2017; Huang, 2023*]. The disaster of debris flow had caused serious damage to the public facilities and personal properties from the case history. In order to monitor the debris flows and better understand the characteristics of the triggering conditions, The Agency of Rural Development and Soil and Water Conservation (ARDSWC) in Taiwan has established debris-flow monitoring stations since 2002 and operates a national debris-flow disaster warning system at present.

To analyze the triggering factors of debris flows, monitoring devices were installed in areas prone to debris flows. Instruments of rain gauges, water level meters, wire sensors, soil water moisture sensors, and CCD cameras are used in most monitoring stations. Full-scale experimental data is difficult to obtain for debris-flow research. Therefore, the observation data from the monitoring sites provides valuable information for debris-flow studies [*Huang et al., 2013; Hürlimann et al, 2019; Huang, 2023*].

In a potential area, the debris flows usually occur in a low frequency and are considered uncommon events when compared to other natural hazards, e.g., heavy rainfalls. But at some locations, the occurrence frequency of debris flow is higher than in other locations [*Marchi et al., 2021*]. The Shenmu area in Taiwan is the "hot spot" where debris flows have occurred more often than in other locations and almost once every year in the past 18 years.

Rainfall thresholds are commonly applied for debris-flow early warning and are currently used by the ARDSWC. A rainfall dataset of debris flows recorded in the Shenmu area between 2004 and 2021 is presented in this study [*Huang, 2023*]. The event data were collected from the Shenmu Village rainfall station (23°31.9645'N, 120°50.62'E) maintained by the Central Weather Administration (CWA) and from the Shenmu debris flow monitoring station (23°31.6938'N, 120°51.3927'E) maintained by the ARDSWC. The data prepared in this study is an update to the previous study [*Huang, 2023*] to complete the event data mainly obtained from the CWA rainfall station. The data include the date of events, time of debris flow occurrence (whenever available), and the triggering rainfalls (rainfall intensity, accumulated rainfall, and duration).

Analysis of debris-flow rainfall triggering factors, the maximum hourly rainfall, and accumulated rainfall of a period are discussed and analyzed from different approaches. The rainfall indices that reflect the characteristics of debris flows in Shenmu are described here and compared with those in the previous study.

Study area and database

The study area is close to the Shenmu Village, located in the watershed of the Chen-Yu-Lan River in central Taiwan. Chen-Yu-Lan River has a length of 42.4 km with an average declination slope of 5%, and its watershed area is about 450 km^2. This area was fragile after the Chi-Chi Earthquake (occurred on September 21, 1999). According to Chen et al. (2012), the landslide ratio (landslide projected area/total catchment area) of this catchment area is about 12% ~ 34.2% (from 1996 to 2009), and there is a trend of increasing year by year. A great percentage of the watershed was affected by significant landslides [*Huang, 2023*].

Based on the recorded rainfall data from June 1987 to February 2017, obtained from the Shenmu Village Station of Taiwan's Central Weather Administration (CWA), 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*]. The slope angle in the upper stream areas of Aiyuzi Stream is about 39.3^o on average [*Wei et al., 2018*].

The three potential 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; Huang 2023*]. The terrain and landslide areas of streams and the basic info are shown in Fig. 1 and Table 1, respectively. Because of its shorter length, larger landslide areas upstream, and heavy rainfalls, debris flows frequently occurred in the downstream section of the Aiyuzi Stream since Typhoon Morakot in 2009 [*Huang et al., 2013*]. The debris flows in the Shenmu area are classified as granular flows.

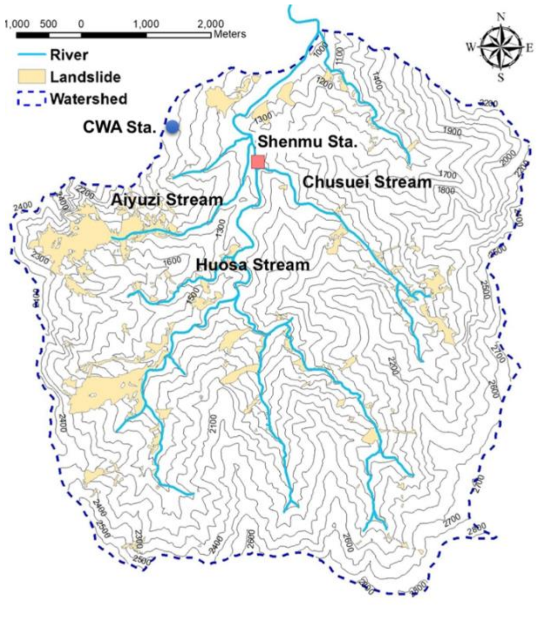


Fig. 1. The maps of terrain and the landslide areas (after 2009) of Shenmu area. (after [*Huang et al., 2019*])

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

Tables 2 and 3 show the events collected for this study, in which the rainfall data were obtained from the Shenmu Village Station of CWA. Fig. 2 shows the definition of a rainfall event. The previous study showed that the debris flows occurred almost every year from 2009 to 2014 [*Huang, 2023*]. From 2014 until 2021, there is only one record of debris flow in Shenmu (Table 2). The occurrence frequency seems to have reduced to very few in the past 7 years (from 2015 to 2021). 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) [*Huang, 2023*].

Table 2. Debris flow events in the Shenmu area (rainfall data obtained from the CWA Rainfall Station)

No	Date (Y/M/D)	Event	Location (stream)	Time of occurrence	Hazard type	Date/time	Rainfall, mm				Duration, h
							I_{max}	$I_{max,24}$	R_{24}	R_{bt}	D_{bt}
1	2004/5/20	0520 Heavy Rainfall	Aiyuzi	14:53	*DF*	5/20/13:00~ 16:00	13.5	13.5	25.5	12	1
2	2004/5/21	0521 Heavy Rainfall	Aiyuzi	16:08	*DF*	5/21/16:00~ 21:00	45.0	13.5	36	13.5	0.13
3	2004/5/29	0529 Heavy Rainfall	Aiyuzi	16:19	*DF*	5/29/16:00~ 17:00	6.5	6.5	6.5	6.5	0.32
4	2004/6/11	-	Aiyuzi	16:42	*DF*	6/11/16:00~ 19:00	15.5	15.5	3	15.5	0.7
5	2004/7/02	Typhoon Mindulle	Aiyuzi	09:16	*DF*	7/2/08:00~ 7/5/6:00	72.5	27.5	53	27.5	0.3
6	2004/7/02	Typhoon Mindulle	Aiyuzi	16:41	*DF*	7/2/08:00~ 7/5/6:00	72.5	36	236	148.5	6
7	2006/6/09	0609 Rainfall	Chusueim, Aiyuzi	08:32 (at Aiyuzi)	*DF*	6/8/11:00~ 6/11/12:00	73	36	285	73	0.5
8	2007/8/13	0809 Rainfall	Chusuei	-	*DF, FLD*	8/12/12:00~ 8/13/13:00	29.5	23.5	183	46.5	3.0
9	2007/8/18	Typhoon Sepat	Chusuei	-	*DF, FLD*	8/18/00:00~ 8/20/17:00	23.5	17.5	93.5	20	1
10	2007/10/06	Typhoon Krosa	Aiyuzi	-	*DF*	10/6/09:00~ 10/7/19:00	74.5	66.5	270	74.5	1
11	2008/7/17	Typhoon Kalmaegi	Chusuei, Aiyuzi	-	*DF, FLD*	7/17/21:00~ 7/18/10:00	77	18	34	60	1
12	2009/8/08	Typhoon Morakot	Chusuei, Huosa, Aiyuzi	04:39 (at Aiyuzi)	*DF, LS*	8/7/1:00~ 8/10/18:00	95	27	217	-	0.67
13	2009/8/08	Typhoon Morakot	Aiyuzi	16:57	*DF*	8/7/1:00~ 8/10/18:00	95	33.5	453.5	76	2
14	2011/7/13	0713 Heavy Rainfall	Aiyuzi	14:33	*DF*	7/13/15:00~ 17:00	15.5	4.5	11	10	1
15	2011/7/19	0719 Heavy Rainfall	Aiyuzi	03:19	*DF*	7/18/23:00~ 7/19/17:00	45	30	105.5	27.5	0.55
16	2011/11/10	1110 Heavy Rainfall	Aiyuzi	13:29	*DF*	11/10/2:00~ 11/11/2:00	16.5	9.5	66.5	46	10
17	2012/5/04	0504 Heavy Rainfall	Aiyuzi	15:56	*DF*	5/4 12:00~ 16:00	17	19	85.5	66.5	23
18	2012/6/10	0610 Rainfall	Aiyuzi	10:34	*DF*	6/10 4:00~ 6/12 21:00	39.5	10	60.5	39.5	14.57
19	2012/6/10	0610 Rainfall	Aiyuzi	15:14	*DF*	6/10 4:00~ 6/12 21:00	39.5	33	179.5	37	2.23
20	2013/5/17	0517 Heavy Rainfall	Aiyuzi	07:02, 5/19	*DF*	5/19 6:00~ 13:00	48	17.5	51.5	-	0.03
21	2013/7/11	Typhoon Soulik	Aiyuzi	06:54, 7/13	*DF*	7/12 20:00~ 7/13 16:00	60.5	60	271.5	134	4.9
22	2014/5/20	0520 Heavy Rainfall	Aiyuzi	12:53	*DF*	5/20 13:00~ 22:00	35.5	7.5	28	9.5	19.88
23	2017/6/01	0601 Heavy Rainfall	Aiyuzi	11:40, 6/02	*DF*	6/1 15:00~ 6/4 19:00	62.5	41	196.5	18	1.73

I_{max} – the maximum hourly rainfall (mm/h) of the whole event; $I_{max,24}$ – the maximum hourly rainfall in the 24 h before the occurrence of the debris flow; R_{24} – the cumulative rainfall in the 24 h before the occurrence of the debris flow; R_{bt} – the cumulative rainfall between $I_{max,24}$ and the occurrence of the debris flow; D_{bt} – the time elapsed between $I_{max,24}$ and the occurrence of the debris flow; *DF* – debris flow; *FLD* – flood; *LS* – landslide. "-"– not available.

Table 3. Non-debris flow events in the Shenmu area (rainfall data obtained from the CWA Rainfall Station)

No	Date (Y/M/D)	Event	Date/Time	Rainfall, mm				Duration, h
				I_{max}	$I_{max,24}$	R_{24}	R_{bt}	D_{bt}
1	2008/7/18	Typhoon Kalmaegi	7/17 21:00 – 7/18 10:00	77	67.5	267	250	4
2	2008/7/28	Typhoon Fungwong	7/28 6:00 – 7/29 15:00	40	16	51	16	2
3	2008/9/14	Typhoon Sinlaku	9/13 5:00 – 9/15 17:00	41	32	326.5	67.5	2
4	2009/6/20	Typhoon Linfa	6/20 18:00 – 6/21 8:00	9.5	2.5	4	1.5	23
5	2009/10/5	Typhoon Parma	10/5 13:00 – 23:00	11.5	7.5	17	11	1
6	2010/5/23	0523 Heavy Rainfall	5/23 10:00 – 5/24 1:00	42	36.5	54.5	42	1
7	2010/5/31	0523 Heavy Rainfall	5/30 22:00 – 24:00	12	12	47	1	1
8	2010/7/28	0726 Heavy Rainfall	7/26 24:00 – 7/28 10:00	11.5	11.5	98	57	10
9	2010/9/1	Typhoon Namtheum-Lionrock	9/1 14:00 – 17:00	5.5	3.5	8.5	5.5	1
10	2010/9/19	Typhoon Fanapi	9/19 5:00 – 16:00	20.5	11	17	17.5	1
11	2011/6/25	Typhoon Meari	6/24 20:00 – 6/25 7:00	21	21	64	61.5	8
12	2011/8/30	Typhoon Nanmadol	8/30 11:00 – 13:00	8.5	5	40	36.5	19
13	2011/10/3	1001 Heavy Rainfall	10/3 3:00 – 6:00	7	6	19	6.5	1
14	2012/5/20	0520 Heavy Rainfall	5/20 2:00 – 10:00	28.5	28.5	74.5	28.5	1
15	2014/6/7	0606 Heavy Rainfall	6/6 14:00 – 23:00	14	9.5	40	14	1
16	2014/6/14	Typhoon Hagibis	6/13 15:00 – 18:00	13	12	29.5	13	1
17	2014/7/21	Typhoon Matmo	7/22 20:0 – 7/23 24:00	30.5	25.5	189	137	9
18	2015/5/23	0520 Heavy Rainfall	5/23 14:00 – 23:00	17.5	7.5	25	34.5	23
19	2015/7/9	Typhoon Chanhorm	7/10 18:00 – 7/11 8:00	19	9.5	78.5	27	2
20	2015/8/6	Typhoon Soudelor	8/8 7:00 -8/9 5:00	29	26	109.5	60.5	4
21	2016/6/11	0611 Heavy Rainfall	6/11 3:00 – 18:00	18	6.5	23.5	18	1
22	2016/9/14	Typhoon Meranti	9/14 10:00 – 13:00	9	8.5	38	16	2
23	2016/9/16	Typhoon Malakas	9/17 5:00 – 13:00	47	13.5	30.5	58	3
24	2016/9/26	Typhoon Megi	9/27 10:00 – 9/28 8:00	31	26.5	158	120.5	8
25	2017/6/14	0613 Heavy Rainfall	6/14 7:00 -20:00	21	17	108.5	83	8
26	2017/6/15	0613 Heavy Rainfall	6/15 10:00 – 21:00	11	21	118	72	19
27	2017/6/17	0613 Heavy Rainfall	6/17 2:00 -15:00	25.5	11.5	42	39.5	3
28	2017/7/29	Typhoon Neast-Haitang	7/29 17:00 – 7/30 2:00	50	20.5	103.5	50	1
29	2017/7/30	Typhoon Neast-Haitang	7/30 19:00 – 7/31 14:00	15.5	11	76	23.5	2

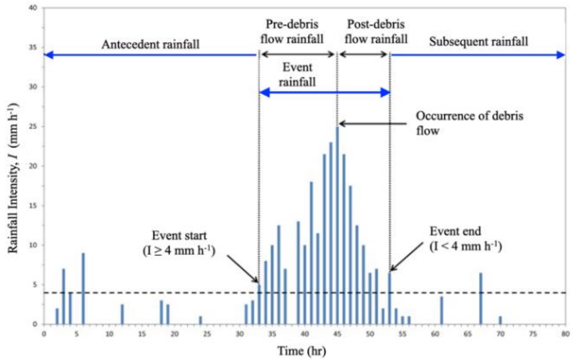


Fig. 2. Schematic diagram of the definition of a rainfall event

From the number of debris-flow events in Table 2, the geological environment of the Shenmu area seemed to reach a balance from 1999 to 2009. After 2009, the environmental conditions greatly changed due to the extremely heavy rainfalls caused by Typhoon Morakot, and the local environmental conditions seemed to reach another balance from 2009 to 2014. Until now, the Shenmu has been threatened by debris flow during typhoons and heavy rainfalls.

Analysis of rainfall characteristics of debris flows in the study area

Based on the event records in Tables 2 and 3, the rainfall indices of the debris-flow events and the rainfall events in which no debris flow occurred are shown on Figs. 3–7. The rainfall distribution of debris-flow and non-debris-flow events are shown on Figs. 3 and 4, respectively. The rainfall indices used in this study are I_{max}, the maximum hourly rainfall of the event, $I_{max,24}$, the maximum hourly rainfall in the 24 h before the occurrence of the debris flow, R_{24}, the cumulative rainfall in the 24 h before the occurrence of the debris flow, R_{bt}, the cumulative rainfall between $I_{max,24}$ and the occurrence of the debris flow, and D_{bt}, the time elapsed (in hour) between $I_{max,24}$ and the occurrence of the debris flow.

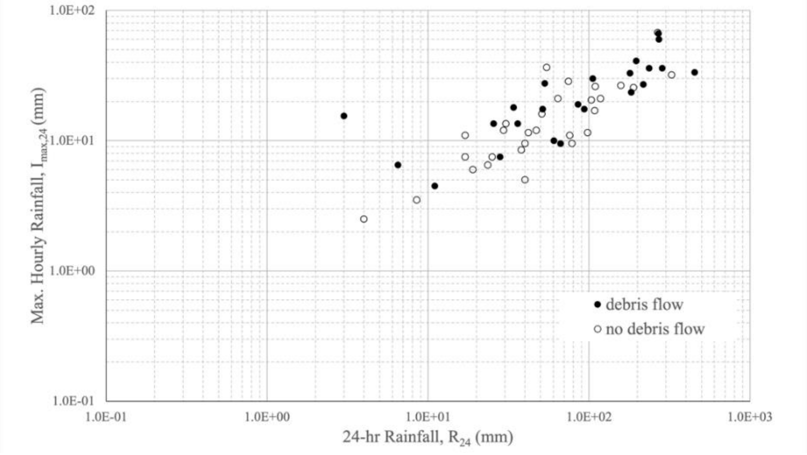


Fig. 3. The rainfall indices of R_{24} and $I_{max,24}$ of observed events between 2004 and 2021

Fig. 3 shows the results of R_{24} and $I_{max,24}$ of events, and Fig. 4 shows the results of R_{24} and I_{max}. For comparison, it is noted that the distribution in Fig. 3 is less scattered than that in Fig. 4 when R_{24} is greater than 10 mm. The distribution difference in Figs. 3 and 4 implies that the rainfall index, $I_{max,24}$, is more suitable to describe the rainfall characteristics of debris flows. Both Figs. 3 and 4 show a similar trend of increasing accumulated rainfall with increasing hourly rainfall.

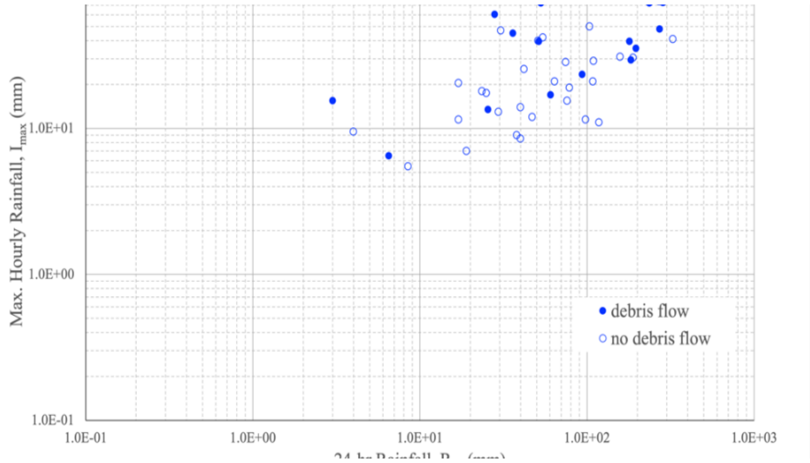


Fig. 4. The rainfall indices of $R_{24}$and I_{max} of observed events between 2004 and 2021

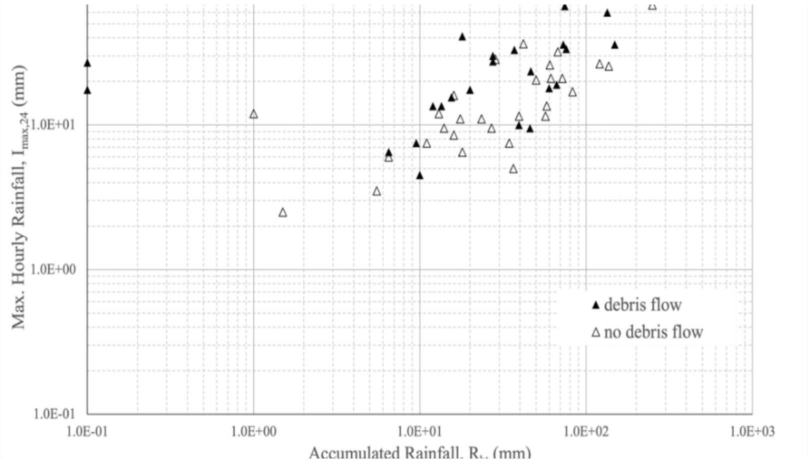


Fig. 5. The rainfall indices of R_{bt} and $I_{max,24}$ of observed events between 2004 and 2021

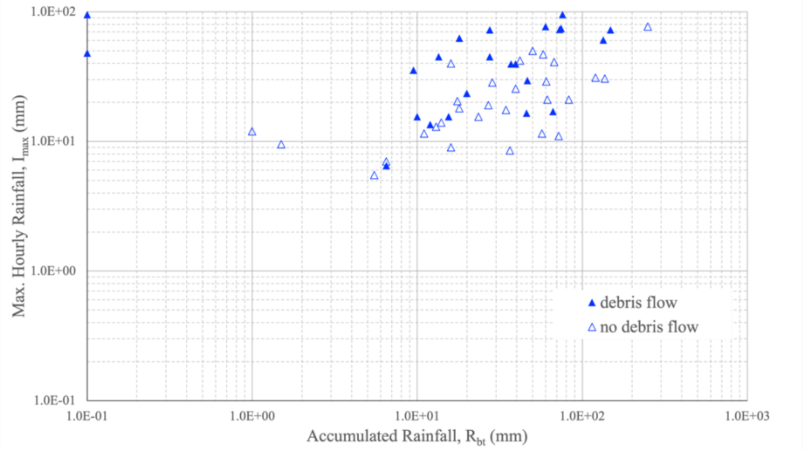
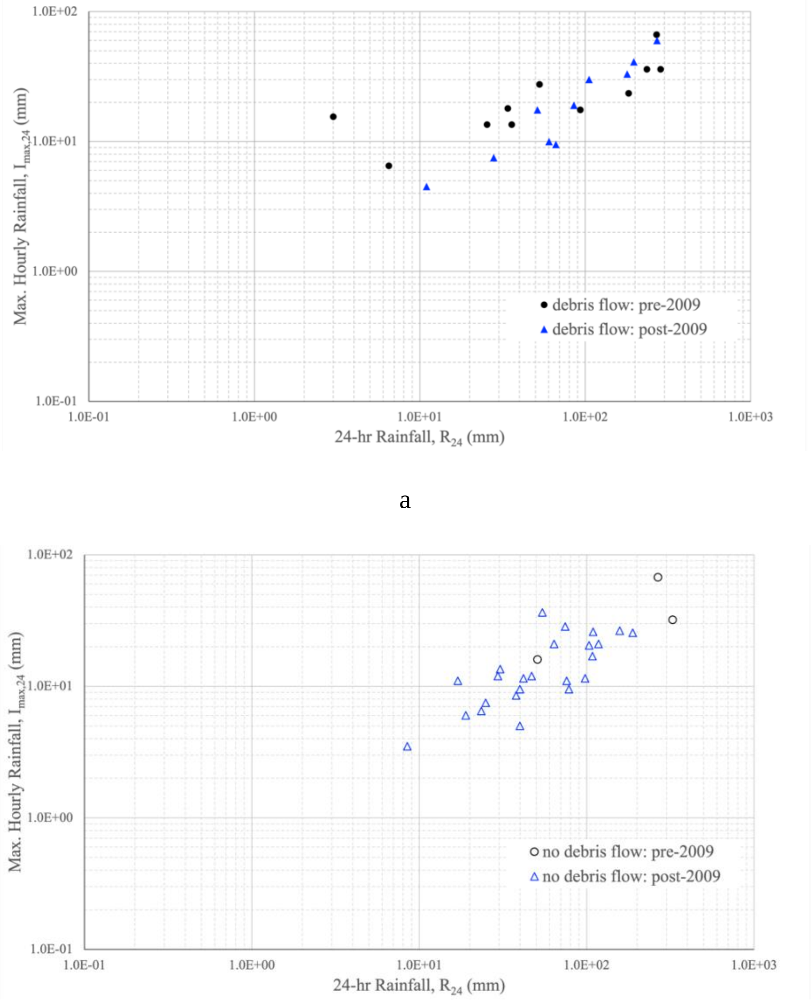


Fig. 6. The rainfall indices of R_{bt} and I_{max} of observed events between 2004 and 2021

Another comparison was made by plotting the indices of R_{bt}, $I_{max,24}$, and I_{max} of events, as shown on Figs. 5 and 6. Both Figs. 5 and 6 represent more scattered data than those in Figs. 3 and 4, which implies that the use of R_{24} is considerably better than R_{bt}. The index performance difference between R_{24} and R_{bt} is possibly due to the likely random time elapsed between the $I_{max,24}$, and the occurrence of debris flow. Typhoon Morakot in 2009 was a major event that significantly impacted the Shenmu area. From Fig. 7, however, the rainfall-index distribution of debris-flow and non-debris-flow events are not quite different before and after 2009. The data shows that the debris flow usually occurs when the R_{24} is greater than 10 mm from previous figures.



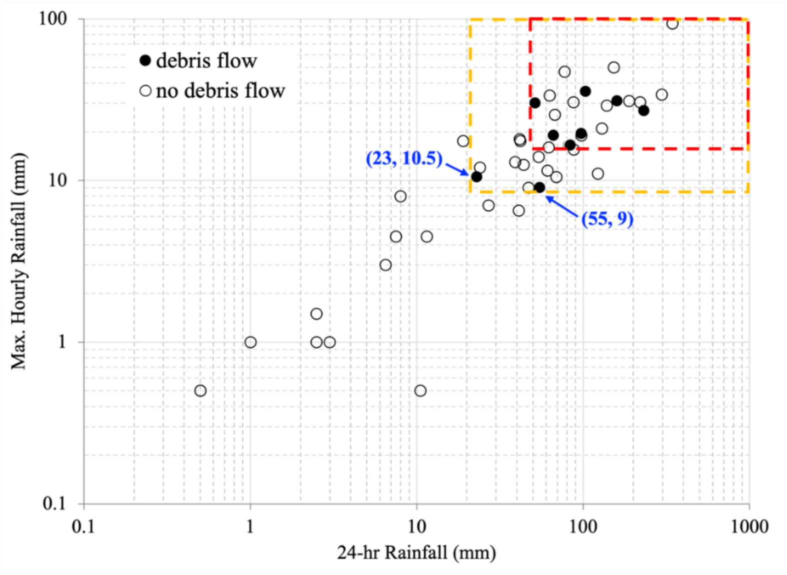
a

b

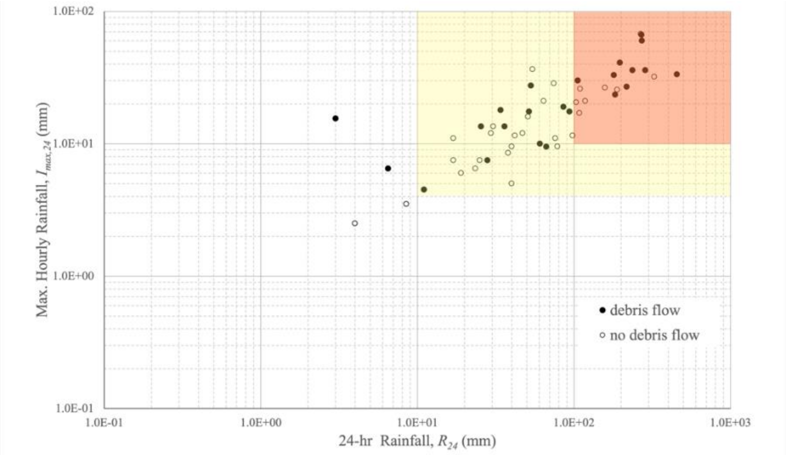
Fig. 7. The rainfall indices, R_{24} and $I_{max,24}$, of events before and after 2009 (a) debris flows (b) no debris flows

Based on these data in Tables 2 and 3, and the comparison results, the rainfall thresholds for the Shenmu area were proposed as shown in Fig. 8. Fig. 8*a* shows the thresholds of R_{24}, 9 mm, and I_{max}, 23 mm, about 30% capture rate of debris flows (10 debris flows and 23 non-debris flows), based on the rainfall data obtained from the Shenmu Debris Flow Monitoring Station [*Huang, 2023*]. In Fig. 8*b*, rainfall thresholds of R_{24} greater than 100 mm and $I_{max,24}$ greater than 10 mm imply about 55.6% capture rate of debris flows (10 debris flows and 8 non-debris flows), and thresholds of R_{24} greater than 10 mm and $I_{max,24}$ greater than 4 mm resulting in the capture rate of debris flows of 43.8% (21 debris flows and 27 non-debris flows). Different rainfall index pairs of R_{24} and $I_{max,24}$ thus were proposed to be applied to debris flow warning, with different levels (Yellow and Orange) of possibility, as shown in Fig. 8*b*.

The results from Fig. 8 indicate that the rainfall indices of R_{24} and $I_{max,24}$ are more suitable for debris-flow rainfall thresholds using the data from CWA Rainfall Station. Overall, the rainfall data from the Shenmu Monitoring Station and CWA are reliable for determining the rainfall thresholds, with an acceptable capture rate of debris flow of around 30% to 50%. Although a capture rate higher than 50% or more is desirable for debris-flow disaster warnings in practice, the proposed rainfall thresholds of this study are still useful for disaster response for current conditions in Shenmu.



a



b

Fig. 8. The rainfall thresholds: a – R_{24} and I_{max} [*Huang, 2023*]; b – the proposed R_{24} and $I_{max,24}$ for debris-flow events

Conclusions

Based on the collected data and case history of debris-flow events in this study, the analysis of rainfall characteristics and rainfall indices led to the following conclusions.

1. The main rainfall characteristics of debris flow in Shenmu area were appropriately described as the 24-hour accumulated rainfall, R_{24}, and the maximum hourly rainfall in the 24 h before the debris flow occurrence, $I_{max,24}$.
2. The thresholds of rainfall indices, R_{24} and Imax,24, are 10 mm and 4 mm, and 100 mm and 10 mm for different levels of capture rate and disaster concerns. These values are considerably useful for debris flow disaster monitoring.
3. Another perspective of rainfall in Shenmu is that the debris flows usually occur during the rainy season, especially during May to August of the year in this area. Debris flows are more likely to occur during heavy rainfalls or intense typhoons.

4. The dataset prepared in this study is useful for further analysis regarding the mechanism and characteristics of debris flows in Taiwan and advantageous to the global debris-flow dataset.

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