forDebris flow triggering characteristics and occurrence probability after extreme rainfalls: case study in the Chenyulan watershed, Taiwan

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ABSTRACT. Rainfall and other extreme events often trigger debris flows in Taiwan. This study examines the debris flow triggering characteristics and probability of debris flow occurrence after extreme rainfalls. The Chenyulan watershed, central Taiwan, which has suffered from the Chi-Chi earthquake and extreme rainfalls, was selected as a study area. The rainfall index (RI) was used to analyze the return period and characteristics of debris flow occurrence after extreme rainfalls. The characteristics of debris flow occurrence included the variation in critical RI, threshold of RI for debris flow triggering, and recovery period, the time required for the lowered threshold to return to the original threshold. The variations in critical RI after extreme rainfall and the recovery period associated with RI are presented. The critical RI threshold was reduced in the years following an extreme rainfall event. The reduction in RI as well as recovery period were influenced by the RI. Reduced RI values showed an increasing trend over time, and it gradually returned to the initial RI. The empirical relationship between the probability of debris flow occurrence (P) and corresponding return period (T) of the rainfall characteristics for areas affected by extreme rainfalls and affected by the Chi-Chi earthquake were developed. Finally, a method for determining the P of a rainfall event is proposed based on the relationship between P and T. This method was successfully applied to evaluate the probability of debris flow occurrence after extreme rainfalls.

Keywords: Probability, Debris flow occurrence, Rainfall index, Recovery period, Return period

1. Introduction

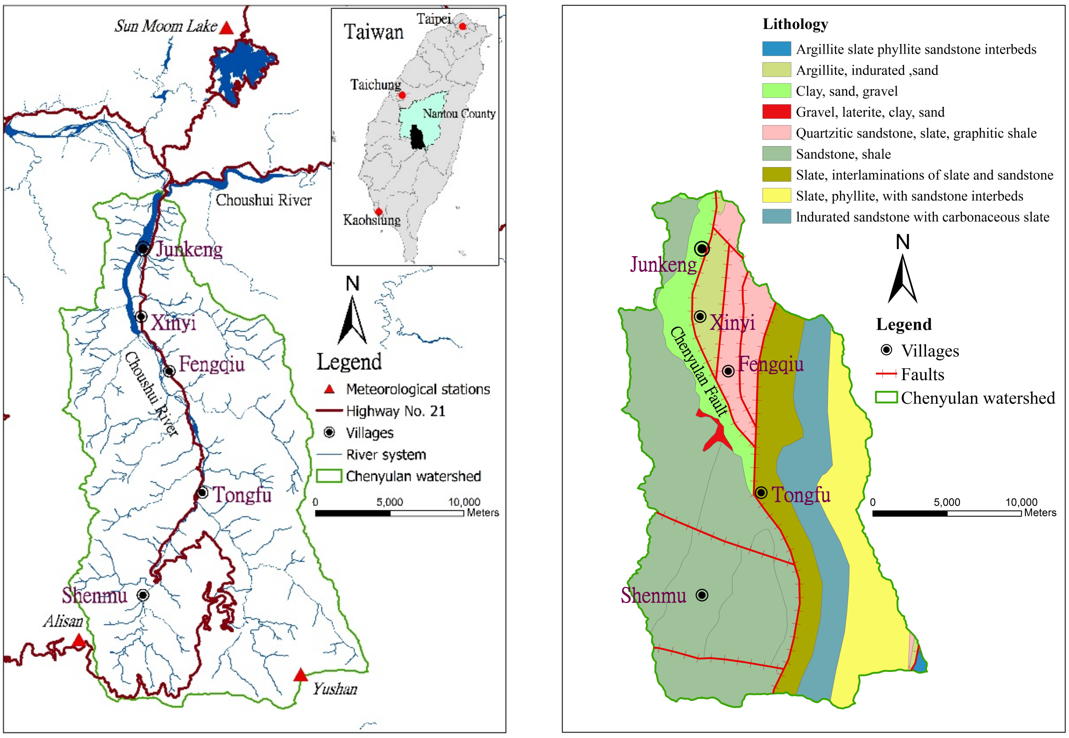
Extreme events such as extreme rainfall and major earthquakes can cause landslides and debris flows in mountainous watersheds; landslides generally deposit large amounts of loose debris in gullies and on slopes (Dong et al., 2009; Chen et al., 2012) and increase the volume of loose debris within a watershed. The supply of loose debris in a watershed may decrease or resume when landslides occur during the stabilization of affected slopes and loose debris left from previous landslides are brought by water flow or debris flow. The supply of loose debris has an important role in the occurrence of future debris flows and may change the critical rainfall threshold for the initiation of debris flows during subsequent rainfall events (Jakob et al., 2005). In other words, the critical rainfall threshold for debris flow initiation may differ before and after an extreme rainfall event or major earthquake. Therefore, understanding the variations in rainfall characteristics after extreme events and their influence on debris flow initiation is important for the implementation of debris flow warnings and hazard mitigation.

Previous investigators have studied debris flows following major earthquakes, such as the effects of the Chi-Chi earthquake on the characteristics of debris flows in Taiwan (Lin et al., 2003; Liu et al., 2008), the variation in rainfall conditions required to trigger debris flows, and the affected period after the Chi-Chi earthquake (Chen, 2011), as well as the impact of the Wenchuan earthquake in China on subsequent long-term debris flow activity (Zhang and Zhang, 2017). Chen et al. (2012) studied recent changes in the number of rainfall events related to debris flow occurrence. They found that the number of extreme rainfall events in the Chenyulan watershed showed an increasing trend. Chen et al. (2013) analyzed the characteristics of rainfall related to debris flow occurrence in the Chenyulan watershed to investigate the variation in the rainfall conditions related to debris flow occurrences, and the empirical relationship between rainfall characteristics and the corresponding number of debris flows. Extreme rainfall events and the Chi-Chi earthquake were shown to affect the critical condition for the occurrence of debris flows in the Chenyulan watershed. The Chi-Chi earthquake significantly lowered the critical rainfall threshold for debris flow occurrence in the subsequent five years. However, there is a lack of studies quantifying the decrease in the critical rainfall threshold and the period affected by extreme rainfalls. Furthermore, the return period (T), also referred to as the recurrence interval, is an important concept that reflects the long-term hydrological characteristics of an area, which is useful for hydrological or hydraulic design. Many studies have analyzed rainfall-triggered shallow landslides using rainfall values obtained by return period (Borga et al., 2002; D'Odorico, 2005; Schilirò et al., 2015; Peres and Cancelliere, 2016; Bogaard and Greco, 2017). However, previous studies mostly focused on hydrological concepts to calculate the return periods of rainfall-triggered shallow landslides. Lack of studies estimated the relationship between the return periods of rainfalls and debris flows occurrence. Therefore, further studies are needed to determine the relationship between the return period T of rainfall characteristics associated with the probability of debris flow occurrence (P) and apply the relationship between P and T to evaluate the probability of debris flow initiation, especially after rainfall and other extreme events.

The Chenyulan watershed in central Taiwan was selected as a study area because it has experienced both the Chi-Chi earthquake and extreme rainfall events. This study had three main purposes: (1) Investigate the debris flow initiation characteristics after extreme rainfall events. Initiation characteristics include the variation in the rainfall index (RI) threshold for debris flow triggering (i.e., the variation in the critical RI), and the recovery period, the time required for the lowered threshold to return to the original threshold. (2) Develop an empirical relationship between P and T for areas affected by extreme rainfalls and the Chi-Chi earthquake. (3) Apply the P–T empirical relationship to evaluate the probability of debris-flow occurrence after extreme rainfall events.

2. Debris flows in the Chenyulan watershed

As the study area, the watershed of the Chenyulan River, located in Nantou County, central Taiwan (Figure 1a), has an area of 449 km^2, main stream length of 42 km, average stream-bed gradient of 4°, and elevation range of 310–3,952 m. The Chenyulan River follows a major fault, the Chenyulan Fault (Figure 1b), which is a boundary fault dividing two major geological zones of Taiwan. In addition to the boundary fault separating geological zones, the watershed of the Chenyulan River also contains many other faults, accompanied by fractured zones. Consequently, fractured rock mass prevails over the study area, accounting for enormous landslides and providing an abundant source of rock debris for debris flow (Lin and Jeng, 2000). The annual rainfall in the watershed is between 2,000 and 5,000 mm, with an average of approximately 3,500 mm. Approximately 80% of the annual rainfall occurs in the rainy season between May and October, especially during typhoons, which generally occur three or four times annually. The Chi-Chi earthquake with a moment magnitude M_W 7.6, on September 21, 1999, was the largest to hit Taiwan in 100 years (Shin and Teng, 2001) and it had significant effects on the watershed. In particular, after the Chi-Chi earthquake, the extremely heavy rains brought by Typhoon Toraji in 2001 caused numerous debris flow events in central Taiwan. Owing to the steep topography, loose soils, young (3 million years) and weak geological formations due to the ongoing orogenesis, heavy rainfall, and active earthquakes, many debris flows were triggered by more than 30 rainfall events in past five decades in the watershed (Chen et al., 2013). Notably among these, severe debris flow events were caused by Typhoon Herb in 1996, Typhoon Toraji in 2001, and Typhoon Morakot in 2009. Characteristics for these debris flow events and damages are listed in Table 1.



(a) Location (b) Geology and lithology

Figure 1: The study area of the Chenyulan watershed in central Taiwan.

Table 1 Severe debris flows events in the Chenyulan watershed

Date	Trigger	Characteristics for debris flows	Damage
July 31–Aug 01, 1996	Typhoon Herb	Over 30 significant debris flows occurred in Fengqiu, Tongfu, Dongpu, Shenmu Villages, etc. in Xinyi Township, and Junkeng, Sinshan, Shanan Villages, etc. in Shueili Township, Nantou County. Among these debris flows, the maximum deposited area of debris flow occurred at the gully near Feng-Chiou elementary school with deposited area of 90,900 m^2 and the deposited volume is estimated to be as 454,500 m^3 (Yu, 1997)	21 deaths, six injured, over 40 houses destroyed, over 40 ha fruit orchard damaged, significant damage to roads, dams, river regulation works, and other properties. (Lin and Jeng, 2000; Cheng et al., 2005; Jan and Chen, 2005)
July 29–30, 2001	Typhoon Toraji	Over 70 debris flows occurred in Fengqiu, Tongfu, Shenmu Villages, etc. in Xinyi Township, and Junkeng, Sinshan, Shanan Villages, etc. in Shueili Township, Nantou County. Among these debris flows, the maximum deposited area of debris flow occurred at the San-Bu-Ken gully, Shang-An Village with deposited area of 39,000 m^2 and the deposited volume is estimated to be as 195,000 m^3 (DPRC, 2001)	19 deaths, over 30 missing and 70 houses destroyed, significant damages to dikes, roads, bridges and buildings. (Cheng et al., 2005; DPRC, 2001)
Aug 06–11, 2009	Typhoon Morakot	Over 40 debris flows occurred in Tongfu, Dongpu, Shenmu Villages, etc. in Xinyi Township, Nantou County. (Chen et al., 2011)	Over 20 houses were buried by debris flows or washed away by floods. No death in this event because of many structure and non-structure countermeasures conducted after Typhoon Herb and Typhoon Toraji. Especially, the non-structure countermeasures for the plan of evacuation and shelter and education of hazard prevention.

3 Regional rainfall, rainfall index, and extreme rainfall events

3-1 Regional average rainfall

To investigate the variation in rainfall characteristics in Chenyulan watershed, long-term rainfall records were obtained from three meteorological stations (Sun Moon Lake, Yushan, and Alisan stations, as shown in Figure 1a). The rainfall data used in this study are limited to hourly rainfall data because minute-scale rainfall data, such as 5 or 10-min rainfall data were not available. The hourly rainfall data collected from these three stations between 1963 and 2016 were used to estimate the regional rainfall characteristics for the entire Chenyulan watershed, via the reciprocal-distance-squared method (Chow et al., 1988). The estimated point using this method was taken at the centroid of the watershed area. The regional average rainfall in the Chenyulan watershed by the reciprocal-distance-squared method can be expressed as (Chen et al., 2012):

$$I=0.099I_1+0.387I_2+0.514I_3 \quad (1)$$

where I_1, I_2, and I_3, represent the hourly rainfall record from the Sun Moon Lake, Yushan, and Alisan meteorological stations, respectively. The rainfall characteristics estimated by the reciprocal-distance-squared method may not actually reflect the rainfall characteristics at specific locations when local rainfall varied significantly owing to abrupt changes in elevation, but it is a simple method to directly compute the regional average rainfall characteristics for a watershed. Moreover, the regional average rainfall estimated using the reciprocal-distance-squared method can easily represent the variation trend for regional rainfall characteristics throughout Chenyulan watershed and it was used to analyze the characteristics of rainfall triggering of debris flows in the watershed.

3-2 Identification of rainfall event

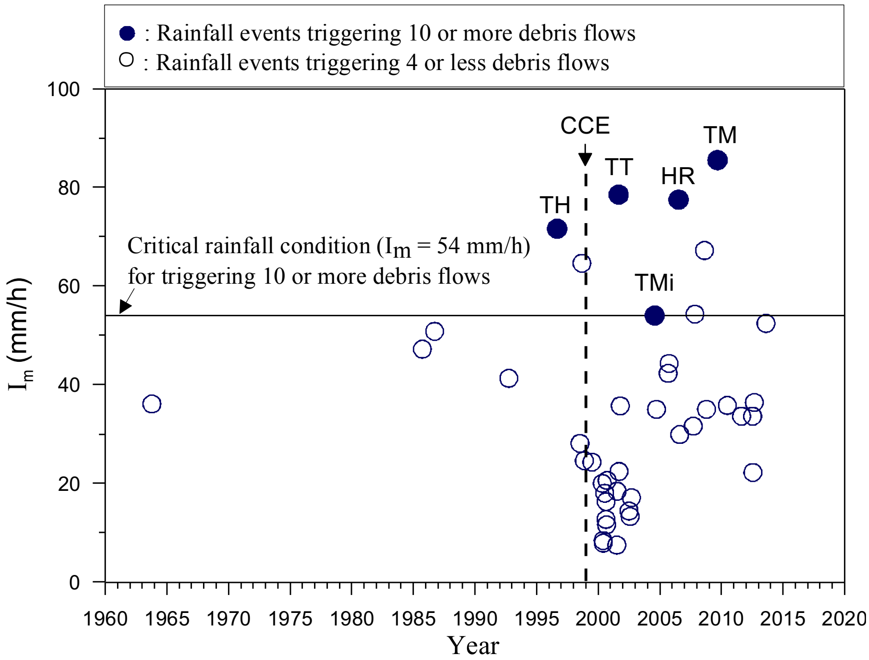
According to the hourly rainfall data of regional average rainfall, the rainfall event can be identified by following a certain criterion. A rainfall event is defined as that when hourly rainfall depth is greater than 4 mm, which is regarded as the beginning of a rainfall event. When hourly rainfall depth remains less than 4 mm continuously for 6 h, the end of that rainfall event is marked. The criterion has been generally used in Taiwan to identify rainfall events for analyzing rainfall events triggering debris flow (Jan et al., 2004). Thirty-eight rainfall events, including 18 rainstorms and 20 typhoon-induced heavy rainfall events, have caused debris flows in the Chenyulan watershed, as listed in Table 2. The maximum hourly rainfall depth I_m, the maximum 24-h rainfall amount R_d, and the number of debris flows for each rainfall even are also shown in Table 2. The number of debris flows N were collected from Chen et al. (2013), and N was identified through interpretation of aerial photographs, satellite images or/and field investigations. Most rainfall events, accounting for 87%, caused four or less debris flows ($N<4$ or $N=1$) and 29% caused one ($N=1$) in the watershed. Five rainfall events caused ten or more debris flows in the watershed. The five extreme rainfall events included Typhoon Herb (TH) in 1996, Typhoon Toraji (TT) in 2001, Typhoon Mindulle (TMi) in 2004, a heavy rainstorm (HR) in 2006, and Typhoon Morakot (TM) in 2009.

3-3 Rainfall index

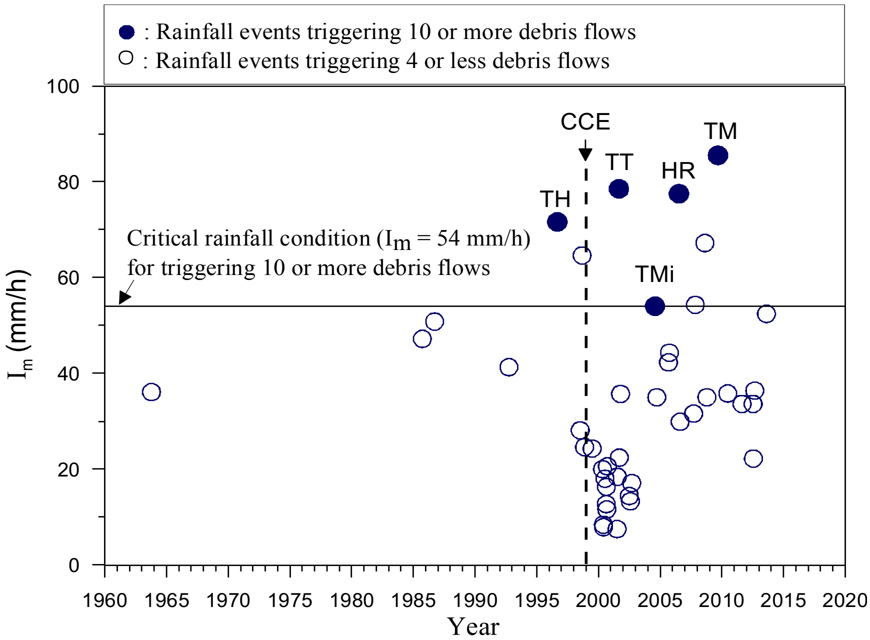
Rainfall parameters such as peak hourly rainfall, daily rainfall, maximum daily rainfall, cumulative rainfall, average rainfall intensity, and rainfall duration have been used by previous researchers to investigate the occurrence of debris flows. The choice of rainfall parameters reflects different research objectives and they have been discussed by Chen et al. (2013). Extreme rainfall refers to events of relatively high rainfall intensity and/or high cumulative rainfall. Debris flows caused by a rainfall event generally occurred within the period of the maximum 24-h rainfall R_d, and were closely related to the maximum hourly rainfall I_m (Lin and Jeng, 2000; Chen et al., 2011; Chen et al., 2012). I_m and R_d for debris flow events have been used to analyze variations of extreme rainfall events in Chenyulan watershed. However, the occurrence of debris flow for extreme rainfall events is related to not only accumulated rainfall but also rainfall intensity. For using R_d or I_m, as shown in Figures 2(a) and 2(b), at $R_d > 580$ mm or $I_m > 54$ mm/h, only five of the eight rainfall events caused 10 or more debris flows. It is inappropriate to apply a single rainfall parameter such as R_d or I_m as a critical condition for the occurrence of multiple debris flows (Chen et al., 2013). Thus, a triggering index RI, an index combining R_d and I_m, is proposed and expressed as follows

$$RI = R_d \times I_m \tag{2}$$

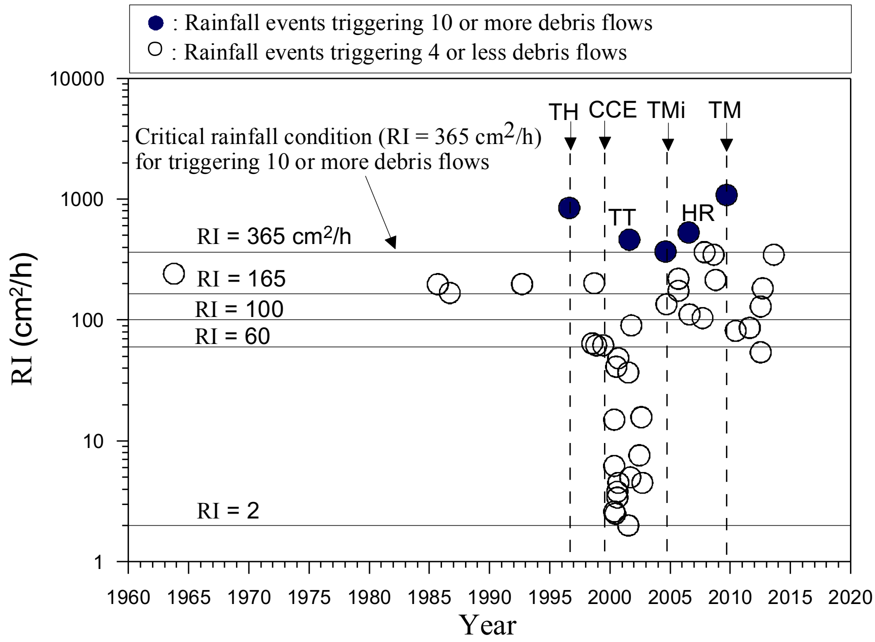
RI could be used as a critical condition for the occurrence of multiple debris flows, as shown in Figure 2(c). Five extreme rainfall events (TH, TT, TMi, HR, and TM) caused ten or more debris flows in the watershed and they had the highest RI values of all rainfall events from 1963 to 2016, with RI > 365 cm^2/h.



(a) R_d index



(b) I_m index



(c) RI index

Figure 2: Variations in three parameters of rainfalls for all rainfall events triggering debris flows between 1963 and 2016 in the Chenyulan watershed (modified from Chen et al., 2013). The Chi-Chi earthquake (CCE) in 1999 had significant effects on the watershed. Five rainfall events, including Typhoon Herb (TH), Typhoon Toraji (TT), Typhoon Mindulle (TMi), a heavy rainstorm (HR), and Typhoon Morakot (TM), caused ten or more debris flows in the watershed.

3-4 Variations in the rainfall index

Extreme rainfall events and the Chi-Chi earthquake (CCE) have been shown to affect the critical conditions required for the occurrence of debris flows, and the critical RI values for the occurrence of debris flows have been classified into four categories (Chen et al., 2013): the periods before TH, between TH and CCE, between CCE and TMi, and between TMi and TM (Figure 2). These periods had critical RI values of approximately 165, 60, 2, and 100 cm^2/h, respectively. These trends showed that TH caused numerous landslides and debris flows in the watershed, which reduced the critical rainfall threshold for debris flows in subsequent years and the CCE significantly lowered the critical rainfall threshold for debris flow occurrence in the subsequent five years. After the CCE, the critical RI dropped sharply to approximately 2 cm^2/h, which was 30 times lower than that before the CCE (critical RI = 60 cm^2/h). The results also showed that, approximately five years after the CCE, the critical RI gradually recovered from 2 cm^2/h to 100 cm^2/h (i.e., the critical RI between TMi and TM).

4. Variations in the rainfall index after extreme events

The extreme events in the Chenyulan watershed included a severe earthquake, the CCE, and the five extreme rainfall events (TH, TT, TMi, HR, and TM). The extreme rainfall events and the severe earthquake affected the critical condition for debris flow occurrence. Here, the index r_{RI}, defined as the ratio of critical RI to the original RI, was used to evaluate the affected period for the variation of RI after an extreme event. The original RI equals 165 cm^2/h (i.e., the critical RI before TH), as shown in Figure 2c, and it represent the critical RI unaffected by extreme events such as extreme rainfall events and the CCE. $r_{RI} < 1.0$ indicates that the critical RI to trigger debris flow is lower than that unaffected by extreme events. $r_{RI} = 1.0$ indicates that the critical RI after an extreme event is equal to that before TH (= 165 cm^2/h), and the critical RI has returned to that unaffected by extreme events.

4-1 Critical lines after extreme events

Table 2 lists numerous debris-flow events triggered by rainstorms and typhoons between 1996 and 2016. The estimated period t from the time of an extreme event, including TH, CCE, TT, TMi, HR, or TM, and the r_{RI} value between extreme events are also presented. A total of six data ranges for r_{RI} against t are plotted in Figure 3. Most ranges showed that the minimum r_{RI} (the maximum reduction of critical RI) generally occurs at the initial stage after an extreme event and the lower bound of r_{RI} has an increasing tendency over the course of time. The minimum r_{RI} values for events after TMi, HR, TH, TM, TT, and CCE are 0.82, 0.63, 0.37, 0.33, 0.03 and 0.01, respectively.

The critical line of r_{RI} after an extreme event is also presented in Figure 3. The critical lines are empirically determined according to the lower bound of the data range and assume that the line at the initial stage follows the minimum r_{RI} and has a tendency of linear increase. The data ranges after TH and after TM have the same critical line because their lower bounds are close. The required period for the critical RI from the drop down to its original value, referred to as the recovery period herein, also could be obtained by the critical line at r_{RI} =1.0. The recovery periods are 1.2, 2.1, 3.2, and 4.5 yr for events after TMi, HR, TH and TM, and CCE, respectively.

Among the critical lines, the lowest r_{RI} was caused by the rainfall event after CCE, as shown by the dashed line in Figure 3. The critical rainfall to trigger debris flow after CCE is significantly lowered in the Chenyulan watershed and its affected period could reach five years, approximately in the period between CCE and TMi. The impact of CCE on the critical RI was more significant than those of the other extreme rainfall events. These findings have been discussed and studied by many researches (Lin et al, 2003; Jan and Chen, 2005, Chen, 2011, Chen et al., 2012). Figure 3 also shows that the recovery period affected by CCE was approximately 5 years, in agreement with the results of previous studies. Typhoon Toraji is one of the rainfall events and the only one extreme rainfall within the five years after CCE. Thus, the critical RI line after Typhoon Toraji is much smaller than that caused by other extreme rainfall events because it could be affected by extreme rainfall and CCE.

The possible mechanism for the change in the critical RI threshold (rainfall conditions that triggered debris flow) after an extreme event may be associated with extreme events that caused numerous landslides and/or debris flows in the Chenyulan watershed in the early stage. Landslides and debris flows generally deposit large amounts of loose debris in gullies and on slopes after extreme events (Lin and Jeng, 2000; Lin et al., 2003; Dong et al., 2009; Chen et al., 2012) and increase the volume of loose debris within the watershed. These loose debris generally have lower soil strength and could be located on higher slopes. This results in low pore-water pressure or a low amount of water required to initiate the movement of the soil sediment (Lin et al. 2003, Chen and Jan 2008). Thus, it becomes much easier for debris flow to occur immediately with little rainfall, and that may lead to the lower critical RI or r_{RI} required to trigger debris flow, especially at the early stage after an extreme event. In general, sediments become consolidated and re-orientated with time, the amounts of soil and rock deposited in streams is reduced after each storm, and the shear strength of soil gradually recovers (Fan et al. 2003). In response, this could lead to the gradually increasing critical RI required to trigger debris flow with time after an extreme event.

4-2 Empirical relationships of RI modification and recovery period

Excluding the extreme rainfall event of Typhoon Toraji (TT) that could be affected by the Chi-Chi earthquake, four data sets were obtained, either for minimum r_{RI} or for recovery period (Figure 4). These data were obtained from the critical lines in Figure 3 for the period after extreme rainfall events TH, TMi, HR, and TM. The minimum r_{RI} values were 0.82, 0.63, 0.37, and 0.33 for events after TMi (RI=368 cm^2/h), HR (RI=529 cm^2/h), TH (RI=846 cm^2/h), and TM (RI=1078 cm^2/h), respectively; and the recovery periods were 1.2, 2.1, 3.2, and 4.5 yr for events after TMi, HR, TH and TM, respectively. Two fit lines for minimum r_{RI} and recovery period against RI are also presented in Figure 4. Minimum r_{RI} decreased and recovery period increased with increasing RI, indicating that after an extreme rainfall event with a higher RI, a lower RI, i.e., a lower value of minimum r_{RI}, was required to trigger debris flow and the effect of the extreme rainfall lasted for a longer period. Results of Figure 4 are helpful for modifying the criteria of debris flow warnings. For example, r_{RI} was 0.4 and recovery period was 3.2 years when an extreme rainfall with RI = 900 cm^2/h occurred, based on the fit lines showed in Figure 4. This indicates that the critical RI after an extreme rainfall event could be modified to 40% of the original criteria (165 cm^2/h) to RI = 66 cm^2/h, and the period of critical RI could be lowered to approximately three years.

Table 2: Debris flow events and related rainfall characteristics between extreme rainfalls and the Chi-Chi earthquake in the Chenyulan watershed between 1996 and 2016 (modified from Chen et al., 2013)

Year	Date of the event	Name of the event	Number of debris flows N	I_m (mm/h)	R_d (mm)	RI (cm^2/h)	t (y)	r_{RI}	Analysis range
1996	July 31–Aug 01	Typhoon Herb	37	71.6	1181.6	846			**TH**
1998	June 07–08	Rainstorm	3	28.1	227.8	64	1.85	0.39	
1998	Aug 04–05	Typhoon Otto	4	64.6	311.7	201.4	2.01	1.22	(1)
1998	Oct 15–16	Typhoon Zeb	2	24.6	251	61.7	2.21	0.37	
1999	May 27–28	Rainstorm	2	24.3	254.3	61.8	2.83	0.37	
1999	Sep 21	Chi-Chi earthquake							**CCE**
2000	Apr 1	Rainstorm	2	20	75.1	15	0.53	0.09	
2000	Apr 25	Rainstorm	1	8.4	30.6	2.6	0.59	0.02	
2000	Apr 28–29	Rainstorm	1	7.9	78.2	6.2	0.61	0.04	
2000	May 2	Rainstorm	1	8.1	30.6	2.5	0.61	0.02	
2000	June 12–14	Rainstorm	4	18	228.1	41.1	0.73	0.25	
2000	July 18	Rainstorm	3	12.7	30	3.8	0.82	0.02	(2)
2000	July 22	Rainstorm	3	16.3	20.7	3.4	0.84	0.02	
2000	Aug 5	Rainstorm	4	11.6	38.8	4.5	0.87	0.03	
2000	Aug 22–23	Typhoon Bilis	2	20.6	234.5	48.3	0.92	0.29	
2001	Jun 5	Rainstorm	1	7.5	27	2	1.71	0.01	
2001	June 14–15	Rainstorm	3	18.4	200.1	36.8	1.73	0.22	
2001	July 29–30	Typhoon Toraji	78	78.5	587.6	461.3			**TT**
2001	Aug 10	Rainstorm	3	22.4	22.4	5	0.03	0.03	
2001	Sep 17	Typhoon Nari	4	35.7	252.5	90.1	0.13	0.55	
2002	May 31	Rainstorm	4	14.4	53	7.6	0.84	0.05	(3)
2002	July 03–04	Rainstorm	2	13.3	117.9	15.7	0.93	0.10	
2002	Aug 12	Rainstorm	1	17.1	26.5	4.5	1.03	0.03	
2004	July 02–03	Typhoon Mindulle	17	54	681.4	368			**TMi**
2004	Aug 23–25	Typhoon Aere	2	35	385.4	134.9	0.14	0.82	
2005	Aug 04–05	Typhoon Matsa	1	42.3	411.9	174.2	1.09	1.06	(4)
2005	Aug 31–Sep 01	Rainstorm	1	44.3	495	219.3	1.16	1.33	
2006	June 08–11	Heavy Rainstorm	10	77.5	682.8	529.2			**HR**
2006	July 13–15	Typhoon Bilis	2	29.9	371.7	111.1	0.09	0.67	
2007	Aug 17–20	Typhoon Sepat	1	31.6	328.4	103.8	1.19	0.63	

2007	Oct 06–07	Typhoon Krosa	1	54.3	669.4	363.5	1.32	2.20	(5)
2008	July 17–18	Typhoon Kalmaegi	3	67.2	515.7	346.6	2.10	2.10	
2008	Sep 12–15	Typhoon Sinlaku	2	35	612.4	214.3	2.26	1.30	
2009	Aug 06–11	Typhoon Morakot	41	85.5	1192.6	1019.7			**TM**
2010	May 23–24	Rainstorm	1	35.8	227.2	81.3	0.78	0.49	
2011	July 17–20	Rainstorm	1	33.6	256.2	86.1	1.94	0.52	
2012	June 9–12	Rainstorm	2	33.6	384.6	129.2	2.84	0.78	(6)
2012	June 18–21	Typhoon Talim	1	22.2	243.4	54	2.86	0.33	
2012	Aug 1–3	Typhoon Saola	1	36.4	502.2	182.8	2.98	1.11	
2013	July 12–13	Typhoon Soulik	3	52.4	661.7	346.7	3.92	2.10	
~2016	No debris flow event								

Notes:

1. N = total number of individual debris flows triggered by each rainfall event; Im(mm/h) = maximum hourly rainfall in each rainfall event; Rd(mm) = maximum 24-h rainfall amount in each rainfall event; RI = rainfall index in each rainfall event, and it can be determined by Eq.(2).

2. CCE = Chi-Chi earthquake; TH = Typhoon Herb; TT = Typhoon Toraji; TMi = Typhoon Mindulle; HR = Heavy rainstorm; TM = Typhoon Morakot (TM)

3. (1) = data between TH and CCE; (2) = data between CCE and TT; (3) = data between TT and TMi; (4) = data between TMi and HR; (5) = data between HR and TM; (6) = data after TM.

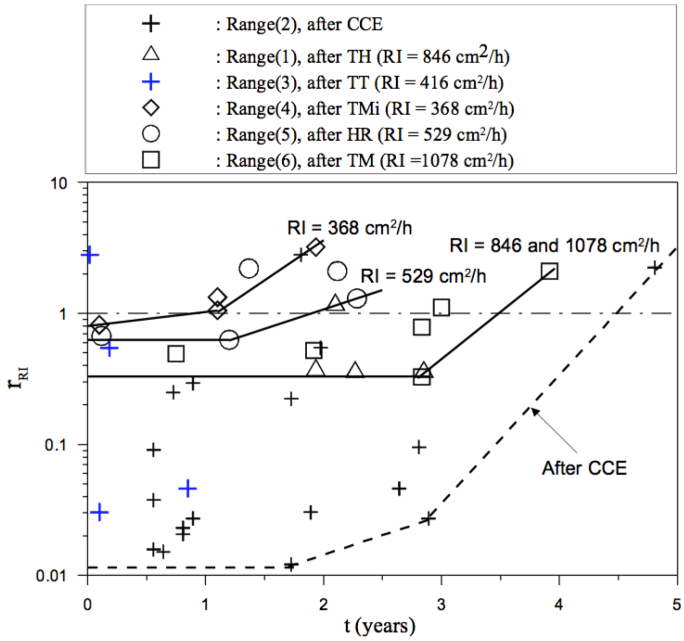


Figure 3: Relationships between the rainfall index ratio r_{RI} and the period t after extreme rainfalls driven by various values of RI. Four critical lines were determined from the lower bounds of ranges (4), (5), (1) and (6), and (2) in Table 2, representing the critical RI affected by extreme event TMi, HR, TH and TM, and CCE.

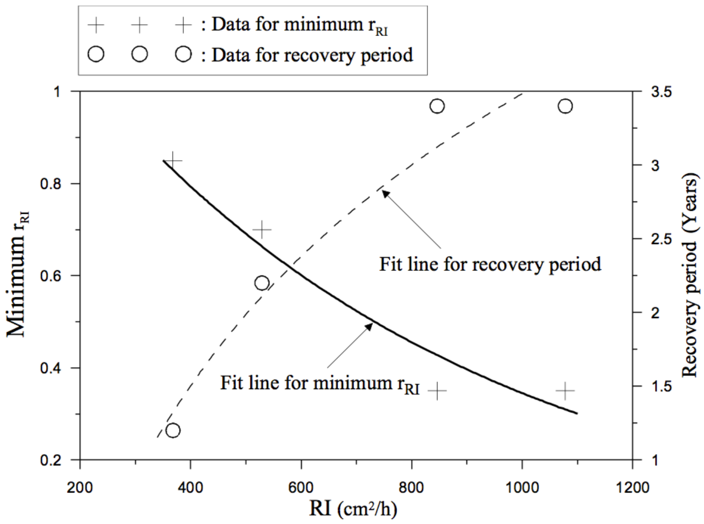


Figure 4: Variations of minimum r_{RI} and recovery period after an extreme rainfall driven by the rainfall index RI. Four data sets for minimum r_{RI} or recovery period were obtained from the critical lines in Figure 3 after extreme events TMi (RI=368 cm^2/h), HR (RI=529 cm^2/h), TH (RI=846 cm^2/h), and TM (RI=1078 cm^2/h).

5. Relationship between the probability of debris flow occurrence and return period

Return period is the average interval in years between events equaling or exceeding a certain magnitude. Return period of rainfall responds the long-term hydrological characteristics of an area and is useful for hydrological or hydraulic design. Therefore, the rainfall index RI associated with return period was determined, and the relationship between the probability of debris flow occurrence and return period was developed.

5-1 Return period of rainfall

Many methods, such as the formulas by Weibull, Jenkinson, and Gringorten, the computational methods, as well as the modified Gumbel method, have been used to evaluate the return period of rainfall (Makkonen, 2006). The Weibull formula was used to estimate return period for the rainfall of annual maximum series in this study because it can predict much shorter return periods of extreme events than the other methods (Makkonen, 2006). Return period T can be estimated by the Weilbull formula as

$$T = (n+1) / m \tag{3}$$

where n refers to the number of years in the record and m is the rank of a value in a list ordered by descending magnitude. The RI data of the annual maximum series collected in the Chenyulan watershed between 1960 and 2016 were used to determine T. Figure 5 shows the relationship between RI and T, which can be expressed as

$$RI = 180\ (T-0.98)^{0.44} \tag{4a}$$

or

$$T = (RI\ /180)^{2.27} + 0.98 \tag{4b}$$

Eq. (4a) or (4b) provide good estimates of rainfall index RI with return period T of less than 50 years. Debris flows could be triggered at lower RI values, corresponding with lower T values for rainfall events within five years after the Chi-Chi earthquake (CCE), as shown by the cross symbols in Figure 5. Five extreme rainfall events, TMi, TT, HR, TH, and TM, are also shown in Figure 5. Excluding TMi and TT, affected by the CCE (within five years after the CCE), the extreme events mostly had T values exceeding 10 years. The T value for the critical RI affected by the CCE was approximately 1 years, much smaller than that affected by extreme events.

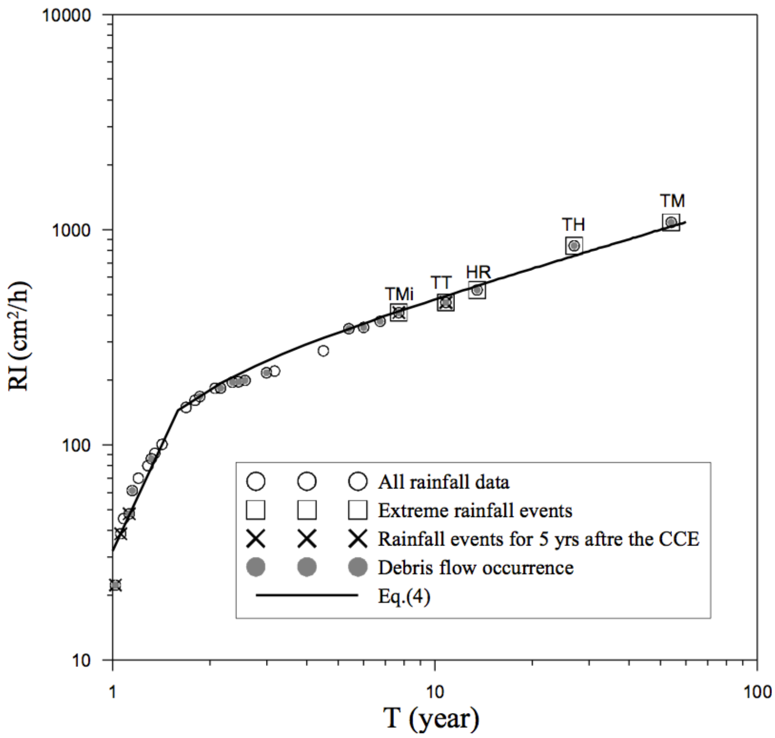


Figure 5: Relationship between the rainfall index (RI) and the return period (T) in the Chenyulan watershed.

5-2 Probability of debris flow occurrence

The probability of debris flow occurrence (P) for a rainfall event greater than the value of RI can be calculated by the number (N_D) of rainfall events that have triggered debris flows divided by the number (N_R) of rainfall events, where $P = N_D/N_R$. Hence, the probability of debris flow occurrence (P) for a rainfall event with given a rainfall characteristic of RI or the return period of rainfall (T) corresponding to RI (based on the data in Figure 5) could be determined. Four empirical curves of P versus RI or T based on different periods were developed. The four periods were: (i) the Chi-Chi earthquake-affected period (CCEAP), (ii) the extreme rainfall-affected period (ERAP), (iii) the whole period (WP) between 1985 and 2016, and (iv) the WP excluding CCEAP and ERAP. After the CCE, the critical RI dropped sharply to approximately 2 cm^2/h, which was 30 times lower than that before (critical RI = 60 cm^2/h) (Figure 2). The CCE significantly lowered the critical rainfall threshold for debris flow occurrence in the subsequent five years (Chen, 2011; Chen et al., 2013). Hence, the CCEAP was considered to be the period of five years after the CCE. Because the critical RI of debris flow occurrence was affected by extreme rainfalls and the affected periods could reach three years (i.e., the maximum recovery period is approximately three years in Figure 4), data within three years after extreme rainfalls were selected to develop the relationship of P versus RI or T for the ERAP. Finally, the WP considered the data of whole period (1985–2016), including CCEAP and ERAP.

Figure 6 shows the relationships between P and T for the four periods, which can be expressed in the form of a logistic function (Hosmer and Lemeshow, 2000)

$$P = \frac{1}{1 + e^{-(\alpha + \beta T)}} \tag{5}$$

where α and β are empirical coefficients that can be determined by fitting the given data. The empirical coefficients α and β for the four periods are listed in Table 3.

Table 3: Empirical coefficients of α and β for the four studied periods

Period	α	β
I. Whole period (WP) (1985–2016)	-1.11	0.98
II. Chi-Chi earthquake-affected period (CCEAP)	-50.0	48.5
III. Extreme rainfall-affected period (ERAP)	-3.97	3.89
IV. WP excluding CCEAP and ERAP	-0.95	0.78

The fitted curve of the P–T relationship for WP was similar to that of WP excluding CCEAP and ERAP. Because WP used long-term data between 1985 and 2016, excluding the short-term data of CCEAP and ERAP to develop the P–T relationship, there was no obvious difference. Meanwhile, P rose significantly after an extreme rainfall event or CCE at the same T or under the same rainfall condition. In particular, the P value affected by CCE was markedly higher than that affected by extreme rainfalls. The benefits of developing the P–T relationship (Figure 6) lie in that P values can be evaluated at various T values (or different rainfall conditions) to understand how P is affected by the CCE or extreme rainfall. For example, P = 59% at T = 1.5 yr (see black curve in Figure 6), while P increases to 87% after an extreme rainfall event (see blue curve) and P = 100% after the CCE (see red curve).

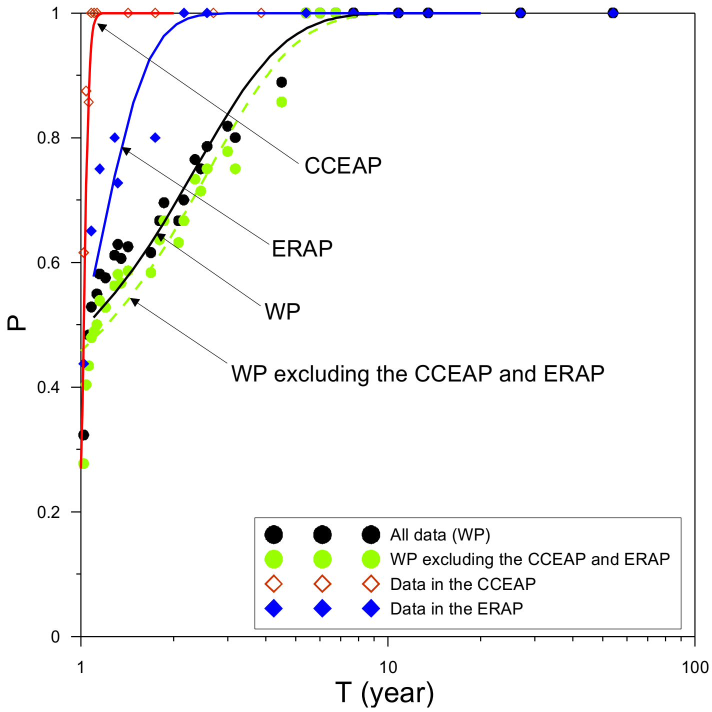


Figure 6: Relationship between the probability of debris flow occurrence P and return period T (the P–T relationship) for the Chi-Chi earthquake-affected period (CCEAP), extreme rainfall-affected period (ERAP), the whole period (WP), and the WP excluding the CCEAP and ERAP

6. Application of the empirical model

The heavy rainfall brought by Typhoon Morakot in August 2009 had a maximum hourly rainfall (I_m) of 123 mm and 48-h rainfall of 2,361 mm (measured at Alishan rainfall station), which caused numerous debris flows that buried more than 20 houses in Shenmu, Tongfu, and Xinyi villages (Chen et al., 2011) in the Chenyulan watershed. The relationship between P and T were applied to evaluate the probability of debris flow occurrence after a recent rainfall event of Typhoon Morakot.

6-1 Procedures

The empirical model for evaluating the probability of debris flow occurrence was applied through the following steps:

1. Input the hourly rainfall data from three metrological stations and evaluate the regional hourly rainfall using Eq. (1)
2. Determine I_m and R_d from regional rainfall data and calculate the rainfall index RI by Eq. (2)
3. Determine the return period T from Eq. (4b) by giving RI
4. Determine the probability of debris flow occurrence using the P–T relationship.

The P–T relationship of the whole period (WP) is

$$P = \frac{1}{1+e^{1.11-0.98T}} \tag{6}$$

and the P–T relationship of the extreme rainfall-affected period (ERAP) is

$$P = \frac{1}{1+e^{3.97-3.89T}} \tag{7}$$

where T is associated with RI and can be determined by Eq. (4), i.e., $T = (RI/180)^{2.27} + 0.98$. The probability of debris flow occurrence (P) can be determined when RI is given according to Eq. (6) or Eq. (7).

However, the two equations were developed based on different periods and different data sets, and the valid conditions for the two equations may not be identical. Eq. (6) predominantly reflects the long-term characteristics of debris flow occurrence, and cannot reflect the short-term characteristic caused by extreme events. In contrast, Eq. (7) focuses on the influence of extreme rainfall events. Hence, field data of debris flow occurrence and rainfall between 2012 and 2014 were collected to assess the proposed equations.

6-2 Results

Figure 7 shows the variation in the predicted probability of debris flow occurrence P (blue dot) derived from Eq. (6) for rainfall events with return period greater than one year (T >1 yr) from 2012 to 2014, and labels debris flow events. There were four debris flow events triggered by the rainstorm and Typhoon Talim in 2012, Typhoon Saola and Typhoon Soulik in 2013 (Table 2). Most debris flow events, three of four, reasonably predicted that three predicted P values exceeding 50%. One debris flow event during Typhoon Talim was not predicted successfully in association with the events occurring within three years after the extreme rainfall event of Typhoon Morakot. The RI for debris flow occurrence decreased in the early stage after the extreme rainfall event owing to the fact that extreme rainfalls result in large amounts of loose debris in gullies and on slopes. When the P–T relationship in ERAP (Eq. (7)) was used, instead of Eq. (6), the predicted P (red dot) with P > 50% was in agreement with the field data of debris flow occurrence, as shown in Figure 8.

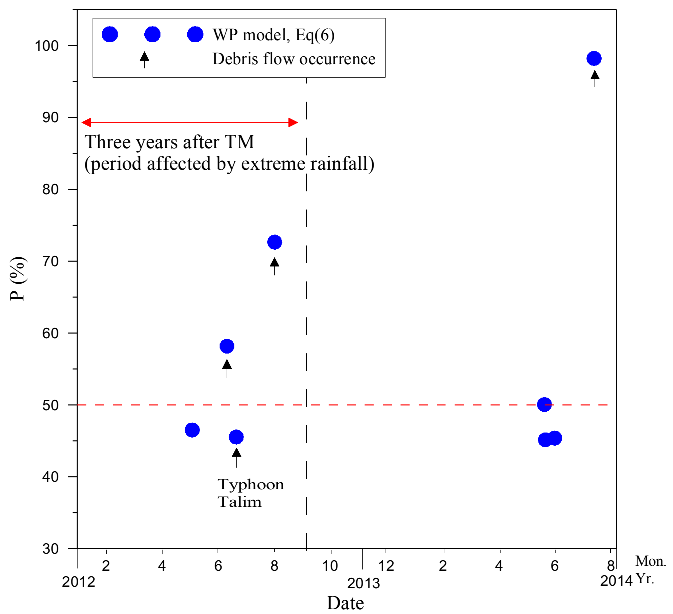


Figure 7: Application of the probabilistic model of debris flow occurrence in the whole period (WP) between 2012 and 2014.

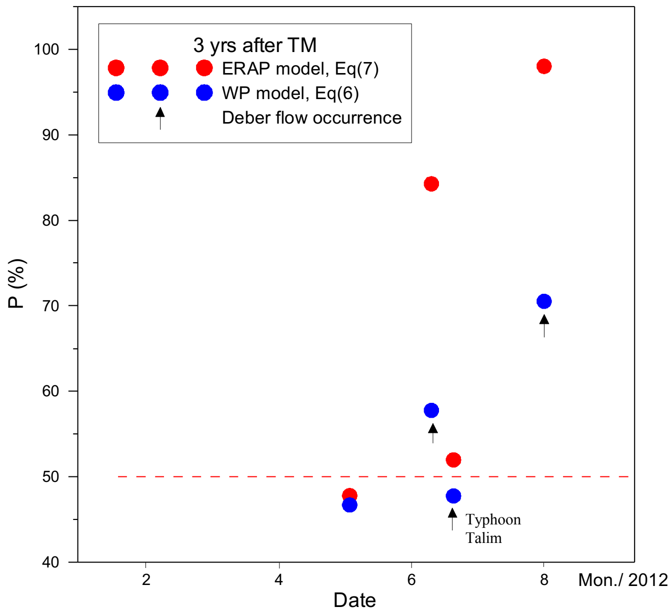


Figure 8: Probabilistic model of debris flow occurrence in the whole period (WP) compared with that in the rainfall-affected period (ERAP) within the three years after Typhoon Morakot. There are three debris flow occurrence events. Three rainfall events show the predicted probability of debris flow occurrence P exceeding 50% by the model in ERAP, and two rainfall events show the predicted P exceeding 50% by the model in WP.

7. Conclusions

1. Debris flows and their corresponding rainfall events in the Chenyulan watershed, central Taiwan were investigated. The rainfall index RI, defined as the product of I_m and R_d, was used to analyze the rainfall conditions critical for debris flow occurrence after extreme events. The extreme events included the Chi-Chi earthquake in 1999 and five extreme rainfalls in 1996, 2001, 2004, 2006, and 2009. The extreme rainfall events and the Chi-Chi earthquake affected the critical condition for the occurrence of debris flows. The rainfall index RI could reflect the debris flow initiation characteristics after extreme rainfall events.
2. The RI threshold for the occurrence of debris flows was reduced in the years following an extreme rainfall event. Reduced RI values showed an increasing trend over time, and it gradually returned to the original RI, representative of the RI unaffected by the extreme rainfall. The required time, i.e., the recovery period, for the decreased RI to return to the original value for

extreme rainfalls was analyzed. The reduction in RI as well as the recovery period were influenced by the RI. The RI at the early stage after an extreme rainfall showed the maximum decrease of approximately 30% of the original RI. The maximum the recovery period was approximately three years. Understanding the reduced RI and the recovery period is helpful for modifying the criteria of debris flow warnings.

3. The rainfall index RI associated with return period was analyzed. The extreme events triggering numerous debris flows, excluding events affected by the Chi-Chi earthquake (CCE), mostly had return period exceeding 10 years. The return period for the critical RI affected by the CCE was approximately 1 year, much smaller than that affected by extreme events. The empirical relationships between the probability of debris flow occurrence P and return period based on the Chi-Chi earthquake and extreme rainfalls were developed. P increased significantly after extreme rainfall events or the Chi-Chi earthquake at the same return period. In particular, the P value influenced by the Chi-Chi earthquake was markedly higher than that affected by extreme rainfall events.
4. The relationship between the probability of debris flow occurrence P and the return period T was applied to evaluate P during recent rainfall events after the extreme rainfall of Typhoon Morakot, which showed that the model was reasonable for explaining debris flow occurrence. The benefits of developing the P–T relationship include that P values can be evaluated at various T values (or different rainfall conditions) to understand how the probability of debris flow occurrence is affected by the Chi-Chi earthquake or extreme rainfall.
5. The empirical model for evaluating the probability of debris flow occurrence was developed based on the regional characteristics of the Chenyulan watershed and it may not be applicable to areas with different hydrogeological properties. The reasonability of this model must be assessed and empirical coefficients are required for calibration if the model is to be applied to other area. In addition, this model mainly reflects the overall critical rainfall conditions to trigger debris flow in a region after extreme events, and it may not be valid for the evaluation of the probability of debris flow occurrence for small catchments with single debris flow. To verify the applicability of

the model to other case studies, more detailed data must be collected and analyzed in order to establish empirical formulas and models.

Appendix A

List of symbols and abbreviations

CCE	Chi-Chi earthquake
CCEAP	Chi-Chi earthquake-affected period
ERAP	Extreme rainfall-affected period
HR	Heavy rainstorm in 2006
I	Region hourly rainfall
I_1, I_2, I_3	Hourly rainfall record from the Sun Moon Lake, Yushan, and Alisan meteorological stations, respectively.
I_m	Maximum hourly rainfall during each rainfall event
N	Total number of individual debris flows triggered by each rainfall event
N_D	Number of rainfall events that have triggered debris flows
N_R	Number of rainfall events
n	Number of years in the record
m	Rank of a value in a list ordered by descending magnitude
P	Probability of debris flow occurrence
R_d	Maximum 24-h rainfall amount during each rainfall event
RI	Rainfall index, $RI = R_d I_m$
r_{RI}	Ratio of RI to original RI (=165 cm^2/h)
T	Return period of rainfall
TH	Typhoon Herb
TM	Typhoon Morakot
TMi	Typhoon Mindulle
TT	Typhoon Toraji
t	Period after an extreme rainfall event, the estimated period from the time of an

	extreme event
WP	Whole period, 1985–2016
α and β	Empirical coefficients in Eq. (5)

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