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Characteristics of rainfall triggering of debris flows in the Chenyulan watershed, Taiwan

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Abstract. This paper reports the variation in rainfall characteristics associated with debris flows in the Chenyulan watershed, central Taiwan, between 1963 and 2009. The maximum hourly rainfall I_m, the maximum 24 h rainfall R_d, and the rainfall index RI (defined as the product $R_\mathrm{d} I_\mathrm{m}$) were analysed for each rainfall event that triggered a debris flow within the watershed. The corresponding number of debris flows initiated by each rainfall event (N) was also investigated via image analysis and/or field investigation. The relationship between N and RI was analysed. Higher RI of a rainfall event would trigger a larger number of debris flows. This paper also discusses the effects of the Chi-Chi earthquake (CCE) on this relationship and on debris flow initiation. The results showed that the critical RI for debris flow initiation had significant variations and was significantly lower in the years immediately following the CCE of 1999, but appeared to revert to the pre-earthquake condition about five years later. Under the same extreme rainfall event of $RI = 365\,\mathrm{cm}^2\,\mathrm{h}^{-1}$, the value of N in the CCE-affected period could be six times larger than that in the non-CCE-affected periods.

1 Introduction

Over the last few decades, global-warming-induced climate change has manifested in a number of ways including extreme rainfall events (for example, Katz and Brown, 1992; Fauchereau et al., 2003; Fowler et al., 2005; Sillmann and Roeckner, 2008). As a consequence, higher frequencies and larger magnitudes of rainfall-induced landslides and/or debris flows have been reported worldwide (Eybergen and Imeson, 1989; Rickenmann and Zimmermann, 1993; Evans and Clague, 1994; Van Steijn, 1996; Jomelli et al., 2007; Pelfini and Santilli, 2008; Floris et al., 2010). This paper examines the variation in the characteristics of rainfall events triggering debris flows and the effects on the number of debris flows in the Chenyulan watershed, central Taiwan. Chen et al. (2012) found that the number of extreme rainfall events within the watershed showed an increasing trend, which was associated with the greater number and magnitude of debris flows during the last decade. Landslides and debris flows caused by severe rainfall events affect the volume of loose debris within a watershed, which may change the critical rainfall threshold for the initiation of debris flow in subsequent rainfall events. Therefore, understanding the variation in rainfall characteristics and its influence on debris flow initiation is important for debris flow warning and hazard mitigation.

Debris flow, a highly hazardous hydrological process, occurs frequently in the Chenyulan watershed. Some significant debris flow events in the watershed were previously studied and documented (Lin and Jeng, 2000; Chang et al., 2001; Cheng et al., 2005; Jan and Chen, 2005; Chen et al., 2011). The major Chi-Chi earthquake of 1999 (7.6 on the moment magnitude scale, 7.3 on the Richter scale) caused numerous landslides in the Chenyulan watershed. Previous investigators examined some phenomena of debris flows following the Chi-Chi earthquake, such as the effect of the earthquake on the characteristics of debris flows (Lin et al., 2003; Liu et al., 2008), the effects of strong ground motion on the susceptibility of debris flows (Liu et al., 2009), the variation in rainfall conditions required to trigger debris flows after the Chi-Chi earthquake (Chen, 2011), and recent changes in the number of rainfall events related to debris flow occurrence (Chen et al., 2012).

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Table 1. Debris flow events and related rainfall characteristics in the Chenyulan watershed between 1963 and 2009 (Modified from Chen et al., 2012).

Year	Date of the rainfall event	Name of rainfall event	Number of debris flows N	Maximum hourly rainfall, I_m (mm h^{-1})	Maximum 24 h rainfall, R_d (mm)	Rainfall duration, T (h)	Rainfall index, RI (cm^2 h^{-1})
1963	10–12 Sep	Typhoon Gloria	1*	36.1	668.1	82.0	241.2
1985	23–25 Aug	Typhoon Nelson	2*	47.2	418.8	50.0	197.7
1986	21–22 Aug	Typhoon Wayne	2*	50.8	329.8	18.0	167.5
1992	30–31 Aug	Typhoon Polly	1*	41.3	479.5	41.0	198.0
1996	31 July–1 Aug	Typhoon Herb	37	71.6	1181.6	35.0	846.0
1998	7–8 June	Rainstorm	3	28.1	227.8	40.0	64.0
1998	4–5 Aug	Typhoon Otto	4	64.6	311.7	19.0	201.4
1998	15–16 Oct	Typhoon Zeb	2	24.6	251.0	31.0	61.7
1999	27–28 May	Rainstorm	2	24.3	254.3	32.0	61.8
2000	01 Apr	Rainstorm	2	20.0	75.1	8.0	15.0
2000	25 Apr	Rainstorm	1	8.4	30.6	9.0	2.6
2000	28–29 Apr	Rainstorm	1	7.9	78.2	14.0	6.2
2000	2 May	Rainstorm	1	8.1	30.6	5.0	2.5
2000	12–14 June	Rainstorm	4	18.0	228.1	47.0	41.1
2000	18 July	Rainstorm	3	12.7	30.0	3.0	3.8
2000	22 July	Rainstorm	3	16.3	20.7	2.0	3.4
2000	5 Aug	Rainstorm	4	11.6	38.8	10.0	4.5
2000	22–23 Aug	Typhoon Bilis	2	20.6	234.5	24.0	48.3
2001	5 June	Rainstorm	1	7.5	27.0	8.0	2.0
2001	14–15 June	Rainstorm	3	18.4	200.1	24.0	36.8
2001	29–30 July	Typhoon Toraji	78	78.5	587.6	18.0	461.3
2001	10 Aug	Rainstorm	3	22.4	22.4	1.0	5.0
2001	17 Sep	Typhoon Nari	4	35.7	252.5	23.0	90.1
2002	31 May	Rainstorm	4	14.4	53.0	7.0	7.6
2002	3–4 July	Rainstorm	2	13.3	117.9	19.0	15.7
2002	12 Aug	Rainstorm	1	17.1	26.5	3.0	4.5
2004	2–3 July	Typhoon Mindulle	17	54.0	681.4	38.0	368.0
2004	23–25 Aug	Typhoon Aere	2	35.0	385.4	47.0	134.9
2005	4–5 Aug	Typhoon Matsa	1	42.3	411.9	34.0	174.2
2005	31 Aug–1 Sep	Rainstorm	1	44.3	495.0	27.0	219.3
2006	8–11 June	Rainstorm	10	77.5	682.8	78.0	529.2
2006	13–15 July	Typhoon Bilis	2	29.9	371.7	56.0	111.1
2007	17–20 Aug	Typhoon Sepat	1	31.6	328.4	66.0	103.8
2007	6–7 Oct	Typhoon Krosa	1	54.3	669.4	35.0	363.5
2008	17–18 July	Typhoon Kalmaegi	3	67.2	515.7	18.0	346.6
2008	12–15 Sep	Typhoon Sinlaku	2	35.0	612.4	66.0	214.3
2009	6–11 Aug	Typhoon Morakot	41	85.5	1192.6	110.0	1019.7

Note: *: Debris flow data obtained only from scientific papers/reports before 1996; no aerial photographs and satellite images were available to identify debris flows in the whole watershed before Typhoon Herb. N = total number of individual debris flow triggered by each rainfall event in the Chenyulan watershed; I_m = maximum hourly rainfall in each rainfall event; R_d = maximum 24 h rainfall amount in each rainfall event; RI = rainfall index, $RI = R_\mathrm{d} I_\mathrm{m}$.

Extreme rainfall causes numerous landslides and debris flows in mountainous watersheds, which generally deposit large amounts of loose debris in gullies and on slopes (Dong et al., 2009; Chen et al., 2012). The supply of loose debris plays an important role in the occurrence of future debris flows during subsequent rainfall events (Jakob et al., 2005). Both the critical rainfall threshold for debris flow initiation and the number of debris flows caused by a rainfall event may differ before and after an extreme rainfall event or a major earthquake. This study analysed the characteristics of rainfall related to debris flow occurrence between 1963 and 2009 in the Chenyulan watershed, in order to investigate (1) the variation in the regional rainfall conditions related to debris flow occurrences, and (2) the empirical relationship between rainfall characteristics and the corresponding number of debris flows.

2 Debris flow events and their corresponding rainfall events

2.1 Debris flows in the Chenyulan watershed

The watershed of Chenyulan stream, located in Nantou County, central Taiwan (Fig. 1), has an area of 449 km^2, main stream length of 42 km, average stream-bed gradient of 4°, and elevations ranging from 310 to 3952 m. The annual regional rainfall in the watershed is between 2000 and 5000 mm, with an average of approximately 3500 mm.

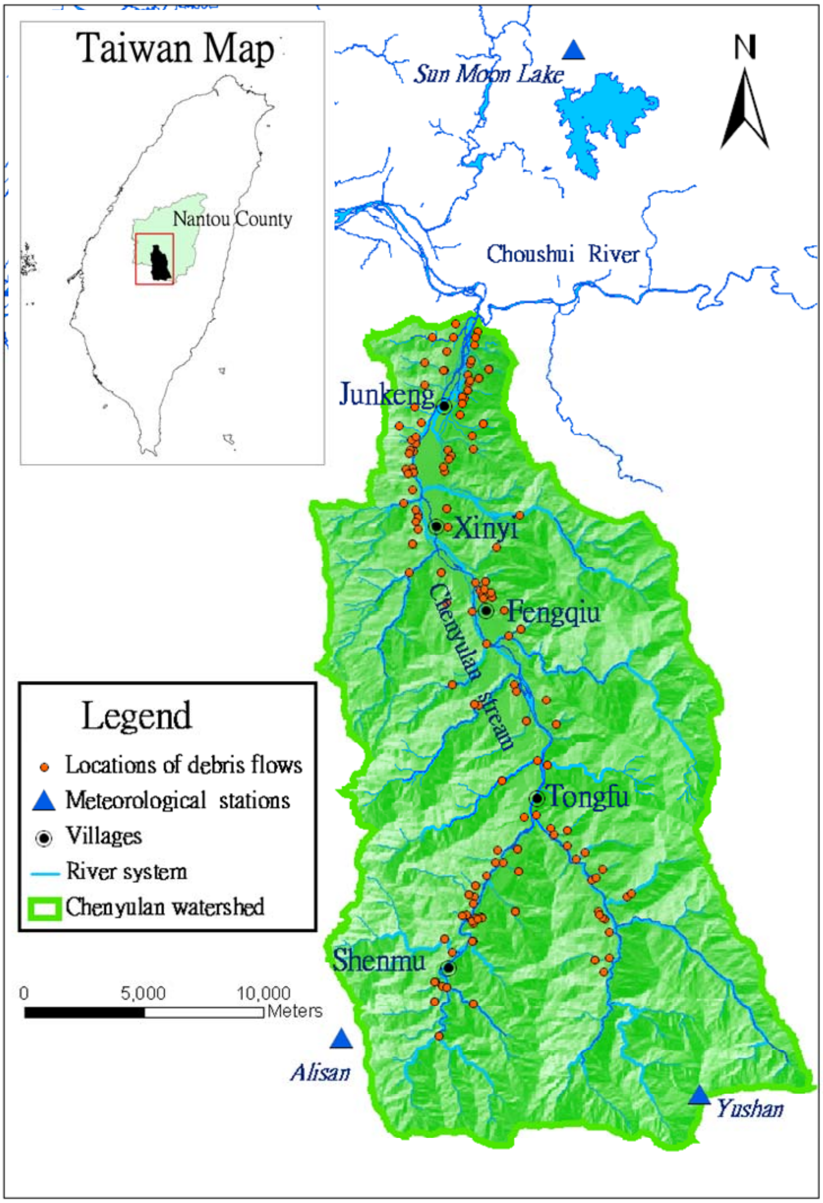


Fig. 1. Locations of debris flows and meteorological stations in the Chenyulan watershed (Modified from Chen et al., 2012).

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. Owing to steep topography, loose soils, young (3 million years) and weak (due to ongoing orogenesis) geological formations, heavy rainfall and active earthquakes, many debris flows were triggered by more than 30 rainfall events between 1963 and 2009 in the watershed, as shown in Table 1. The most significant debris flow events were those caused by heavy rainfall brought by Typhoon Herb in 1996, Typhoon Toraji in 2001 and Typhoon Morakot in 2009. During the two day period from 31 July to 1 August 1996, Typhoon Herb brought an unexpectedly high cumulative rainfall of almost 2000 mm, which initiated 37 debris flows, leading to 27 deaths and 14 people being reported missing in the watershed (Jan and Chen, 2005). The Chi-Chi earthquake of 21 September 1999 was the largest earthquake in Taiwan for a hundred years (Shin and Teng, 2001), and caused numerous landslides in the Chenyulan watershed. The extreme rainfall event caused by Typhoon Toraji from 29–30 July 2001 had a maximum hourly rainfall of 78.5 mm and 24 h rainfall of 587.6 mm; this event caused more than 30 debris flows in the watershed, resulting in more than 100 people being reported dead or missing, and widespread damage to houses, roads and bridges (Chen et al., 2012). The heavy rainfall brought by Typhoon Morakot in August 2009 had a maximum hourly rainfall of 123 mm and 48 h rainfall of 2361 mm (measured at Alishan rainfall station), and caused numerous debris flows that buried more than 20 houses, especially in Shenmu, Tongfu and Xinyi villages (Chen et al., 2011).

2.2 Identification of debris flow events

Naturally occurring high-discharge flows of water and sediment in open channels vary over a wide and continuous spectrum of sediment concentration and particle-size distribution (Pierson, 2005). Water floods normally transport relatively small quantities of mostly fine sediment. At the other end of the spectrum, high-discharge debris flows may transport more sediment than water. The term "debris flood" or "mud flood" is often applied to flows intermediate between these two extremes (Pierson, 2005). For hazard management purposes, only a debris flow that occurs in a watershed with an area more than 3.0 ha and of main upstream slope more than 10° is officially recognised as a debris flow in Taiwan; otherwise, the flow would be treated as a sediment-laden flow, a debris flood or a mud flood. Therefore, the present study also adopts this classification when counting the number of debris flows triggered during a rainfall event. Debris flow data prior to 1996 was obtained from the scientific literature (such as Yu and Chen, 1987; Chiang and Lin, 1991; Chang et al., 2001). No aerial photographs and satellite images were available to identify debris flows in the whole watershed before 1996. After 1996, according to their specific features, debris flows were identified through interpretation of aerial photographs, satellite images or/and field investigations. The identification of debris flows involved two basic stages. In the first stage, the possible locations of debris flow were identified from media reports (local newspapers, TV news), related documents and papers (Lin and Jeng, 2000; Cheng et al., 2005; Jan and Chen, 2005; Chen et al., 2009, 2012; Chen, 2011), and interpretation of images, such as aerial photographs and satellite images (SPOT images before 2004; FORMOSAT2 images after 2004) to assess whether the event was classified as a debris flow. The second stage was to conduct a field investigation to confirm whether the event identified in the first stage qualified as a debris flow.

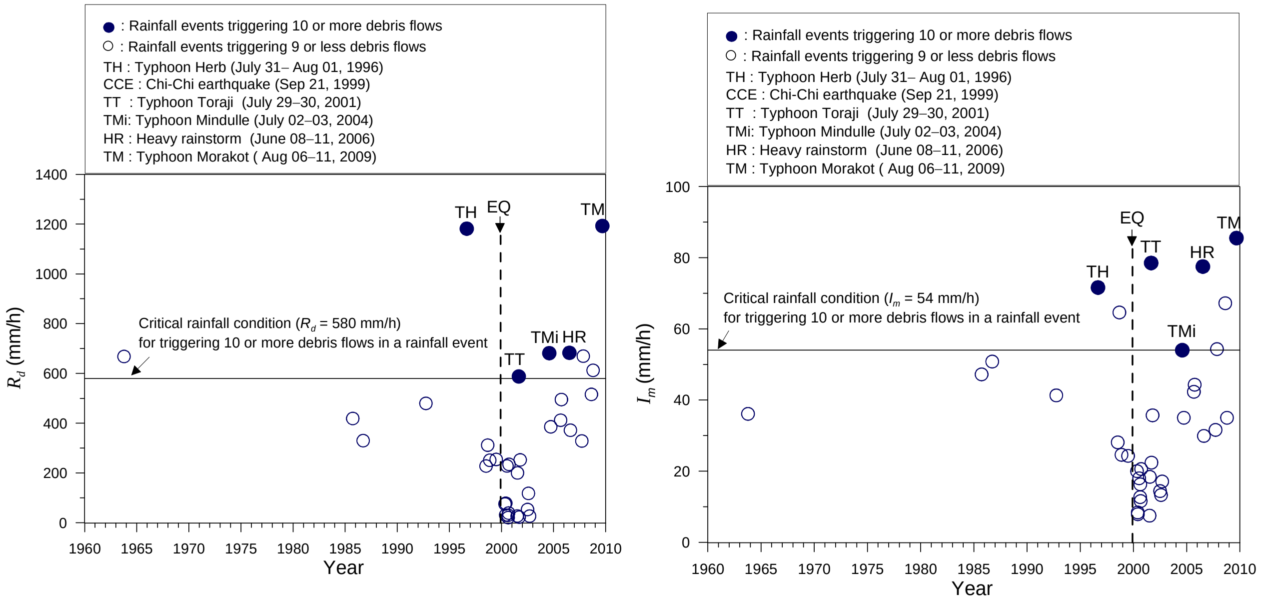
Identifying debris flows, it was decided that each of the soil slip, flow path and deposits should be identifiable from the images – that is, the source, transportation, and deposition zones should be identifiable from aerial photographs or satellite images. These features on aerial photographs were previously used by Liu et al. (2008) to identify debris flows. A debris flow is a rapid movement of debris materials along the flow path. Some important features of a debris flow include traces of channelised stream flow, a large erosion capacity (such as sharp bank erosion, fallen tree trunks), the transport of large boulders, the formation of levees, uneven and poorly sorted deposits, and scarring high on streamsides and deposits high in trees (Costa, 1984). These features provide evidence of debris flow, and can be used to identify debris flow in field investigation. In this study, only gullies with obvious patterns of debris flow were identified as debris flow events.

Table 1 shows 37 rainfall events, including 18 rainstorms and 19 typhoon-induced heavy rainfall events, that triggered debris flows in the Chenyulan watershed during the study period; and the number of debris flow events (N) for each rainfall event throughout the watershed. Table 1 shows that most rainfall events triggered four or fewer debris flows, but that some particularly severe events, such as those associated with heavy rainstorms in 2006, and with Typhoons Herb (1996), Toraji (2001), Mindulle (2004) and Morakot (2009), induced ten or more debris flows. The maximum number of debris flows was 78, which were triggered by Typhoon Toraji, approximately two years after the Chi-Chi earthquake; Typhoons Herb and Morakot triggered 37 and 41 debris flows, respectively, within the watershed.

2.3 Regional rainfall characteristics versus debris flows

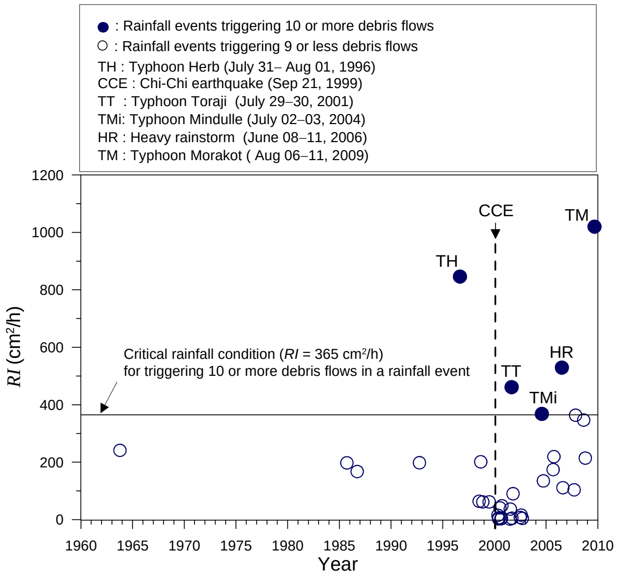
To investigate the variation in rainfall characteristics in the Chenyulan watershed, long-term rainfall records were obtained from three meteorological stations (Sun Moon Lake, Yushan and Alisan stations, as shown in Fig. 1). These data were used to estimate the regional rainfall characteristics for the whole Chenyulan watershed, via the reciprocal-distance-squared (RDS) method (Chow et al., 1988). The estimated point using this method was taken at the centroid of the watershed area. The rainfall characteristics estimated by the RDS 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 RDS method can easily represent the variation trend for regional rainfall characteristics throughout the Chenyulan watershed (Chen et al., 2012). The present paper calculated regional hourly rainfall, cumulative rainfall and rainfall duration, etc., of each rainfall event associated with debris flow occurrence, in order to study the relationship between rainfall characteristics and debris flow occurrence.

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. For example, the empirical relationship between average rainfall intensity and rainfall duration was used to assess the potential for debris flow occurrence in a rainfall event (Caine, 1980; Keefer et al., 1987; Chen, 2011). Rainfall data on a daily scale, such as maximum 24 h rainfall, daily rainfall, or 3 day rainfall, have been used to analyse the influence of rainfall change on debris flow



(a) R_d index

(b) I_m index



(c) RI index

Fig. 2. Variations in three rainfall parameters contributing to debris flows between 1963 and 2009 in the Chenyulan watershed. The Chi-Chi earthquake significantly lowered the rainfall threshold for debris flow occurrence, during approximately the subsequent 5 yr.

activity (Rebetez et al., 1997; Zhuang et al., 2011; Chen et al., 2012). 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, and were closely related to the maximum hourly rainfall I_m (Lin and Jeng, 2000; Chen et al., 2011, 2012). The corresponding I_m and R_d for debris flow events in the Chenyulan watershed between 1963 and 2009 (see Table 1) shows that Typhoons Herb (1996), Toraji (2001), Mindulle (2004), heavy rainstorm in 2006, and Typhoon Morakot (2009), all had the extreme characteristics, of $R_\mathrm{d} > 580$ mm (this threshold was used by Chen et al. (2012) to analyse the variation of extreme rainfall events in the Chenyulan watershed) and $I_\mathrm{m} > 54\,\mathrm{mm\,h^{-1}}$, especially Typhoon Morakot, with $R_\mathrm{d} = 1192.6$ mm and $I_\mathrm{m} = 85.5\,\mathrm{mm\,h^{-1}}$. Each of these five extreme rainfall events caused 10 or more debris flows. However, as shown in Table 1 and Fig. 2a and b, only five of the eight $R_\mathrm{d} > 580$ mm or $I_\mathrm{m} > 54\,\mathrm{mm\,h^{-1}}$ extreme rainfall events caused 10 or more debris flows. Therefore, 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. The occurrence of debris flow is related to not only accumulated rainfall, but also rainfall intensity. A triggering index *RI* of a rainfall event, defined as the product of R_d and I_m (i.e., $RI = R_\mathrm{d} I_\mathrm{m}$), could be used as a critical condition for the occurrence of multiple debris flows. As shown in Fig. 2c, for $RI > 365\,\mathrm{cm^2\,h^{-1}}$, all five of the extreme rainfall events caused multiple debris flows, with $N \geq 10$. The rainfall data used in this study is limited to hourly rainfall data because the minute-scale rainfall data, such as 5 or 10 min rainfall data was not available. Other rainfall indices, such as total storm rainfall, or rainfall duration, have less correlation with the number of debris flow events when compared to the *RI* index.

3 Influence of rainfall variation on debris flows occurrence

Figures 2a–c show parameters for rainfall events that initiated debris flows between 1936 and 2009. There are eight rainfall events with maximum 24 h rainfall R_d greater than 580 mm, of which seven occurred after 1996; rainfall events with maximum hourly rainfall I_m greater than 54 mm or rainfall index *RI* larger than $365\,\mathrm{cm^2\,h^{-1}}$ all occurred after 1996. This implies that rainfall events became more severe after 1996.

As shown in Fig. 3, the critical *RI*s for debris flow occurrence were approximately 165 cm^2/h before Typhoon Herb (TH) in 1996; $60\,\mathrm{cm^2\,h^{-1}}$ between TH and the Chi-Chi earthquake (CCE) in 1999; $2\,\mathrm{cm^2\,h^{-1}}$ between CCE and Typhoon Mindulle (TMi) in 2004; and $100\,\mathrm{cm^2\,h^{-1}}$ between TMi and Typhoon Morakot (TM) in 2009.

Between 1963 and 1996, the most severe rainfall event was TH, and the condition for debris flow occurrence was $RI > 165\,\mathrm{cm^2\,h^{-1}}$. TH brought severe rainfall and caused numerous landslides and debris flows in the Chenyulan watershed. Subsequently, abundant loose debris deposits remained on slopes or in gullies to serve as source material for later rainfall-induced debris flows. Since this loose sediment was generally of lower soil strength, less rainfall (with *RI* approximately equal or greater than 60 cm^2 h$-$1) was needed to trigger debris flows in subsequent years, between TH and CCE.

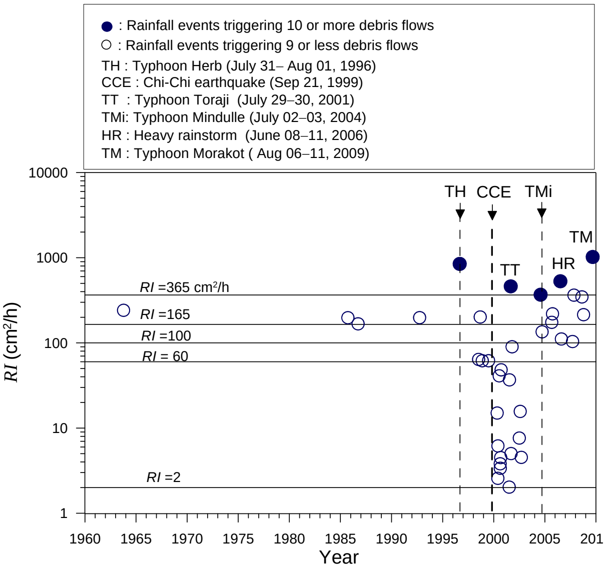


Fig. 3. The variations in rainfall index *RI* for all rainfall events triggering debris flows between 1963 and 2009 in the Chenyulan watershed. The critical *RI* for debris flow occurrence in the years following the Chi-Chi earthquake is much smaller than those before the earthquake and five years after the earthquake.

The CCE in 1999 was the largest earthquake in Taiwan for a century, and caused numerous landslides in the Chenyulan watershed. Since a large amount of loose sediment with lower soil strength was deposited on streambeds or hillsides after the earthquake, much lower pore water pressure or rainfall was required to initiate the movement of this sediment (Lin et al., 2003; Chen et al., 2007; Chen and Jan, 2008). Therefore, the critical *RI* for debris flow occurrence dropped sharply in the subsequent early years, to $2\,\mathrm{cm^2\,h^{-1}}$. That is to say that the critical *RI* ($2\,\mathrm{cm^2\,h^{-1}}$) for debris flow occurrence in the period between CCE and TMi was only one-thirtieth of that ($60\,\mathrm{cm^2\,h^{-1}}$) before the CCE (between TH and CCE). After about 5 years, the loose sediment generally became consolidated and re-orientated over time, less soil and rock remained deposited in streams, and the shear strength of the soil gradually increased (Fan et al., 2003; Chen, 2011). The critical *RI* gradually recovered from $2\,\mathrm{cm^2\,h^{-1}}$ to $100\,\mathrm{cm^2\,h^{-1}}$. The variation of critical *RI* is related to debris supply within the watershed. Dong et al. (2009) developed a susceptibility index (*SI*) that accounted for debris supply to estimate the susceptibility to debris flow. They reported that the *SI* increased following the CCE and after TT (before the occurrence of debris flow), because the volume of debris contributed by shallow landslides increased; and that *SI* decreased when the volume of debris was reduced by debris outflow during TT and TMi. A higher *SI* may lead to a smaller critical *RI*; conversely, a lower *SI* may require a larger critical *RI* to trigger debris flow. These results confirm that the *RI* for debris flow occurrence decreased in the early periods after the CCE and that the *RI* showed an increasing tendency between TT and TMi, as shown in Fig. 3. Our results are consistent with those obtained by Dong et al. (2009). Both severe rainfall and earthquakes would change the condition of *RI*, in terms of both the magnitude and number of debris flow events. The data for the Chenyulan watershed suggest that the Chi-Chi earthquake was the most significant influence on the rainfall threshold for debris flow occurrence.

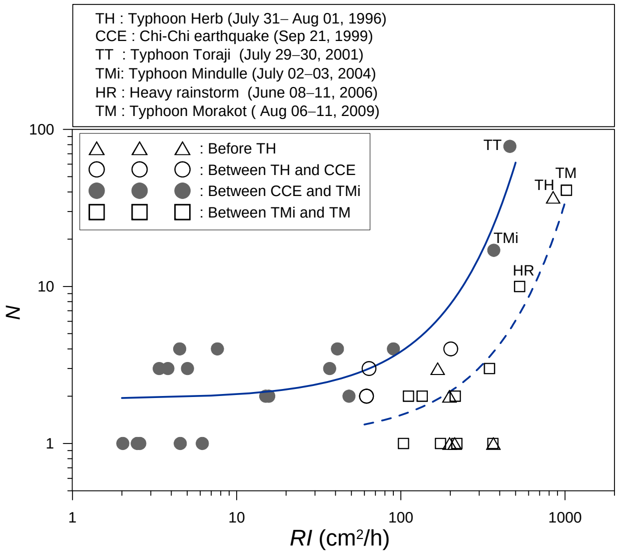


Fig. 4. Relationships between the number of debris flows N in a rainfall event and corresponding rainfall index RI for two groups. The first group refers to the period significantly affected by the Chi-Chi earthquake (2000–2004; solid line), while the second group represents the periods not significantly affected by the Chi-Chi earthquake (dashed line).

4 Relationship between rainfall characteristics and the number of debris flows

We allocated the debris flows to two groups: one representing the period between CCE and TMi (2000–2004), in which the rainfall condition required for debris flow occurrence is significantly affected by CCE (shown in Fig. 4 as solid circles); the other representing the periods that were unaffected by the CCE, i.e., before TH, between TH and CCE, and between TMi and TM (shown in Fig. 4 as open triangles, circles and rectangles, respectively). Comparison within the periods without CCE effect shows that the *RI*s between TH and CCE (open circles in Fig. 4) are smaller, and the corresponding number of debris flows N is slightly greater compared to other periods (before TH, and between TMi and TM). This result may be attributed to abundant loose debris remaining on slopes or in gullies in the early periods after TH; these deposits were more susceptible to the effects of rainfall, and served as source material for subsequent debris flows. The relationships for the number of debris flows (N) associated with a rainfall event of rainfall index (RI) in the two groups are shown in Fig. 4, and represented by Eqs. (1) and (2).

$$\log(N) = 0.290 + 0.003(RI - 2) \qquad (1)$$

for the period between 2000 and 2004

$$\log(N) = 0.121 + 0.0015(RI - 60) \text{ for other periods} \qquad (2)$$

Here, the coefficients of determination for Eqs. (1) and (2) are $r^2 = 0.78$ and 0.75, respectively. Equations (1) and (2) show that the number of debris flow events increases with the increase of rainfall index. N is larger during the period affected by CCE than the periods unaffected by CCE. According to Eqs. (1) and (2), for a rainfall event of $RI = 60\,\text{cm}^2\,\text{h}^{-1}$, the number N of debris flows in the CCE-affected period could potentially be double that of the non-CCE periods. However, for an extreme rainfall event of $RI = 365\,\text{cm}^2\,\text{h}^{-1}$, the value of N in the CCE-affected period could be about six times larger than in the non-CCE periods.

5 Conclusions

Debris flows and their corresponding rainfall events were studied in the Chenyulan watershed, central Taiwan, between 1963 and 2009. A rainfall index *RI*, defined as the product of the maximum 24 h rainfall R_d and the maximum hourly rainfall I_m (i.e., $RI = R_\text{d} I_\text{m}$), was used to analyse rainfall conditions critical for debris flow occurrence. Since the occurrence of debris flow depends not only on the accumulated rainfall, but also on the rainfall intensity, the triggering index *RI* of a rainfall event is introduced herein to indicate either high accumulated rainfall or high rainfall intensity could trigger debris flows. The results show that there were five extreme rainfall events with $RI > 365\,\text{cm}^2\,\text{h}^{-1}$ during the study period (1963–2009), each of which caused 10 or more debris flows in the watershed. These five extreme rainfall events were associated with Typhoon Herb (TH) in 1996, Typhoon Toraji (TT) in 2001, Typhoon Mindulle (TMi) in 2004, heavy rainstorm (HR) in 2006 and Typhoon Morakot (TM) in 2009.

The Chi-Chi earthquake (CCE) occurred in 1999, and caused severe landslides in the Chenyulan watershed. The extreme rainfall events and the severe earthquake were shown to affect the critical condition for the occurrence of debris flows. The critical *RI*s for occurrence of debris flows between 1963 and 2009 could be classified into four categories: the periods before TH, between TH and CCE, between CCE and TMi, and between TMi and TM; and had critical *RI*s of approximately 165, 60, 2 and $100\,\text{cm}^2\,\text{h}^{-1}$, respectively. It is shown that: (1) TH caused numerous landslides and debris flows in the watershed, which reduced the critical rainfall threshold for debris flow in subsequent years; (2) CCE significantly lowered the critical rainfall threshold for debris flow occurrence in the subsequent five years – after CCE, the critical *RI* dropped sharply to approximately $2\,\text{cm}^2\,\text{h}^{-1}$, which was one-thirtieth of that before the CCE (critical $RI = 60\,\text{cm}^2\,\text{h}^{-1}$). The results also show that, approximately five years after the CCE, the critical *RI* gradually recovered from $2\,\text{cm}^2\,\text{h}^{-1}$ to $100\,\text{cm}^2\,\text{h}^{-1}$ (the critical *RI* between TMi and TM).

The study also presented two empirical relationships between the number of debris flows N in a rainfall event and their corresponding rainfall index *RI* for the CCE-affected period (between 2000 and 2004) and the non-CCE-affected periods (1963–1999 and 2004–2009). Higher *RI* of a rainfall event would trigger a larger number of debris flows. According to the empirical relationships, for a rainfall event of $RI = 60\,\mathrm{cm}^2\,\mathrm{h}^{-1}$, the potential number N of debris flows in the CCE-affected period could be double that in the non-CCE-affected periods. However, for an extreme rainfall event of $RI = 365\,\mathrm{cm}^2\,\mathrm{h}^{-1}$, the value of N in the CCE-affected period could be six times larger than that in the non-CCE-affected periods.

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