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ORIGINAL ARTICLE

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Rainfall duration and debris-flow initiated studies for real-time monitoring

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Abstract A rainfall-induced debris flow warning is implemented employing real-time rain gauge data. The pre-warning for the time of landslide triggering derives the threshold or critical rainfall from historical events involving regional rainfall patterns and geological conditions. In cases of debris flow, the time taken cumulative runoff, to yield abundant water for debris triggering, is an important index that needs monitoring. In gathered historical cases, rainfall time history data from the nearest rain gauge stations to debris-flow sites connected to debris flow are used to define relationships between the rainfall intensity and duration. The effects by which the regional rainfall patterns (antecedent rainfall, duration, intensity, cumulative rainfall) and geological settings combine together to trigger a debris-flow are analyzed for real-time monitoring. The analyses focused on 61 historical hazard events with the timing of debris flow initiation and rainfall duration to burst debris-flow characteristics recorded. A combination of averaged rainfall intensity and duration is a more practical index for debris-flow monitoring than critical or threshold rainfall intensity. Because, the outburst timing of debris flows correlates closely to the peak hourly rainfall and the forecasting of peak hourly rainfall reached in a meteorological event could be a valuable index for real-time debris-flow warning.

Keywords Landslides · Debris flows · Real-time monitoring · Rainfall thresholds · Chichi earthquake · Taiwan

Introduction

Duration is an important parameter with which to forecast the burst time of debris flows, particularly for a real-time monitoring system. The main triggering factor for landslides is rainfall, which is normally monitored and recorded by the distributed rain gauge stations. Therefore, the intensity versus duration relationship based on rain gauge data is used to monitor landslide and debris flow in real-time. Crosta and Frattini (2002) gathered a worldwide data set and fit as a lower bounds threshold for landslides of pyroclastic covers. The effects of rainstorm characteristics (mean and maximum hourly intensity, duration, and rainfall amount) on triggering of shallow landslides were assessed by Dhakal and Sidle (2004), and Aleotti (2004).

Historical rainstorms demonstrate that a critical combination of rainfall intensity and duration was essential to triggering a debris flow in the San Francisco Bay region (Cannon and Ellen 1985). The threshold combination of rainfall intensity and duration could relate to the balance between the rates at which rainfall infiltrates and drains out of the colluvium (Campbell 1975). Various rainfall parameters including antecedent rainfall, duration, intensity, and cumulative rainfall are used to reflect the rainstorm characteristics for delimiting the threshold or critical rainfall. Keefer et al. (1987) calculated the critical volume of water required to trigger a debris flow based on the threshold parameters of the rainfall intensity and duration. The meteorological parameters of rainfall intensity and duration were also used for mapping rainfall thresholds of debris flow in the San Francisco Bay Region, California (Wilson and Jayko 1997).

In this study, 1,104 slopeland hazard events data, including 153 debris-flow cases, were gathered. Among these, 96 collected historical cases, with the date on which debris-flow was initiated, were recorded, together with 61 cases with reported detail of debris-flow outburst time. This investigation collected and analyzed relationships between rainfall characteristics of peak hourly rainfall, duration and the time of debris-flow burst, as only rarely have studies focused on the influence of rainfall characteristics on the initiation and duration of debris-flows.

Fig. 1 Debris-flow hazard in Hontong primary school hit by Xangsane typhoon in year 2000

Debris-flow historical events collection

Data of hydroclimatic events induced by debris flows were collected from 1989 until the end of 2001. Meteorological events in the data include five rainstorm events and five typhoon-induced heavy rainfalls from Ofelia (June 1990), Herb (October 1998), Xangsane (November 2000), Toraji (July 2001), to Nari (September 2001) typhoon. In these data, only 61 debris-flow events were documented with the triggering time taken from newspapers or reported by interview with local residents.

In 1990, when Ofelia typhoon hit Taiwan, 430 mm of cumulative rainfall and 106 mm of intense peak hourly rainfall, resulted in 29 deaths and 6 people missing island-wide. In 1996, Herb typhoon hit Taiwan, bringing an unexpectedly high cumulative rainfall, up to 1,994 mm, leading to 27 people dead and 14 missing. After the Chichi earthquake happened in 1999, Xangsane typhoon in 2000 hit Taiwan resulting in 78 people dead and 11 people missing. Figure 1 shows the debris-flow hazard in northern Taiwan, where a primary school was catastrophically damaged when the Xangsane typhoon hit Taiwan. In July 2001, Toraji typhoon struck Taiwan for 10 h, causing a high magnitude of slopeland hazards and resulting in 103 people dead and 111 people missing. During September 2001, Nari typhoon hit Taiwan accompanied by high daily rainfall, up to 820 mm within 1.5 days. The typhoon caused serious flood hazards, with 94 people dead and 10 people missing. In the typhoons, which hit Taiwan after the 921 earthquakes, rainfall related disasters caused considerably more deaths because of the earthquake induced loosening of soil mantles, leading to slopeland hazards which were easily triggered.

The 61 historical debris-flow events were categorized in a debris-flow inventory as shown in Table 1. Information from each event was condensed in a table, including the rainfall histogram, typhoon route, site location, triggering time, and geological information as

Table 1 Time of debris flows initiated and their corresponded rainfall characteristics

Rainfall parameters	Debris-flow corresponded rainfall characteristics		
Time of debris flow initiated	Prior to hourly peak rainfall (16 cases)	At the instance of hourly peak rainfall (10 cases)	Afterward hourly peak rainfall (13 cases)
Rainfall histogram characteristics	Debris flows initiated under intermittent rainfall (within 5 days)	–	Initiated under a rolling rainfall
	Initiated at secondary hourly peak rainfall	–	–
Averaged duration	19 h	25 h	43 h
Averaged rainfall intensity at triggering	50 mm	75 mm	30 mm
Averaged effective cumulative rainfall	302 mm	390 mm	633 mm

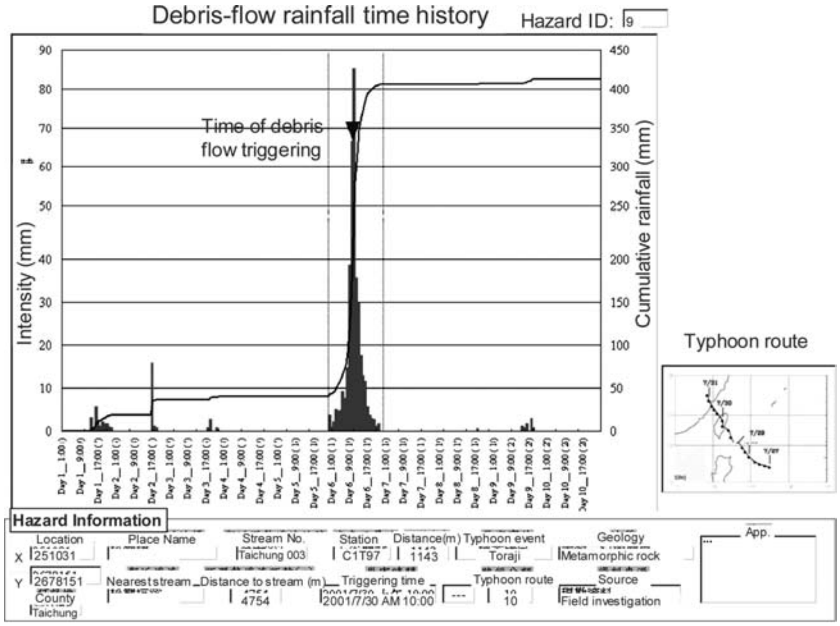


Fig. 2 Histogram of rainfall time history and cumulative rainfall

shown in Fig. 2. The data are divided into three categories: beforehand, afterward, and at the instance of peak hourly rainfall, by the time of debris-flow initiation and its correspondence with the peak hourly rainfall. The effective cumulative rainfall is the summation of cumulative rainfall (14 days prior to debris-flow triggering) and the antecedent rainfall multiplied by a decay factor of 0.9, defining the rate of soil moisture decline within a specific period by the Antecedent Soil Water Status Model (Glade et al. 2000). Two types of rainfall characteristics were separated and analyzed for intermittent rainfall type (within 5 days prior to initiated debris-flow) and rolling rainfall type as shown in Fig. 3.

The data were collected from nine counties, which covering three serious debris-flow counties, including Taipei, Nantou, and Hualian county as delineated in Fig. 4.

Geological setting

To understand the bedrock properties and the effects of rainfall duration on the time of debris-mass outbursts, 61 collected data were superimposed on the simplified geologic map in Taiwan as shown in Fig. 5.

Collected debris-flow sites in northern Taiwan are mainly positioned in alluvium stratum and sedimentary rocks, while those in western Taiwan are settled in sedimentary rock and metamorphic rock. The rocks in the eastern Central Range of Taiwan differ significantly from metamorphic to igneous rock (andesite and andesite proclastics) and to slate rock in the eastern coastal range. The longitudinal valley fault sits in the common boundary of metamorphic rock and the eastern coastal range, in which four debris-flow sites are also located.

Statistical analysis

Statistics and regression analyses were adopted to explore the effects of rainfall characteristics (critical rainfall intensity, duration, and rainfall patterns) on the triggering mechanism of debris flow (rainfall time lag to initiate a debris flow) based on the debris-flow inventory.

Figure 6 presents the statistical frequency histogram for critical rainfall duration to trigger debris flows.

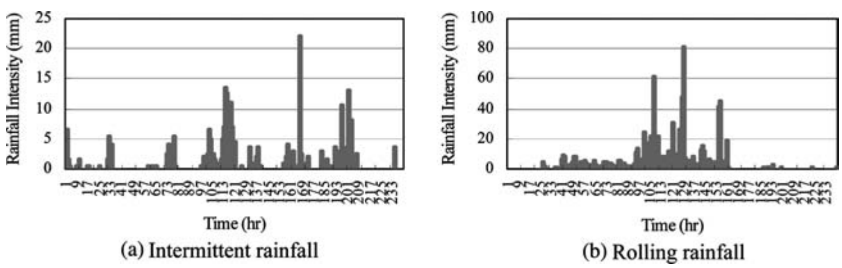


Fig. 3 Example of two types of rainfall characteristics to initiate debris-flow: **a** intermittent rainfall; **b** Rolling rainfall

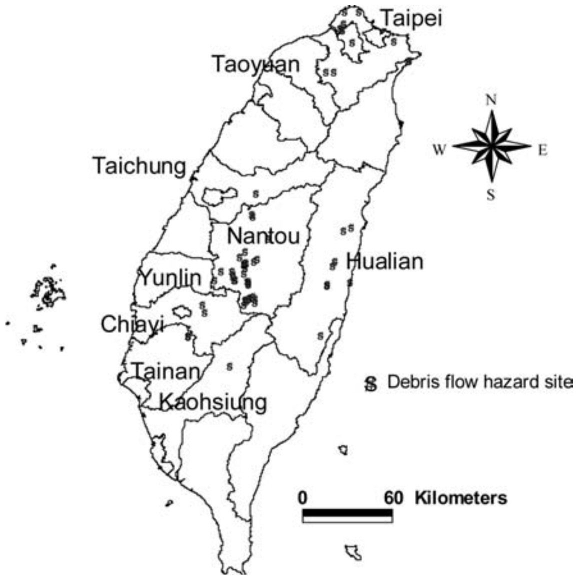


Fig. 4 Site locations of 61 historical debris-flow cases

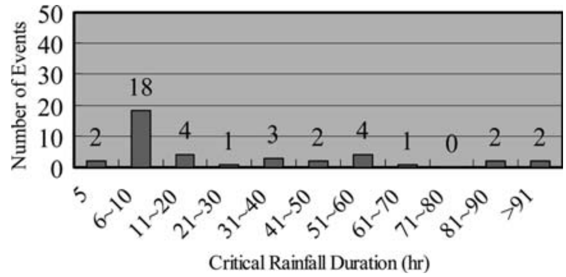
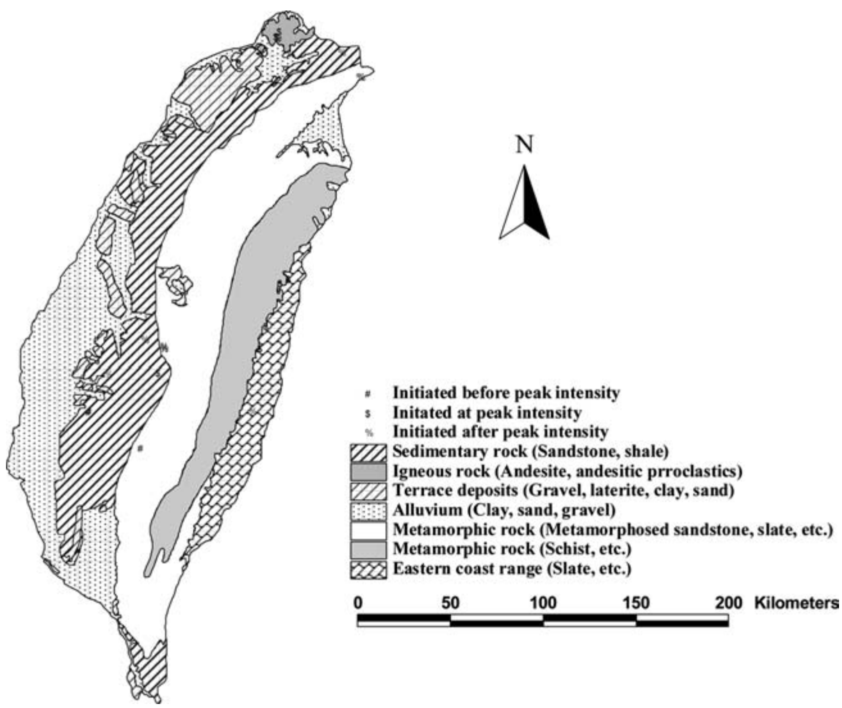


Fig. 6 Frequency statistic for critical rainfall duration

There are 39 statistical cases after taking out debris-flow cases using the same rain gauge station data (39 statistical cases are left). Most debris flows were initiated within 10 h (20 cases) after rainfall started, including cases initiated following the Chichi earthquake (21 September 1999) caused by the Toraji typhoon, reveals the influence of the 921 earthquake in reducing the critical rainfall duration characteristics necessary to trigger a debris-flow.

The time lag histogram for debris-flow initiation to peak hourly rainfall is presented in Fig. 7. Most debris flows (59%) were initiated 1 h prior to and following the time of peak hourly rainfall. The time lag for initiating debris flows is within −13 (prior to the peak hourly rainfall) ~45 h (after the peak hourly rainfall), −1~18 h, and −5 ~ 10 h, for the rainstorm induced, typhoon induced and post −921 earthquake, respectively. The time lag of typhoon-induced debris flows was shorter than rainstorm-induced, and the effects of the 921 earthquakes reduced the time lag for initiating debris flows. The time lag from peak hourly rainfall to initiate debris-flow is further classified into two groups for rolling rainfall and intermittent rainfall (a series of discontinuous rainfalls within 5 days of initiated debris-flow) characteristics as depicted in Fig. 8. Debris flows initiated under the intermittent rainfall were more closely correlated to the peak hourly rainfall than under the rolling rainfall.

Fig. 5 Simplified geologic map in Taiwan (after Central Geologic Survey)



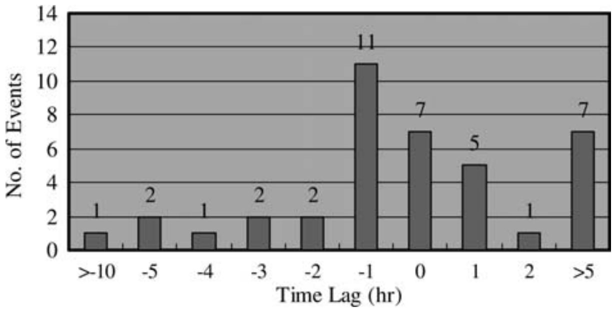


Fig. 7 Time lag for peak hourly rainfall to the triggering of debris flows

Figure 9 shows the critical rainfall intensity versus duration graph. There were 19 debris flows triggered after the 921 earthquakes, in which there were seismically induced landslides within the watersheds, an example of which is shown in Fig. 10 for Hazard ID 455 with 13,400 m^2 (3.9% of the watershed) of landslide areas. The lower initiated rainfall threshold intensity or lower critical rainfall duration to outburst debris-flow is governed by the seismic effects. The lower bound of the rainfall intensity–duration relationship, after excluding the effects of the 921 earthquakes, can be referred to as:

$$I_c = 38.86D^{-0.34} \quad (1)$$

The mean rainfall intensity and critical rainfall duration relationship for the historical data is shown in Fig. 11. The lower bound of the mean rainfall intensity–duration can be regressed as:

$$I = 115.47D^{-0.80} \quad (2)$$

The regressed threshold equation is close to the averaged line as suggested by Guadagno (1991). This finding suggests that a higher rainfall threshold under the same duration is essential to initiate a debris-flow than by the Caine (1980), Ceriani et al. (1992), and Calcaterra et al. (2000) results that were mainly considering shallow landslide cases. A comparison between Figs. 9 and 11 for the critical rainfall-intensity duration and mean rainfall-intensity duration relationships, respectively, reveals that seismically induced landslides within a watershed would reduce the critical rainfall intensity to trigger a debris-flow while there was little reduction of mean rainfall intensity. This observation implies that for those debris-flow cases, the interaction between debris-flow triggering and earthquake effects is undefinable herein. Therefore, the mean rainfall-intensity duration relationship is a better index than the index of critical rainfall-intensity duration for debris flows in real-time rainfall monitoring.

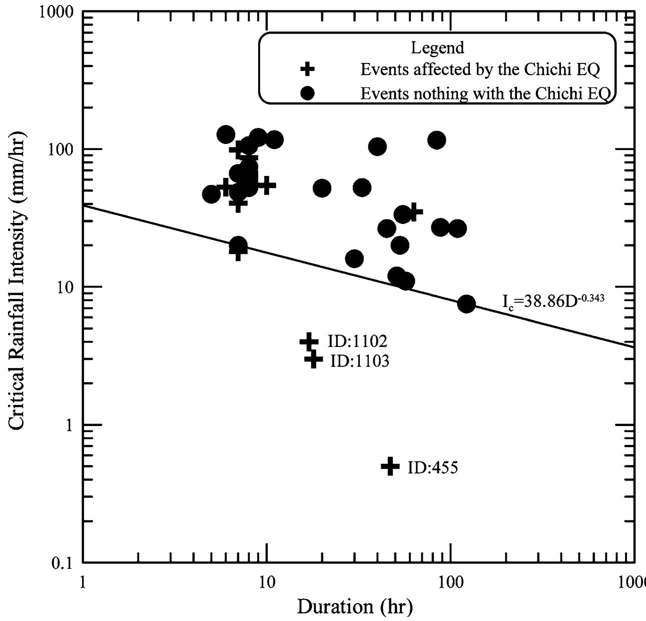
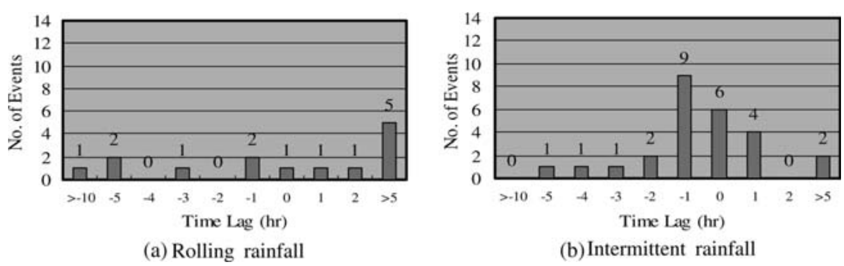


Fig. 9 Critical rainfall intensity–duration graph

Implications for real-time rainfall monitoring

Using the results of statistical analyses, steps toward real-time debris-flow monitoring are divisible into three sequences, including real-time rainfall monitoring for debris-flow triggering mechanisms, geological conditions, and debris-flow initiated time estimation. The first step, monitoring the rainfall by rain gauge, leads to judging the possibility of triggering debris flows by current rainfall data. The geological condition aids the comprehension of source material properties and re-

Fig. 8 Time lag to the triggering of debris flows for different rainfall characteristics: **a** rolling rainfall; **b** intermittent rainfall



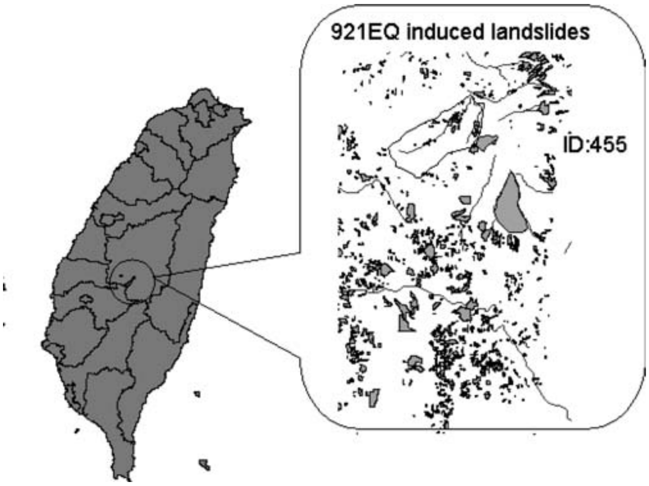


Fig. 10 Debris-flow watersheds affected by the 921 earthquakes

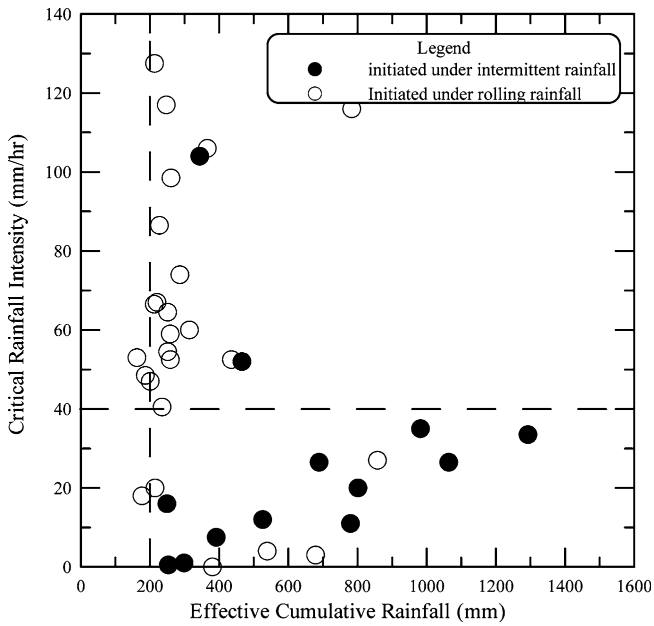


Fig. 12 Critical rainfall intensity and effective cumulative rainfall

gional debris-flow triggering characteristics. Debris-flow initiation time is established by the statistical results of historical events and regional geological conditions.

Triggering mechanism for debris-flow monitoring

Debris flows initiated under a rolling rainfall often burst under higher rainfall intensity than those which were initiated by intermittent rainfall as shown in Fig. 12. The intermittent rainfall-induced debris flows were determined by higher effective accumulated rainfall. In the historical data, the minimum effective cumulative rainfall to initiate a debris-flow was over 150 mm. The 200 mm of cumulative rainfall and 20 mm/h of rainfall intensity or over about 400 mm of effective cumulative rainfall were necessary to burst a debris-flow under a rolling rainfall. For debris flows, initiated through intermittent rainfall, a minimum of 200 mm rainfall was required to trigger debris flows.

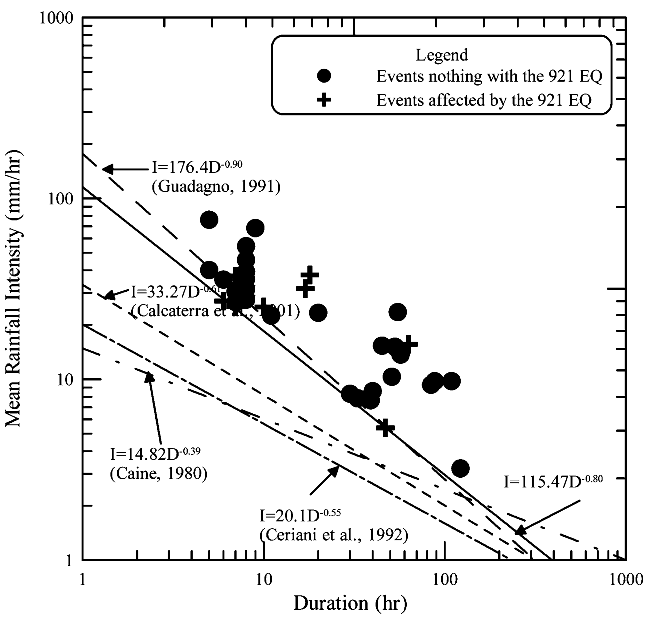


Fig. 11 Critical rainfall duration and mean intensity for initiation the debris flows

Regional debris-flow outburst characteristics

Figure 13 summarizes the statistical results of stream bedrocks and their corresponding debris-flow initiation time. Among the 61 collected data with the initiation time of the debris-flow 90% of debris flows with igneous bedrock were initiated at approximately the same time as the peak hourly rainfall was reached, and only minor cases occurred sometime beforehand. In the eastern coast range, four debris-flow events within the longitudinal valley fault were outbursts at the peak hourly rainfall and only one site in the eastern coast range was initiated afterwards. Streams in sedimentary and metamorphic rocks triggered debris flows less frequently at the instance of peak hourly rainfall and tended to initiate the debris-flow after the peak hourly rainfall, which could reflect the loose or fracture characteristics of bedrocks. In addition to the important effects of regional rainfall characteristics, other factors, e.g., the material properties and physiographic factors, will control the initiated time of debris masses.

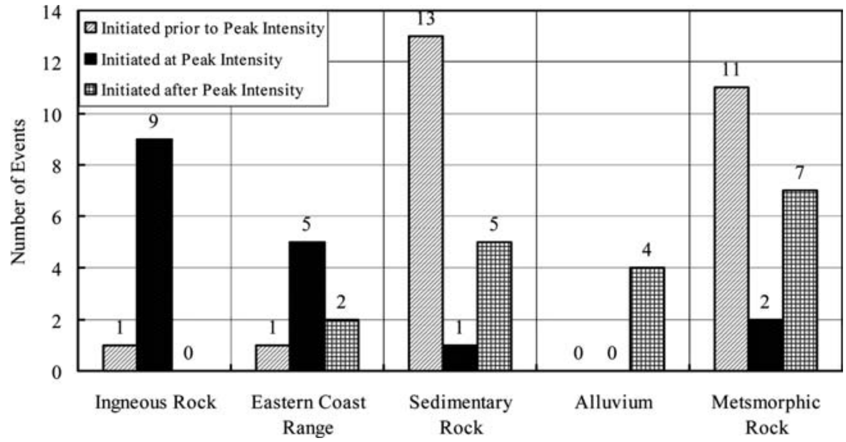


Fig. 13 Histogram showing the stream bedrocks and their corresponded debris flows initiated time

Debris-flow initiated time estimation

Table 2 lists the initiation time of debris flows and corresponding rainfall characteristics for the 61 collected cases, but no rain gauge data were repeated (39 rainfall stations). Debris flows initiated before and after the hourly peak rainfall were ascribed to the longer duration than that initiated at the time of peak hourly rainfall. Debris flows initiated before the peak hourly rainfall were frequently triggered by intermittent rainfall and burst at the secondary peak hourly rainfall. Debris flows that triggered after the hourly peak rainfall were observed to be initiated after a rolling rainfall and attributed to higher cumulative rainfall than other types. Those debris flows initiated at the instance of peak hourly rainfall were triggered at higher rainfall intensity than in the other two cases.

Debris-flow triggering time is estimated based on the rainfall characteristics (duration, intensity, and cumulative rainfall), geological conditions, and is closely correlated to the time of peak hourly rainfall for intermittent rainfall characteristic. Means to measure the time of peak hourly rainfall by satellite or radar images (Hsu et al. 2002; Kidd et al. 2003) is in development and not discussed herein.

Flowchart for debris-flow real-time monitoring by rain gauge

An operating procedure is proposed for debris-flow precautions based on real-time rainfall monitoring. The flowchart for debris-flow monitoring is shown in Fig. 14, with comments as follows:

1. Triggering mechanism for debris-flow monitoring as cumulative rainfall up to 150 mm
2. For an intermittent rainfall characteristic, debris flows could trigger as

(a) cumulative rainfall up to 200 mm, and
(b) reach to Eq. 2,

3. For a rolling rainfall characteristic, debris flows could trigger as,

(a) cumulative rainfall up to 400 mm, or
(b) rainfall intensity over 20 mm and cumulative rainfall over 200 mm, and
(c) reach to Eq. 2,

4. Verifying the regional geologic conditions and debris-flow triggering characteristics, for debris-flow initiated time prior to, at the instance or after the peak hourly rainfall,
5. Debris-flow initiation time estimation.

Nearly 60% of debris flows initiated within the period of prior to and afterward 1 h to the time of peak hourly rainfall reached through an intermittent rainfall was observed by the statistic analysis result. For watersheds under a rolling rainfall accompanied by high cumulative rainfall, debris flows tend to initiate after the hourly peak rainfall. For watersheds through high rainfall intensity, debris-flow is likely to initiate at the instance of hourly peak rainfall.

Conclusions

This study presents an operational procedure based on rainfall characteristics and geological setting, for debris-flow monitoring. According to statistical results of historical debris-flow, rainfall characteristics and regional geological conditions are attributable to the debris-flow outburst time prior to, at the time or after the hourly peak rainfall. Additionally, the seismically induced landslides in the watershed would reduce the critical rainfall duration to trigger a debris-flow and the mean rainfall intensity duration relationship is an applicable

Hazard ID	Time of Triggering		X-coordinate	Y-coordinate	Rain station	Distance to rain station (km)	Typhoon event	Critical intensity (mm/h)	Effective cumulative rainfall (mm)	Duration (h)
1	11 Dec 2000	0:00	300591	2795804	C0A92	5556	Xangsane	116	783.4	84
3	1 Nov 2000	01:00	310375	2795945	C0A93	4088	Xangsane	27	857.7	88
6	30 July 2001	10:00	242060	2675568	C1F88	9399	Toraji	117	247.1	11
9	30 July 2001	2:00	289233	2615065	C1T97	3955	Toraji	74	286.4	8
11	30 July 2001	2:40	294560	2630979	C1T93	4326	Toraji	106	365.8	8
13	30 July 2001	0:00	304203	2617294	C1T96	10823	Toraji	127.5	213.2	6
14	30 July 2001	7:00	231665	2634130	C1I16	5529	Toraji	86.5	227.3	8
16	30 July 2001	7:00	234892	2637620	C1I16	6898	Toraji	86.5	227.3	8
17	30 July 2001	7:00	234730	2626688	C1I16	4361	Toraji	86.5	227.3	8
18	30 July 2001	7:00	235700	2629600	C1I16	1292	Toraji	86.5	227.3	8
19	30 July 2001	7:00	235607	2629326	C1I16	1581	Toraji	86.5	227.3	8
20	30 July 2001	7:00	234436	2628758	C1I16	2656	Toraji	86.5	227.3	8
21	30 July 2001	7:30	234526	2629318	C1I16	2182	Toraji	86.5	227.3	8
22	30 July 2001	7:30	234750	2630092	C1I16	1538	Toraji	86.5	227.3	8
25	30 July 2001	8:00	218876	2624235	C0I11	5078	Toraji	59	258.6	8
28	30 July 2001	6:00	215099	2618839	C1I13	3460	Toraji	18	176.8	7
29	30 July 2001	7:00	240769	2631255	C1I15	3660	Toraji	67	220.3	8
30	30 July 2001	7:30	238221	2606999	C1I07	2935	Toraji	60	314.1	8
31	30 July 2001	7:30	237313	2606253	C1I07	3693	Toraji	60	314.1	8
33	30 July 2001	7:50	241361	2604198	C1I07	6710	Toraji	60	314.1	8
34	30 July 2001	7:30	242919	2632252	C1I15	1301	Toraji	67	220.3	8
35	30 July 2001	7:20	234262	2622926	C1I08	2088	Toraji	64.5	251.1	8
36	30 July 2001	7:30	239915	2608231	C1I07	2670	Toraji	60	314.1	8
37	30 July 2001	7:30	241881	2606503	C1I07	5286	Toraji	60	314.1	8
38	30 July 2001	7:30	235294	2605886	C0H9A	3102	Toraji	52.5	435.3	8
40	30 July 2001	7:30	235550	2604852	C0H9A	2699	Toraji	52.5	435.3	8
45	30 July 2001	6:30	236488	2618346	C1I08	3584	Toraji	48.5	186.6	7
46	30 July 2001	9:00	250292	2646469	C1I03	4995	Toraji	54.5	251.1	10
47	30 July 2001	8:30	240087	2660721	C1H90	6436	Toraji	18.5	73.6	8
48	30 July 2001	8:30	239571	2661941	C1H92	5267	Toraji	16.5	57.2	8
49	30 July 2001	6:00	226458	2624661	C0I09	1124	Toraji	53	162.2	6
50	30 July 2001	7:00	227535	2618605	C1I10	2163	Toraji	40.5	235.0	7
51	30 July 2001	7:00	228575	2618415	C1I10	1161	Toraji	40.5	235.0	7
52	30 July 2001	7:30	227079	2622213	C0I09	2933	Toraji	98.5	260.7	7
55	5 Sep 2001	20:00	299444	2783981	46691	3936	Rainstorm	121.5	616.1	9
56	5 Sep 2001	20:10	299069	2784308	46691	4037	Rainstorm	121.5	616.1	9
57	17 Sep 2001	22:30	208431	2597687	C1M57	2027	Nari	52	465.8	20
58	17 Sep 2001	23:30	293469	2755953	C0A51	2764	Nari	11	779.7	57
59	18 Sep 2001	5:00	288744	2756103	C0A51	3945	Nari	35	982.1	63
26	16 Oct 1998	17:41	305662	2775893	C0A9F	1781	Herb	12	5200	56
106	01 Nov 2000	13:00	333178	2776465	C1A66	3937	Xangsane	26.5	10465	205
148	18 Sep 2001	06:30	197244	2582382	C1O87	4630	Nari	16	4435	57
152	08 June 1998	03:00	197197	2582000	C1O87	4382	Rainstorm	7.5	5590	205
180	09 Nov 2000	03:00	343580	2763359	C0A88	4926	Rainstorm	20	6325	239
199	30 July 2001	01:00	289526	2615798	C1T97	4284	Toraji	66.5	4335	26
228	23 June 1990	14:40	300386	2651249	46699	11262	Ofelia	104	5035	57
248	25 Oct 1998	13:00	292655	2628273	C1T90	5696	Rainstrom	26.5	6245	105
388	20 July 1999	18:20	234572	2602950	C0H9A	1616	Rainstrom	52.5	1565	74
455	18 Sep 2001	06:00	227191	2621039	C1I12	2918	Nari	0.5	2520	61
570	18 Sep 2001	15:00	207091	2602698	C1M48	2392	Nari	33.5	12670	131
686	09 Nov 2000	03:00	342855	2763105	C0A88	5325	Rainstrom	20	6325	239
695	23 June 1990	14:40	305024	2653619	46699	6618	Ofelia	104	5035	57
696	23 June 1990	14:40	285075	2582619	46761	27396	Ofelia	1	2869	52
1031	05 Sep 2001	16:50	299756	2783771	46691	3854	rainstrom	0	4940	34
1050	05 Sep 2001	20:33	298232	2785011	46690	3963	Rainstrom	20	1871	31
1051	05 Sep 2001	20:37	300029	2787714	46691	2668	Rainstrom	121.5	4940	34
1052	05 Sep 2001	20:39	298357	2784784	46690	4045	Rainstrom	20	1871	31
1054	05 Sep 2001	20:13	298230	2785031	46690	3964	Rainstrom	20	1871	31
1055	05 Sep 2001	20:43	298310	2784930	46690	4023	Rainstrom	20	1871	31
1056	05 Sep 2001	20:41	298239	2785012	46690	3969	Rainstrom	20	1871	31
1088	30 July 2001	02:00	225073	2562167	C1V22	4797	Toraji	47	7615	93
1102	30 July 2001	16:00	237123	2617512	C1I08	4624	Toraji	4	4725	19
1103	30 July 2001	16:00	237443	2616453	C1I06	5314	Toraji	3	5990	22

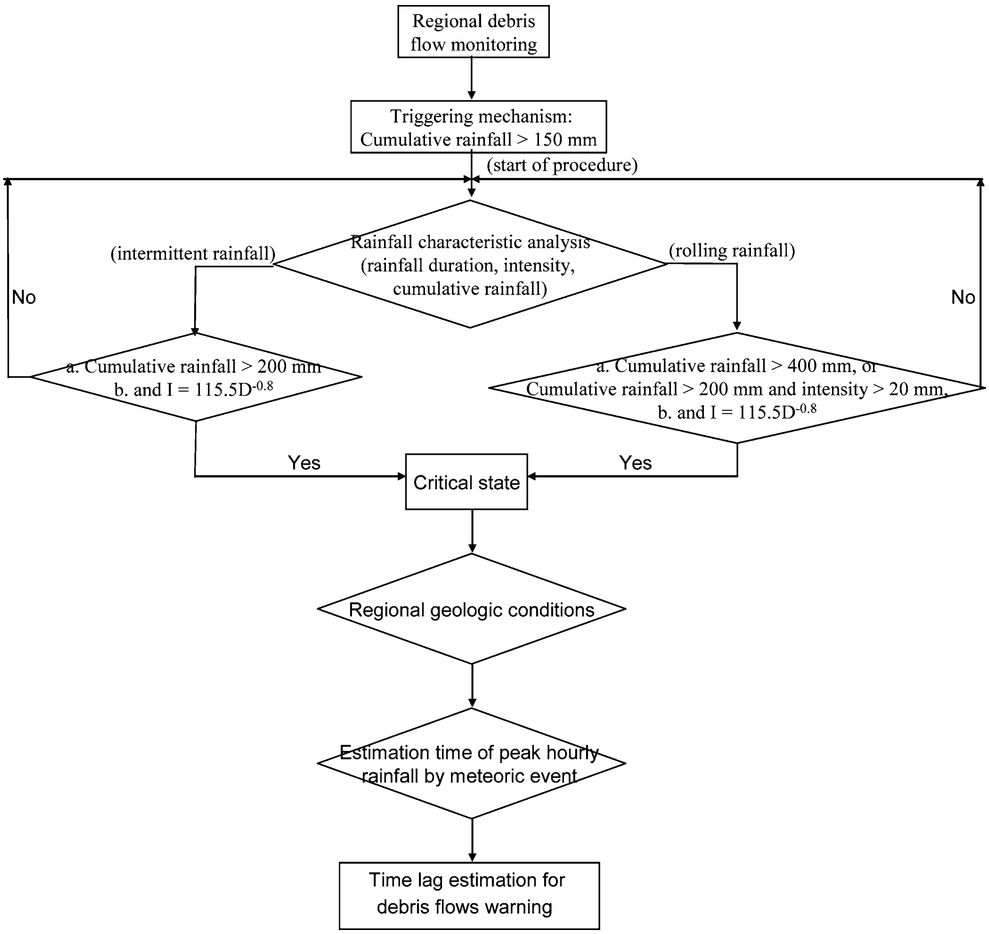


Fig. 14 Operation procedure for debris-flow real-time rainfall monitoring

index for debris-flow rainfall monitoring. Results of this investigation also suggest that a debris-flow monitoring system for island-wide Taiwan considering the different geological conditions and rainfall characteristics is essential for monitoring regional debris-flow outburst characteristics.

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